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A.Executive Summary

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Summary

This document contains:
Introduction where “the delimitation of the field and general methodology are described.

Application domains where the main fields of haptic uses are reviewed. This is an external point of view where social aspects and task characterization are treated.

The functional analysis of haptic interfaces aims to underline some aspects related to antagonist constraints coming from both application demands and technological limitations.

As a complement to functional analysis a special chapter is devoted to tactile interfaces. These devices may indeed be considered as complementary of haptic interfaces to enhance some functional properties of haptic devices. This special chapter also includes an overview on issues concerning tactile devices.

The following chapter deal with the technological analysis and especially with internal components that are mechanical structure, actuators ,sensors and signal processing parts of Haptic interfaces.

The raw material for the 3axis above analysis is gathered in the following part.that is a tour of devices. This technical data-base is established from document collection and from practical exercise of some devices.

Finally this document resumes the activity of the first 9 months period and gives orientations for a preliminary road map.

1 INTRODUCTION

(INPG)

This State of the art is to be considered as a preliminary raw material for the main task of the WP that is the guideline for future developments of Haptic and Tactile Interfaces. This roadmap will aim at considering the today limitations and uses and applications of these devices and will try to propose new perspectives for overcoming these drawbacks. These perpective must emerge from a multidisciplinary approach since the todays tendency seems to be more sector oriented.

The field covered is focused in tactiles and haptic interfaces including both kinaesthetic devices and tactile stimulators.

Terminology and definition :

We will use the term "haptic interface" to design a system that consists at least of a mechanical actuation system able to interact with the human hand or body and in such a way that this mechanical interaction is controlled by a set of input signals. The haptic interface may be also provided with mechanical sensors and in this case it produces data through output signal associated to these sensors.

This definition is more consensual than really pertinent compared to the classical significance of the term "haptics"that refers to the human sensori-motor system. The definition also includes "tactile interfaces" whose another more precise definition is given in the following.

Tactile interface (UNEXE): A device to produce virtual touch sensations. A tactile interface delivers a time-varying spatial distribution of mechanical disturbance at the surface of the skin, usually at the fingertips. Spatial control is achieved by using an array of contactors on the skin, each with its own channel of computer control. The intention is to produce, within the various populations of mechanoreceptors in the skin, activation patterns that correspond to those experienced during "real" touch perception. Spatial distribution of touch sensations is important for representation of edges, corners and surface features of real or virtual objects.

Object of the STA.

The initial object was "Actuators and sensors" for haptic interfaces. It has been extended to the whole technology of these devices that present other critical aspects than simply the actuating and sensing components. The investigation is extended to the mechanical parts and in particular to the related complex kinematics issues, and to the local or low level data treatments associated with haptic interfaces. This last part concerns the local control loops and the data treatment technology that support the virtual objects simulation (for virtual reality uses) or the link with a remote environment (for teleoperation uses).

Methodology

The first step has consisted in gathering general data from two types of sources (1) general bibliographic documents and (2) direct exercise of devices in the places where there are used or developed.

All these data were gathered into technical sheets that were a priori structured according to the 4 mains parts that can be identified in a general way in any haptic interface and already mentioned above : actuation, sensing, mechanical and data treatments (local loop and eventually more general)

The second step is the analysis that we have oriented according 3 directions. 1) The application analysis from which we intend to get more clear understanding of the haptic needs, economical and social importance, specific developments that could bring new technical improvement for the domain, and tasks specifications. 2) The functional analysis is related to the functional modelisation of haptic interface. The work will consist in evaluating the existing systems and from these concept elaborate a common conceptual framework for representing haptic interfaces properties in an unified way. 3) The technical analysis will examine the basic technology employed and try to identify which are the specific and fundamental technological needs for haptic interface that is not satisfied today. These 3 types of investigations are interdependent and these interdependences will also be developed in further steps.

Only a part of these objective has been carried on during this 1rst period. However first orientations for preliminary roadmap on some technical points can have been highlighted and are presented in the last section.

2 APPLICATION DOMAINS.

2.1 Overview

The early haptic interfaces are commonly known as appearing in the teleoperation domain (see §5.1.1) with first active teleoperators as the famous Argone systems. We can remark that the technology required for these systems was based only on elementary servo-control without any heavy dynamic or kinematical computation. Moreover these systems were made of a single position control loop by degree of freedom and consequently the electrical link between the master and slave was not a low energy data link since the corresponding master and slave motors were supplied from a same amplifier.
The active teleoperator technics developed by Goertz at Argone center [Goertz,54] was followed by many developments and uses not only in nuclear domain but also in other scientic, industrial, and hostile spaces exploration domains (see also Annex: history table). Some of these systems were using hydraulic technology especially for obtaining important power amplification while maintaining the similitude of the master and the robot.
The haptic interfaces built in these systems early illustrate the concept of “vis-à-vis” that is related to the human/object position (ref D4b.1 deliverable report). A dual immersive situation appeared a few years later with a wearable system built by General-Electric in which the master and the slave robot were one inside the other in order to obtain a force amplifier exo-squeletton.
A significant technical evolution took place with the Grope project [Batter,Brooks,71] that is a first haptic interactive simulation system. The use of a master interface in conjunction with a computer simulation asked for 3 new technical questions :

1) The computation of the model that replaces the slave/object of a teleoperating chain.
2) The introduction of sampled / digitized data, while teleoperators used mainly analogical links.
3) The supplementary kinematics computation to match joint controls data of the master to the space coordinates of the computed model.

At the time of this project (1971) the computer performances did not allow high computation rate and consequently the performances of this simulator were modest.
At the same time the industrial robotic domains that (as underlined in §2.1.1) could also be seen as another result of the meeting of teleoperation systems and of computers, had already hosted developments since more than ten years. But while sharing the same ancestors the two cousins will not grow at the same speed. The computer role is very different in the two cases and the autonomous robotics did not encounter the same computational limits than early interactive haptic simulators.
During the end of 80s the interest for haptics grew fastly and haptic appeared in particular as a complementary means to enhance the representations of virtual objects and environments that existed in the field of computer graphics. This field of research that will be identified by the term “Virtual Realities” [Lanier,88] could grow significantly thanks to the fast developments of computers and to simulation techniques developped in the domain of computer graphics (see also D4b.1 raport).

The apparition of general purpose commercial devices, in particular, the PHANTOM in 1994 had greatly contributed to popularize the use of haptic interfaces in various domains. Since then, the two important haptic using domains: teleoperation and simulation develop simultaneously and enrich mutually by the technlogy of haptic interface, the conceptual tools for control, the complementary modelisation techniques brought by VR that may be complementary in a teleoperation chain [D4b.1].

This section describes some representative applications domains of haptic interfaces. The primary objective was to propose an axis of analysis of the technology trough the tour of important applications domains and to extract from this analysis:

- Tasks specificities of concerned application. In particular, specific constraints due to the task environment.
- Technology employed concerning in particular the critical component as actuators and mechanics.
- Theoretical background the discipline had provided to haptics.

The intended application domains to examine in such a way were:

- General teleoperation for various industrial, scientific, medical, exploration domains.
- Force amplifiers.
- Cobots.
- Human computer interfaces. Human machines and technical instrument interfaces.
- Simulation in various domains:
    - Training for specialized tasks as surgery, dental, task based on manual skill,
    - Training for piloting and driving.
    - Design simulation, structural design, functional testing.
    - Scientific simulation
- Artistic creation.
    - Virtual musical instrument. Musical synthesis.
    - Instrumental animation, instrumental multisensory art.
    - Virtual sculpture.
- Other general virtual world or objects representation based applications.

The following section is a primary overview that deals only with a part of these topics, and the work must continue during 2nd period.

2.2 Robotics and Teleoperation. (CEIT)

The term robot is very general and hard to define because it can include a large number of machines or elements put together for do a specific task. Usually the word robot is related to a machine with some animal or human like element and able to achieve the same functions.

The fact that the term robot is so general has made it very difficult to agree on a universally accepted definition. The RIA (Robot Institute of America) defined, in 1979, a robot as "A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks". For his part McKerrow (1986) defines it as "A machine which can be programmed to do a variety of tasks in the same way a computer is an electronic circuit which can be programmed to do a variety of tasks".

A robot is made up of functional subsystems composed of:

- **Mechanical System:** Responsible for the interaction with the environment and, usually, fulfils the task. It's made up of a motor subsystem, arms, joints, wrists, tolls, power transmission system etc.
- **Electrical System:** Composed of actuators, control computers, interfaces and power supply. In the case of a pneumatic or hydraulic system, the actuators can be controlled electronically via electronic valves.
- **Control System:** In this system, a computer is in charge of converting high level commands into references for the actuators by applying an algorithm able to guarantee the stability of the whole system.
- **Sensors System:** Responsible for obtaining the robot's status. Therefore, it includes internal sensors for position measure and external visual, sound and touch sensors.

Robotics is the science concearned with the study of robots, and therefore in charge of the integration and coordination of each of these subsystems. In the beginning, robotics was bound to the study of industrial robots, typically used for manipulate objects inside a workspace. Gradually it moves to mobile robotics where the robot moves to the place where it must work.

The main cause for the great development of robotics in the last decades has been the higher efficiency of robots, compared to humans, for simple, repetitive or very accurate tasks. Moreover, robots have allowed humans to expand their ability to inaccessible or hazardous places like space, radioactive environments, high temperature environments or the depths of sea.

Although robotics keep advancing at a great pace, there are still tasks where humans are superior to machines. Robots act logically but must be reprogrammed for make any new task. Humans, on the other hand, can think by themselves, collaborate among themselves and can make decisions when they encounter unusual situations.

Artificial Intelligence is becoming the new research field for robotics. Its objective, is to find a way for solve problems where imagination or human intelligence are required. At the same time, research had been done on the so-called expert systems, these systems try to assimilate, store and learn how to use the knowledge of professions like engineering, medicine or law. In this way, hypothetically, it could be possible to access the acquired knowledge of one of these professionals without the needs for teach another (a time-consuming and expensive task).

2.2.1 Industrial Robots

These robots are the ones used in industry, and are designed to replace humans in repetitive, dangerous or difficult tasks.

Modern industrial robotics have been supported by two connected technologies numeric control and teleoperator. Numeric control is a method for controlling machine tool through coded numbers stored in a storage device. It was developed in the end of the 40s and beginning of the 50s. The first Numeric control machine was presented in 1952 in the United States at the Massachusetts Institute of Technology (MIT). Subsequent investigations lead to the definition of the APT language for programming mechanized centres. A teleoperator is a mechanical manipulator that is controlled by a human from a remote place. The initial work in the design of teleoperators began in the 40s, when the need to handle radioactive material first appeared. A man moves a mechanical arm to a position and these movements are replicated by the remote manipulator. The industrial robotics can be seen as a combination of numeric control and teleoperators technologies. Numeric control brings the programmable industrial machine concept while teleoperation contributes to the notion of a mechanical arm to achieve the task.

The first industrial robot was installed in 1961 to unload parts in die cut operations. Its development was due to the effort of the American inventor George C. Devol and the businessman Joseph F. Englberger who establish the first robots company: Unimation, Inc.

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Figure 2.1 Isaac Asimov and Joseph F. Engelberger

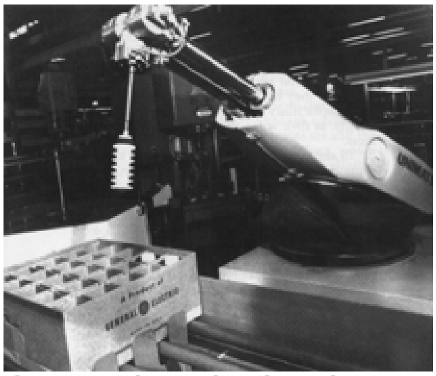

Figure 2.2 First Unimation robot.

One of the first experimental robots, called SHAKEY, was designed by the researchers of the Stanford Institute at the end of 60s. It was able to arrange blocks in stacks using a television camera as a sensor and processing this information on a small computer.

From these beginnings the engineers have been trying to adapt robotics elements to useful tasks. In the middle 70s, General Motors financed a development program, on which the MIT investigator Victor Scheinman built up the so called universal programmable manipulator for assembly, or PUMA. This was the beginning of the robot era.

The gradual automation of industrial companies, most of it in the automobile industry, led to the growth in the use of automatic devices and controls in the production lines. The "automation" term was introduced around the year 1946 and is attributed to D. S. Harder chief engineer at the Ford company. The term is used widely in the manufacturing context but also, to describe a significant substitution of effort and human intelligence by a mechanic, electric or computerized action.

Automation can be defined as a technology related to the achievement of a process using programmed commands, combined with a feedback control that guarantees a correct instruction execution. The resulting system is able to operate without human intervention. The development of this technology has become more dependent on computers and consequently they become more sophisticated and complex.

Figure 2.3 Industrial Robot PUMA 700

In the 80s the automobile industry started introducing robots in their production lines. This trend was more significant in Japan, due to lack of manpower. The companies were forced to search for substitutes to manpower in the only place where they could find it: robotics. Production lines have been automated to the highest degree and have not been equalled up to date by Europe and EEUU. This way Japan has become the most influential country in the development of industrial robots.

The fact that in the 80s many robot manufacturing companies were born, taking advantage of the robotics boom made the market spread. Since then, many small companies have closed, leaving the market to a few but influential ones.

2.2.2 Teleoperation

Teleoperation means remote operation ; that is to have control over something that is far and out of our reach. Teleoperation is applicable when the task is dangerous for the operator or when the scale between operator and workspace are different. That is, when the task is carried out on a hostile environment, as for example at the bottom of the sea, in radioactive environment, space or explosives deactivation or when it is necessary to operate in large or microscopic environments.

In teleoperation an operator handles a multiple degree of freedom robot (called master) which, thanks to a control algorithm, can influence the remote manipulator (called slave). Figure 2.4 shows the relationship between teleoperation elements: operator, master robot, slave robot and control.

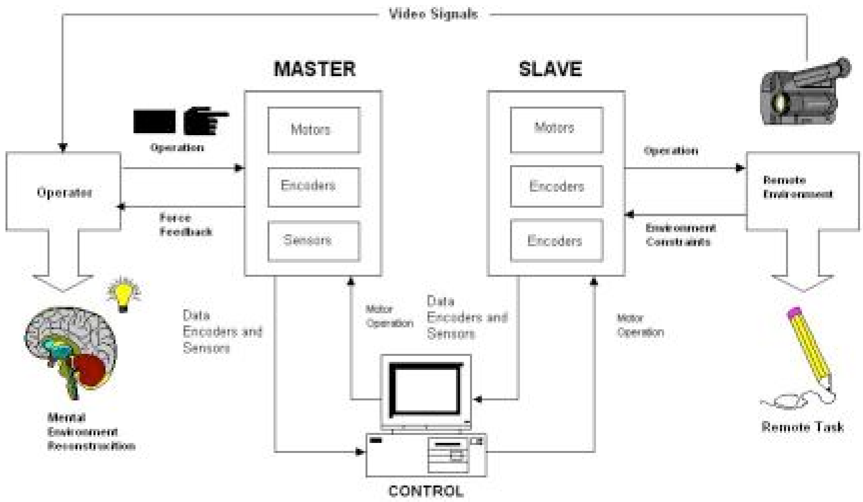

Figure 2.4 Teleoperation Scheme

Teleoperations is sometimes confused with similar terms like telepresence and telerobotics or teleactuation. Some definitions are necessary for a better understanding.

Tele-sense includes touching, seeing, force feeling, proximity sensing, motion sensing and the proprioception (knowing where every extremity is at each moment). The achievement of all of these segments leads to the ideal of telepresence.

Telepresence is the existence of enough sensitive information between the operator and the workspace. This information must be communicated in a natural way to the operator; in a manner that imakes him feel as if he was physically in the remote place. To accomplish this, is necessary to know the human body in detail, how it acts and the type and magnitude of the perceptive signals. Knowing all this data will make it possible to show all these signals to the operator in the best way according to his abilities (Lee et al., 1994; Lavest et al., 1993).

Televisualization is the visualization of remote images. It is one of the most important parts of telepresence. An important drawback is the lack of depth vision, although recent work in stereoscopic vision has been carried out and it is more often used.

Telerobotics is a kind of teleoperation, in which a human acts as a supervisor, communicating information about objectives, bounds, plans, contingencies, assumptions, suggestions, and commands related to a task and, at the same time, receiving information about complains, difficulties or sensorial data while the slave robot realizes the task based on information received from the human operator, its own artificial sensations and intelligence. In this case the slave robot is called semi-autonomous.

Teleoperation means remote operation. It is a more complicated case than telesensation because it includes the operator's actuation over the sensorized motor and decision making. In this case the kinematics and dynamics of the operator must be taken into account.

Finally there is the teleexistence, which is an advanced form of teleoperation; its allows the operator to realize tasks with the feeling that he really is present in the remote environment where the robot works.

Tele-operation, as a means for doing remote tasks, has been present since robotics' beginnings. In fact, industrial robotics is traditionally considered as a convergence of machine tool technology and teleoperated devices. In the 40s, teleoperated devices development began, mostly caused by the need of handle radioactive materials. This was the case of the first teleoperated system built by Goertz at the Argonne National laboratory. Although, this was a fully mechanical system, it had force feedback capabilities (Goertz, 1952). Later on the mechanical transmission was replaced by an electrical one (Goertz, 1954).

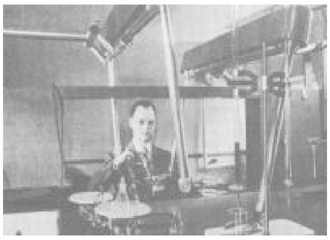

Figure 2.5 First Tele-operated Device with Force Feedback

The concept of radioactive materials tele-manipulation was taken rapidly again and developed at the CEA (Commisariat à l´Energie Atomique) by Jean Vertut.

It was not until the beginnings of 70s when the first teleoperated undersea vehicle was tested, known as Cable-controlled Undersea Recovery Vehicle (CURV). It was developed by the Ordnance Test Station, one of the father laboratories that originated the company SSC San Diego Robotics.

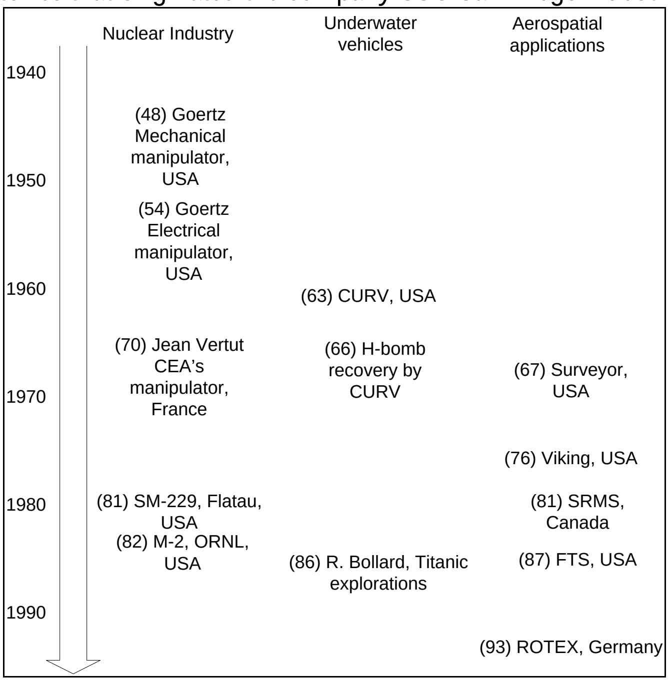

Figure 2.6 First advances in teleoperation systems.

Subsequently, teleoperated systems began to be used on mission outside earth. This figure resumes the principal developments in teleoperation until the beginning of 90s.

Control of Teleoperated Systems

The control of teleoperated systems can be achieved through two strategies. The first is known as unilateral control, that is, the master generates a reference trajectory that must be followed by the slave robot. The second is bilateral control, where in addition to the trajectory generation there is a contact force feedback from the slave to the master. This feature is known as force-feedback.

Ideally, bilateral control pursues a perfect coupling between both robots, as if there was a rigid link connecting them. Three ideal working situation can be distinguished:

1. Positions of the master and the slave robot are identical, no matter what input of the system is.
2. The master and the slave are subject to the same force, no matter the environment and operator's arm dynamics.
3. Response 1 and 2 are fulfilled at the same time.

If the last point is verified the system is able to transmit to the operator the remote environment accurately. This means that the system is perfectly transparent. Unfortunately, an opposition between stability and transparency exists (Lawrence, 1993). A stable control scheme for any kind of task normally would not be very transparent and another transparent scheme could easily be unstable.

Bilateral control algorithms have been traditionally classified according to the exchanged information between the master and the slave robots:

- Force-Force: applied force upon the master is transmitted as a reference to the slave and the applied force upon the slave is transmitted to the master (Kazerooni, 1993). These controllers are transparent but tend to be unstable.
- Position-Position: The slave robot controller receives the master's real position as reference and vice versa. Historically, it was the first control used for force feedback. Is very stable but little transparent. (Salcudean, 2000).
- Force-Position: The master sends his position and the slave its force (Peñín, 1997). It is the most intuitive structure and its stability and transparency characteristics are intermediate.
- Position-Force: the master is position controlled while the slave is force controlled. Rarely used.

These schemes are generalized in the four channels controller (Lawerence, 1993), where the exchanged informations are the positions and forces of both robots.

This classification implicitly refers to the duality of a robot's work position. On the one hand it is interesting to have a good position controller, which permits the positioning of the manipulators in the desired positions, and on the other hand, the force control is needed when a task with contact is executed.

Teleoperation Issues

One of the main problems in the realization of a teleoperated systems is to get the operator to interact with the slave robot in the most human way possible. The most natural way to achieve this is by giving commands and receiving information via voice or stereoscopic images with force feedback, roughness, optional predictive simulation and assistance to solve any kind of errors that can arise. Integration of all these characteristics is a difficult task, and usually it is common practice to develop a system specialised in only one of these characteristics.

The fact that every mechanical system has an associated mass makes it very difficult to achieve the force feedback ideal case for any situation and any object. The drawback effect generated by the mass can be masked using control techniques but is very difficult to eliminate because of the instabilities that arise. Therefore it is necessary to find a compromise that guarantees an adequate behaviour in any situation.

In any robotic system with force control and especially in a teleoperated one, two fundamental tasks can be distinguished: position control for positioning the manipulator and force control for the desired task. These two tasks have opposing characteristics: a position controller it is not suitable for force control and vice versa. Due to this, it is easy to find systems where the architecture of the controller is switched depending of the task. This is the basis for the impedance hybrid control. The switch between architectures can be the source of instabilities since the collisions are very fast transitions.

At the same time, an opposition between stability and transparency exists (Lawrence, 1993). A stable control scheme for any kind of task would normally not be very transparent (the behaviour will be "sluggish", showing an excessive damping), and a transparent control scheme for some other task could be instable when it collides with a rigid object.

Another important problem with force feedback is the delay of the signal (Sheridan, 1993). This is a very interesting problem and it has been the aim of many studies. This situation can happen in control of artificial satellites or spatial vehicles where the control signal takes a long time to travel the long distance that separates them from their controllers. To solve this problem a number of solutions can be adopted. One of them is to give some autonomy and intelligence to the slave robot, in a way that knowing the final position, where we want it to go, the robot will be able to do the intermediate steps to reach it. Another interesting solution is to have a simulation of the remote environment that informs us of the situation of the slave robot taking into account the time difference. In (JiaCheng Tan et al., 2000) can be seen an application of this idea running on internet. The most important problems of this kind of system is the discrepancy between the virtual model and the real slave dynamics.

Applications

This section summarizes the main fields in which examples of teleoperated systems can be found: space, underwater, mining, As it is said, mainly, a teleoperated system is used if a task must be undertaken in hostile environments for humans such as in mines, outerspace, zones of high radioactivity, bomb disposal sites, underwater, etc. In these situations, the master robot is kept in a safe zone while the slave performs the desired task in the remote hazardous environment.

Note, that not every teleoperated system is capable of force feedback. However, the force information is very important for the operator to get the feeling of the magnitude of the force/torque exerted by the slave robot in the remote environment.

Moreover, samples of partially teleoperated semi-autonomous working machines can be found: Simple tasks can be automated easily whereas more sophisticated ones still require the skills of an experienced operator. When most of the work cycle of the robot machines is automated one operator can easily handle several machines from the one place. However, teleoperation is also the most natural technical solution in cases where robotic machines are used for individual and unique operations (Sheridan, 1995).

<u>Space</u>

Space applications may be one of the most popular field for teleoperation. The main issues are:

- Safety: in all space operations there are important risks, which can lead to the loss of astronauts' lives.
- Costs: in space operations the equipment needed for human passengers is much more expensive and weights more than teleoperation systems.
- Time: long space missions can take several years, which is not possible for manned flights.
- This last point brings the problem of teleoperation over long time delay, which is typical for space missions: among the scientific community it is well know that the longer the distance between the master and slave robot, the longer the communication delay between the local and remote systems will be. Specially in the force feedback loop, this time delay may cause system instability.

In those cases, instead of closed loop control, a "move and wait method" is used. The vehicle is operated by open loop commands without immediate feedback. After one or more commands have been executed, the operator waits for confirmation and feedback.

Another possible solution is to generate force feedback information from a virtual reality environment. The virtual model is created in the ground-based computer, and force reflection information is provided to the operator from this environment. Unfortunately, there is always a mismatch between the virtual and the real world.

The first successfully teleoperated vehicle on the moon was Russian Lunakhod 1 at the start of the 1970's. Lunakhod ran 10 kilometers over 11 days. The communication delay was of several seconds.

A much longer delay was faced at the end of 1990 when NASA's Sojourner landed on Mars. Despite the 10 - 20 min. control delay, Sojourner was successfully operated over the planned 7-sol (Martian day) period.

Figure 2.7 Teleoperated space rovers: Lunakhod 1 and Sojourner.

In 1993, the German Space Research DLR developed the Robotic Technology Experiment, ROTEX, aboard the Space Shuttle Spacelab mission D-2 (Hirzinger et al., 1993). This experiment was a modified version of an industrial robot manipulator mounted inside an enlarged Spacelab experiment rack. The ROTEX robot arm contained a computer controlled gripper, and a rich array of sensors for position, contact force, and proximity.

More recent example can be found in (Hannaford et al, 1995), were a small serial manipulator is described to perform high precision teleoperated tasks (about 5-10 microns) in space.

ARS/A(Aerospace Robot System for Aoba arm) [1] is another test-bed to establish technologies for earth-to-space teleoperation. This prototype is a 6DoF teleoperated system composed of an industrial manipulator A-ARM (Aoba-ARM) as the slave, and a 6-DOF compact haptic interface as the master arm.

The main challenges in space applications are: communication time delay, restrictions of communication capacity, limitations of computation power on board etc. In addition, the space systems demand a high level of safety and reliability since a miss-operation may induce serious damages to human life or to the space system itself (Tsumaki, 1997).

To validate the development, the system was Internet tested between DLR in Germany and Tohoku University in Japan.

[1] http://www.space.mech.tohoku.ac.jp/html/research.html

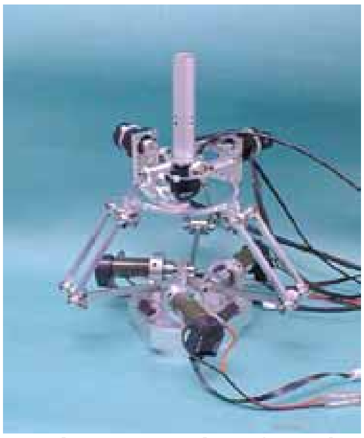

Figure 2.8 The master robot of ARS/A system.

Underwater

The underwater explorations and water structures building require the use of Remote Operated Vehicles (ROVs) and teleoperated systems. One example of underwater pipeline assembly can be seen in (Messina, 1998).

It can be said that the underwater operations were one of the first mobile applications where teleoperation techniques were adopted. Today, these techniques are quite developed.

The underwater ROVs probably represent the largest commercial market for mobile vehicle teleoperation. ROVs are used in surveying, inspections, oceanography and different simple manipulation and work tasks, which were traditionally performed by divers. The most recent systems can also perform some autonomous tasks. One sample is 'Victor'[2]

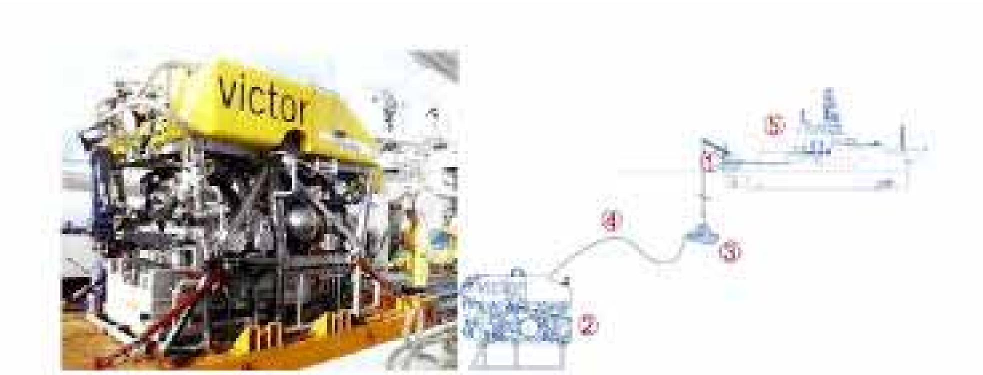

Figure 2.9 Submersible Victor.

If a task must be undertaken too deep for traditional divers, a ROV can be used instead. Such a situation occurred in November 11th, 2002, when the Prestige oil tanker sank about 250 km off the northwest coast of Spain, causing considerable environmental damage along the coasts of both Spain and France.

One possible solutions to the pollution problems caused by the wreck of the Prestige is to send a ROVs to seal the oil tanker at 4000m. This kind of robots should be able to overcome the following problems:

- High pressure.
- Waterproof.
- Use of stainless steel (sea water contains high salt levels).
- Batteries with high autonomy (or use of umbilicals)

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[2] http://www.ifremer.fr/fleet/systemes_sm/engins/victor.htm

A brief survey of ROVs can be found in (Yuh, 2000) and in (Yuh et ak., 2001).
Some of those ROVs have on-board robotic arm. Those arms are used as the slave robot of a bilateral controlled system.

Military and Antiterrorist

The military field provides several possibilities for teleoperated systems. Some of the most common is bomb disposal, such as the example that can be seen in (Hirose, 1998), or surveillance. These vehicles are teleoperated with closed loop control over radio or cable connection. Typical of vehicle equipment are camera, infrared cameras, manipulators, hydraulic guns, shotguns and non-lethal guns. In this case, the manipulator may or may not have a force-feedback loop.

More samples of military teleoperators can be found in (Davies, 2001), (Hewish, 2001). In any case, the main features of these telerobots are the robustness, reliability and capability in overcoming unforeseen obstacles.

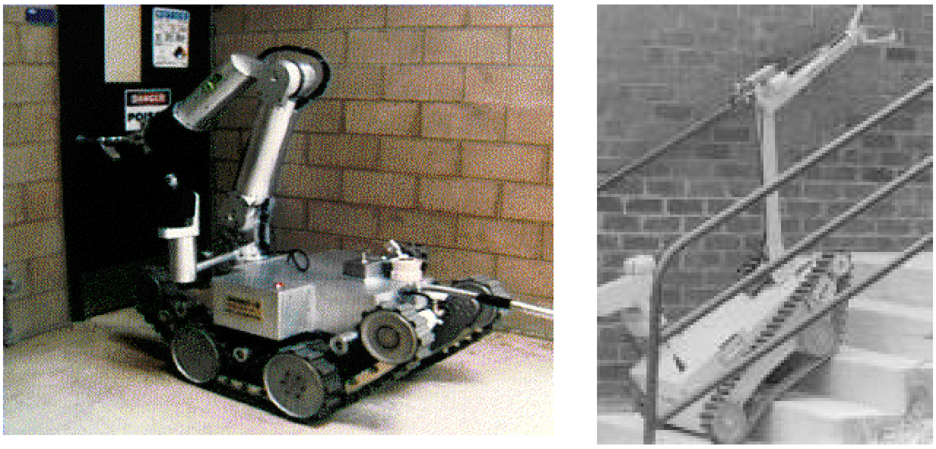

Figure 2.10 Bomb disposal robots.

Medicine

Medicine is a promising field for robotics and teleoperation: The robots can be used for local surgery and telesurgery, robotic systems with integrated imaging for computer-enhanced surgery, and virtual reality (VR) simulators enhanced with haptic feedback, for surgical training, etcetera. Surgical robots can be classified into three categories:

- semi-autonomous systems,
- guided systems,
- teleoperation systems.

Special robotic arms have been designed in one or more of these categories to meet the requirements of various surgical specialties, since in surgery each discipline has a special set of requirements, dictated by the anatomical structure and the surgical procedure.

A teleoperated system can also aim to enhance the dexterity and sensation (micromanipulation) of regular and minimally invasive surgery (ex. A laparoscopic surgery can be seen in (Cavusoglu, 1999)).

In those cases, the risks are smaller and the recovery time remarkably shorter than in the traditional open wound surgery.

Figure 2.11 Laparoscopic nose operation

Figure 2.12 Transatlantic surgical operation, using ZEUS system by Computer Motion.

Provided with high band communication links, it would also be possible to operate on people remotely, especially in isolated areas where this kind of cares is unavailable.

ZEUS is a sample of commercially available surgical robot (Steven, 2003), that has appeared even in non-scientific journals on September 2001, when a patient in Strasbourg (France) was successfully operated from New York (USA). Another example of commercial surgical robot is da Vinci by Intuitive Surgical[3]. ZEUS and da Vinci are designed and equipped with a wide variety of tools in order to be used across different surgical operations.

Figure 2.13 Da Vinci device.

Interested readers can find a brief review of medical robotics in (Russell, 20039.

Civil engineering applications

In civil engineering, the use of robots is very useful due to the large number of accidents that occur in the working area. That's why it is convenient to use teleoperated robots to carry heavy loads or to perform very repetitive movements. The machine is always supervised by the human while accidents are almost completely avoided. There are many examples but a small subset of them is described below.

For example, in mining, teleoperation has already been in use for two decades in cases where the mining area was not totally safe. Drill vehicles and loaders are driven manually in the safe parts of the mine, but teleoperated in areas where safety can not be guaranteed (Shyu, 1997).

Teleoperated rescue vehicles have also been developed for mines (Ralston et al., 1998) called Numbat. It operates in conjunction with rescue teams as they enter a mine after an emergency. It moves ahead of

[3] http://www.intuitivesurgical.com

the teams under remote control through the mine and transmits to the surface video or infrared images of the hazardous areas, as well as data on the atmospheric conditions.

Figure 2.14 Mine emergency response robot Numbat[4]

Figure 2.15 Robot Crane for Equipment Transport

Another well known sample is the teleoperated crane for building construction. They carry all the materials form the ground to different levels. It should be very difficult to perform it in a manual way.

The excavators are also obtaining benefits with the teleoperation technologies. The operators usually command the hydraulic cylinders separately and spend too much time learning the behaviour of these machines. The use of advanced operated systems permits the user to perform the precise movements of the end-effector of the excavator in a more intuitive manner (Salcudean et al., 1999).

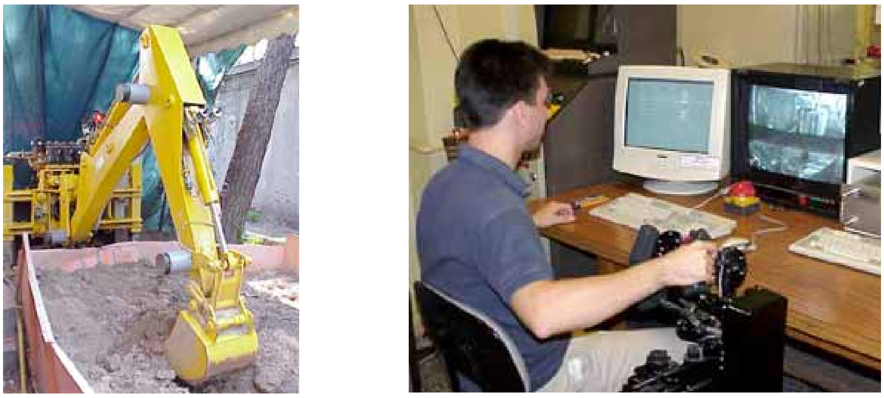

Figure 2.16 RETINA Project: a Teleoperated Excavator (Barrientos et al, 1999).

Nuclear installations

It is clear that radioactive material is very dangerous for human beings. Thus, the exposition time during which the operators are in a radioactive environment, must be as short as possible. For this reason, telemanipulators have been developed around the international nuclear industry, in order to improve the safe by means of remote handling of irradiated material under direct human control. (Bustamante, 1996) summarizes the tasks which have to be undertaken by robotic systems:

- Monitoring: radiation levels, temperature, humidity, noise, equipment tests…
- Surveillance: nuclear power station security, operator's work in contaminated areas.
- Checking: valve conditions, pipe leakage, hot spots, cracks on the reactor's vessels, etcetera.
- Maintenance: Repairing or replacing parts, filters, tool and equipment transportation, painting, tank and polluted pool cleaning, welding, dismantling, etcetera.

[4] http://www.cat.csiro.au/automation/projects/numbat/numbat.htm

The monitorization can be undertaken by means of fixed or mobile robots. The main issue of fixed robots is that they received radiation continuously, so their lifetime is greatly reduced. To avoid this problem, the robots are mounted on ROVs (with or without guidance). Those ROVs can be kept in a shielded garage, protected against the radiation sources. Examples of this kind of robots are the MARK series by Toshiba.

Figure 2.17 MARK II Toshiba Corp.

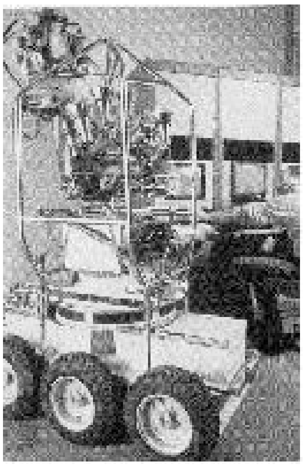

Figure 2.18 Inspection robots: ROVER I, Carnegie Mellon University (left), ROBICEN III, CEIT (right).

Two robots specialized on remote inspection are : ROVER I, used in Three Mile Island plant and ROBICEN III (Savall, 1999) that can measure the thickness of the wall of vessels.

Bilateral Master-Slave Manipulators have been developed around the international nuclear industry in order to improve safety by means of remote handling of irradiated material under direct human control.

A master control arm is typically a mechanical reproduction of a remote slave arm (the master gripper being replaced on the slave by a scissor, pistol, or similar control grip device). In the very first prototypes, we can find the master and slave robots linked by means of chains, cables and the most recent ones, by some other electromechanical motion system.

The master robots may or may not be kinematically similar to the remote slave device, such as the NEATER system of AEA Technology Products & Systems[5] that has a Stewart platform as the master and an anthropomorphic robot as the slave. A similar prototype developed by CEIT can be found in (Sánchez, 2002). This prototype was designed to perform simple tasks such as drilling, milling and handling material inside the controlled area.

Figure 2.19 NEATER teleoperated system of AEA.

[5] http://www.aeat.co.uk/prodsys/subdivisions-div/NEATER/BSP_joystick.html

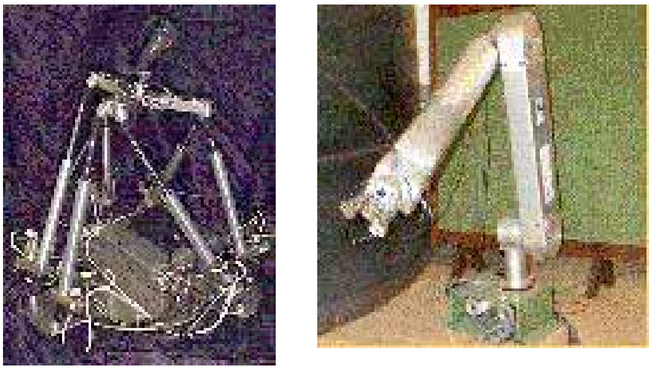

Figure 2.20 Stewart-Maliba: a 6DoF teleoperated system, CEIT.

In the case of complex tasks, a redundant robot can be used as the slave (Rubí, Rubio et al. 2002).

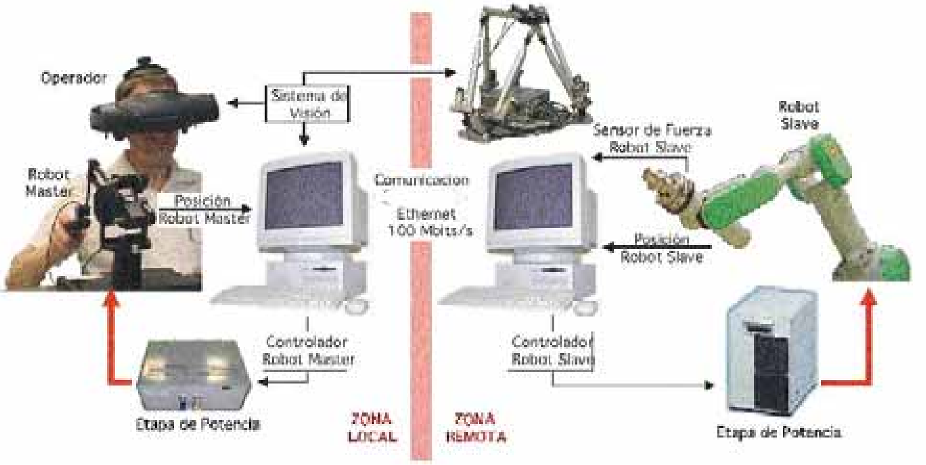

Figure 2.21 SIMANTEL teleoperated system (Rubi, et al, 2002).

<u>Other applications</u>

Generally speaking, teleoperated systems can be used whenever a task must be undertaken in hostile or hazardous environments. Thus the list of applications should be very large. However, only one more example is given in this section.

This example is related to the electric industry : the ROBTET teleoperated system presented in (Aracil R., et al, 1995). ROBTET is designed for repair and inspection of high voltage lines without cutting off electrical supply.

Figure 2.22 ROBTET prototype.

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2.2.3 Haptic technology in nano-manipulation. (INPG)

In the field of nanotechnologies, the use of force feedback devices linked to the Scanning Probe Microscopes started recently [Robinet, 92]. Only few research groups succeded to develop a so-called nanomanipulator allowing the user to act at a nanometer scale. From the family of SPM instruments, the Scanning Tunneling Microscopes (STM) and Atomic Force Microscopes (AFM) are the most widely used in the nanomanipulator chains. A STM probe allows manipulation of atoms or molecules by applying voltage pulses between the probe and the conducting sample. AFM probe has a cantilever with a very sharp tip such that the cantilever deflection or vibration resonant frequency are changed due to the attractive or repulsive interatomic forces between the tip and the sample atoms, and thus, an AFM can realize more mechanical tasks like pushing and identing micro/nanoparticles. Different from a STM that gives only 3D topology data, an AFM can provide both topology and interaction force data. This property makes AFM reliable instruments for force feedback from the nanoworld to the macroworld. Some technical data are presented in the following for the most known nanomanipulators presented in a chronological order.

University of North Carolina

The nanomanipulator [Robinet, 92] developed at Center for Computer Integrated Systems for Microscopy and Manipulation (CSIMM), Chapel Hill, USA consists in three parts that are interconnected by software: an AFM (plus controller), a graphics engine/interface and a Phantom force stylus (plus controller).

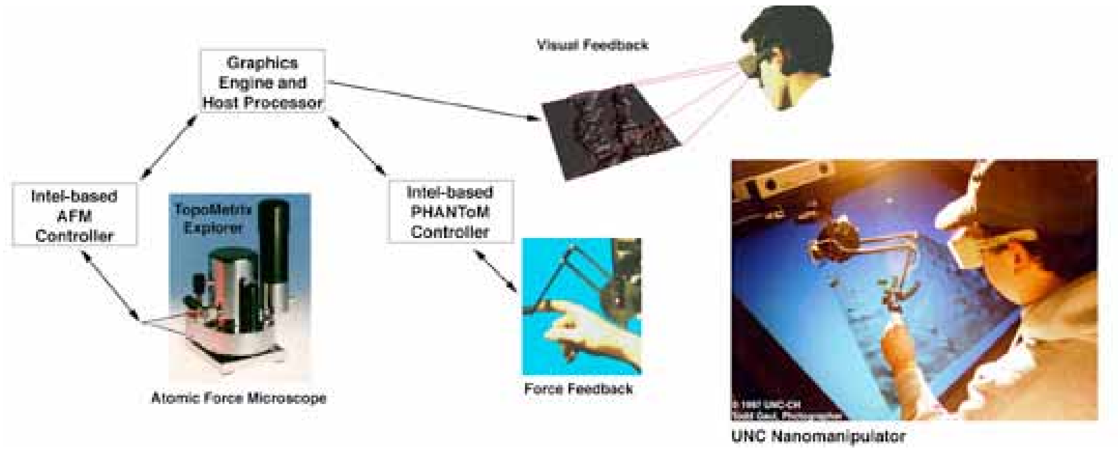

Figure 2.23 North Carolina nanomanipulator

Applications: This device is used to examine and manipulate carbon nanotubes, adeno virus particles, fibrin, DNA/protein complexes, and mucin [Taylor, 93]. By means of Phantom device the lateral position of the AFM tip is directly controled; real-time force feedback indicates surface height and allows guiding the motion of the nanotubes during manipulation, when the tip cannot scan the surface.
Used technology: The data coming from the microscope (topography, frictional force images, error signal images, compliance) are sent to the Phantom controller, which re-construct a "feelable" surface for the user. The data are presented to the user as a hard surface that can be traced with the stylus. The user just feels the 'bumps' or 'valleys' of the topography of the sample, or raised regions corresponding to high friction, respectively lower regions as low friction. The user does not directly feel forces proportional to the actual forces acting on the cantilever, but a surface representation that is simultaneously reconstructed by Phantom controller from the microscope data. In imaging mode, the Phantom force stylus can be used to either feel the surface, to move the surface with 6 DOF or to zoom in and out. In manipulation mode, the user has control over the movement of the AFM tip.
Signals processing: The AFM tip can be moved following the x-y-z directions, while the user feels the lateral forces (x-y direction) related to the direction of tip displacement (normal force is kept constant) and the normal force (z direction) when the tip is placed on the sample (lateral force is kept constant). The microscope controller runs at 100 kHz for data collection and microscope feedback, the Phantom

controller runs at 1kHz to reconstruct the surface, while the graphics engine updates the 3D VR display at 20 Hz.

Workspace: The scaling factor between the Phantom force stylus and the image is such that the range of the stylus (30cm) corresponds to the range of the image on the screen [Guthold, 00]. Operating on a 300x300nm^2 or a 30x30µm^2 image translates into a scaling factor of 10^6 or 10^4, respectively.

Carnegie Mellon University

The nanomanipulator developed by Metin Sitti and Hideki Hashimoto [Sitti, 98] links an AFM with a 1DOF custom developed haptic device.

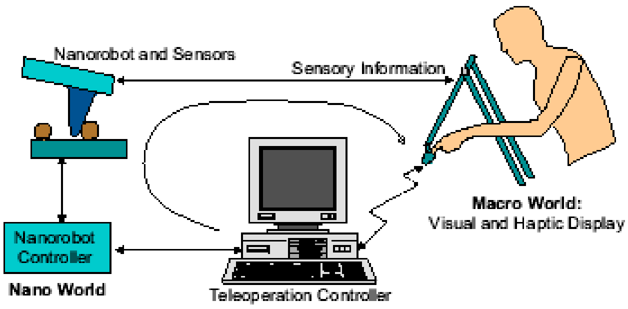

Figure 2.24 Direct teleoperation control

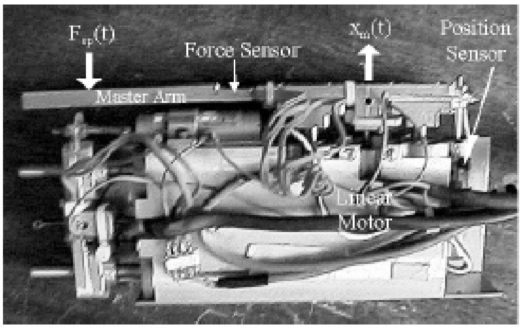

Figure 2.25 1DOF haptic device with linear motor, and force and position sensors

Applications: Main manipulation tasks are pushing/pulling, indenting and touching nanoobjects.

Used technology: In the former approach, a human operator directly in the control-loop manipulates the nanoobjects by using a man-machine user interface. Later developments, the operator controls the nanorobot or sends task commands to the nanorobot controller. The developed haptic device is used as master device and consists of a linear motor, which can be modeled as a simple DC motor and has the following parameters: bandwidth 30Hz, range 20mm, friction ± 3.15mNm. The operator puts the hand to the master arm, applies a normal force to the arm tip and meanwhile feels the arm motion. There is no power transmission from the operator to the master arm, the arm moves by motor control every time in accordance with the operator force.

Signals processing: In the AFM system, x-y scanning bandwidth is around 50Hz in closed-loop or around 200Hz in the open loop, while the force feedback device bandwidth is around 30Hz without any dedicated hardware.

Workspace: The resulting tactile-sensing can be obtained with the scale parameter that is 10^{-6} in position (ratio between the nanoprobe position and the bar pushed by operator position), and 10^6 in force (ratio between the applied operator force and the nanoforce on the surface).

Ecole Polytechnique Fédérale de Lausanne

The VRAI (Virtual Reality and Active Interfaces) team from Robotic Systems Institute, EPFL, Lausanne, Switzerland has linked the 6DOF Delta haptic device (DHD) to an AFM [Grange, 01].

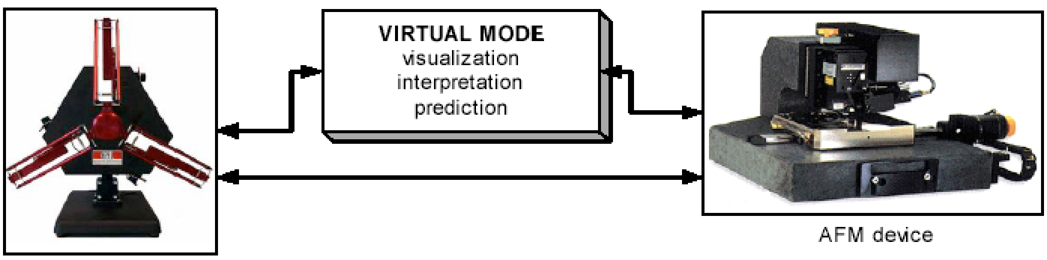

Figure 2.26 EPFL nanomanipulation system architecture

Applications: The aim of this development is to make manipulation of carbon nanotubes possible by including physical models of nanotubes behavior into the control loop. In a first stage of the project [Grange, 01], it is possible to “feel” in real-time the topology of a given sample while visualizing it in 3D.

Used technology: The system is based on the Delta robotic structure, which provides 3 translational DOFs. A mechanical wrist plug-in provides 3 rotational DOFs. All DOFs are active and generate forces and torques. It renders 25N as continous force, 0.2Nm as torque. Curently, the DHD can control 3-translation axis of the AFM, while the VR engine can display scans taken by the AFM in 3D. At the same time, the DHD can interact with the VR engine and allow user to feel the scanned sample. Future developments are oriented to the implementation of a modeling layer to make the display dynamic.
Signals processing: The force control in signal processing loop runs at 1kHz, refresh rate. The pseudo-real-time kernels used in the VR engine make possible to run complex simulations at a 25Hz refresh rate on the PC hardware.
Workspace: Cylinder, ϕ360mmx200mm, +/- 20° for each rotation.
Resolution: Less then 0.1mm (translation), less then 0.04°(rotation).

VEECO

The MultiMode PicoForce system [Russell, 02] is designed by Veeco Instruments Inc., and is available on the market since 2002.

Figure 2.27 Haptic Interface System

Figure 2.28 MultiMode PicoForce system

Applications: This system is designed for studies in molecular biology (protein unfolding, antigen-antibody binding) and nanoscale material research (membrane elasticity and Van der Waals forces).
Used technology: The realized system contains a PicoForce scanner (that incorporates a closed-loop Z-axis with a 20 microns vertical range and an X–Y scan size of >40 microns), a controler type NanoScope IIIa or IVused to provide in-line control of the closed-loop Z-axis and the PicoAngler with force-feedback knob that enables the user to "feel" the force of interaction, for example, of a molecule stretching and then suddenly unfolding. The system is based on solid friction, which is proportional to the 1D force (z direction).

Asylum Research

The Haptic Interface System (HIS) is comercialized by Asylum Research company [Asylum, 03], Santa Brabara, California, USA and was developed in cooperation with Novint Technologies of New Mexico and the Robert Cohn Group at University of Louisville.
Applications: The HIS system enables real time manipulation and measurement applications of the MFP-3D system such as carbon nanotubes, single molecules, quantum dots and more.
Used technology: The Haptic Interface System is available with the PHANTOM as the standard configuration linked to an MFP-3D AFM.
Signals processing: The force feedback haptic magnifies the forces between the cantilever and sample by almost a factor of 10^9, allowing the user to 'feel' the surface as the AFM cantilever moves over it. The motion of the user's hand is demagnified by a similar factor and directly controls the cantilever motion.

<u>ACROE</u>

The nanomanipulator system [Luciani, 03] developed by ACROE-ICA team, INPG, Grenoble, France brings together performant tools like Atomic Force Microscope, Real-Time Modelling Station and Modular Gestural Device creating thus an augmented reality system.

AFM Real-time Workstation *(Telluris)* TGR

Figure 2.29 ACROE-ICA Nanomanipulator

Applications: The developed system aims to open new possibilities in programming the AFM running modes as well as in the user control and assistance. Curently it allows the user to experiment nanoscale phenomena as the approach-retract one or the nanoobjects displacement.
Used technology: The tool is based on the connection of an AFM to a multisensory and real-time workstation (*Telluris*) simulating physical-based models. Through this workstation, a bidirectional link is established between a custom-made TGR (Retroactive Gestural Transducer) and the AFM. The signals detected by the AFM probe are transmitted to the virtual nano-scene, which amplifies the signal and send it to the user. At the same time, the user movements are sent back to the AFM probe through the workstation. The force applied on the key of the haptic device and its resulting position is the permanent information exchanged with the real-time workstation.
Signals processing: Data transfer and computation take place at 3 kHz frequency in reactive mode. The force feedback device reaches a maximum speed of 2 m/s, supports a force of 50N in permanent regime and 200 N in transitory regime and is caracterized by 10 kHz cutting frequency in force control loop.
Workspace: The workspace is related to the mechanical morphology used for the force feedback device. When the keyboard is used, then the available workspace is 20 mm vertical displacement.

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2.2.4 Cobots applications. (INPG,PERCRO)

Introduction.

The cobots applications differs from teleoperation in the fact that the user workspace and task workspace are confused, the cobots being a special tool system that constrains the user object interaction under data treatment system control. Since the cobots have mainly been developed in order to introduce only a correcting effect into an existing operator / object physical interaction, specific actuation technology have been developped that avoids the usual drawbacks of instabilities encountered in general active actuation systems. This technology is based on the CVT that is a structurally passive component. The cobots part in this section deals with the cobots application analysis and the specific cobot technologies are more detailed in the section IV.

Definition and application domain (INPG)

Cobot stands for collaborative robot. Edward Colgate, Witaya Wannasuphoprasit and Michael Peshkin first proposed this term in 1996: they defined a cobot as “a robotic device, which manipulates objects in collaboration with a human operator” [Colgate et al., 1996b]. Cobots are first designed in order to constraint human operator movements in particular man-machine environments, but maintaining the human-object mechanical interaction: human movements are constrained by the definition of virtual surfaces.

One compelling example of cobot use is shown in [Peshkin et al., 2001], where in a car factory a cobot helps the operator removing doors from newly painted cars without marrying the car’s surfaces. The cobot helps the operator carrying the door like a usual chariot would do, but furthermore prevents hazardous movements that would damage the car’s painting by defining safe surfaces or escape paths. Because of the particular features of the cobot in terms of stiffness for the constrained surfaces (see the technical text from PERCRO in this document), cobots are mainly used where hazardous human movements could damage the operated environment.

Cobots are thus defined as mechanical interfaces designed to interact with people without masking the mechanical interaction between the human (manipulating-person) and the manipulated object. The philosophy of such systems remains indeed in a shared control of motion between the user and the cobot, and in the fact that a cobot mechanically interacts both with the human and the manipulated object. To perform that, cobots interact with people only by producing software-define “virtual surfaces”, which constraint and guide the motion of the shared payload, but add little or no power.

In cobots, the source of mechanical energy remains the user, and a cobot is only able to modify the energetic link between the user and the manipulated object: from that point of view, the cobot is a passive device because it does not bring supplementary energy to the human or to the manipulated object. In other words, if the user does not move the manipulated object, the cobot is not able to generate motion on its own.

From a functional point of view, the way cobots interact with humans is rather different from teleoperation. In the teleoperation process (see Figure 2-30), the human interacts with a mechanical device usually called the “master” (the mechanical relation is represented in the figure by a large blank arrow). In the same way, the slave part of the device mechanically interacts with the physical world. The relation between the master and the slave parts of the teleoperation systems, and the compelling impression for the human operator of being in mechanical contact with the physical world are ensured by exchanges of information (such as electrical signals). The information level in the teleoperation chain somehow introduces a break in the usual mechanical coupling between the human and the physical world.

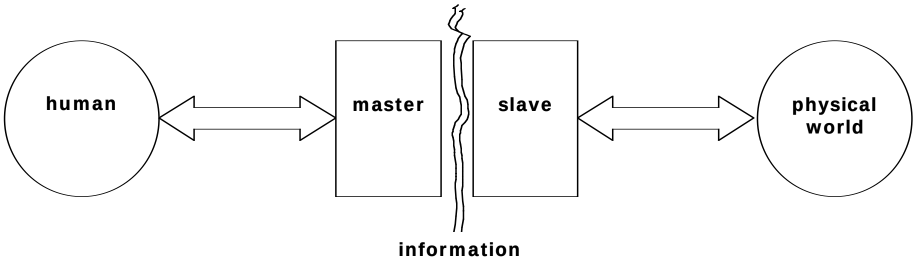

Figure 2-30 Diagram of the teleoperation chain

Conversely, in the cobot implementation, the mechanical interaction between the human and the physical world is somehow maintained; one (purely mechanical) part of the cobot system is involved in the mechanical relation between the human and the physical world, but there is no break in this relation. The particularity of the cobot is rather to modify this relation by introducing constraints. We can say that the information level in this particular chain is set up between the cobot and the human-world mechanical relation (Figure 2-31).

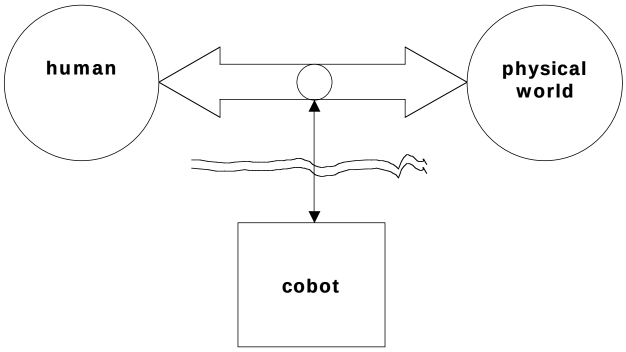

Figure 2-31 Diagram of the cobot in the human-world interaction

Hence, cobots do not have actuators in direct mechanical interaction with the user. Cobots make use of actuators only to modify their kinematical configuration. The stiffness of a simulated virtual surface does indeed not depend on the stiffness provided by the actuators, but by the rigidity of the cobot's structure, and by the friction forces generated at the point of contact between the cobot and the ground. As explained in the technical text about cobots in this document, these particular systems propose interesting solutions for specific human-world interaction cases where conventional haptic systems do not completely cope for example with stability or with the implementation of stiff surfaces.

Cobots as nonholonomic systems

Hence, cobots are particular nonholonomic systems, as they can modify the available taskspace of the manipulation[6] [Colgate et al., 1996a]. In nonholonomic systems, the number of degrees of freedom currently available (i.e. the dimensionality of the space of available velocities at any instant) might be inferior to the taskspace dimensionality, which refers to the space of endpoint poses that can be reached over time.

Two functional modes are commonly available in cobots. The first one is referred as the free mode, in which the number of available degree-of-freedom corresponds to the dimensionality of the taskspace; in this mode, the possible reduction of the number of degree-of-freedom compared to free movement does not come from the interposition of the cobot between the human and the manipulated object, but from the interaction of the human with the object, and from the interaction of the object with its environment (for instance, I cannot move a book lower because it lays on the table). The second

[6] A holonomic system constrains both position and velocity of two linked parameters. At the opposite, a nonholonomic system, constraining two parameters in position, does not constrain these parameters for velocity as well, and vice versa.

available mode in cobot control is path mode [Peshkin and Colgate, 1999]. By limiting the number of degree-of-freedom available in the interaction between the human and the manipulated object, a cobot can constraint the possible movements to a single path (i.e. reducing the number of degree-of-freedom to 1) or enclose the taskspace by virtual surfaces (1 or more degree-of-freedom).

The programmable constraint machine and CVT

The functional core of cobots remains in the CVT (Continuously Variable Transmission) concept [Gillespie et al., 2001]. This kinematical mechanism ensures that the whole cobot remains coupled to the ground (through the mechanical structure of the cobot, including CVT), but still allows modifying the way the end-effector movements are constrained. The simplest example illustrating this concept is the rolling wheel: the user can move a wheel rolling on a plane, which rotating angle is controlled by another system. By monitoring the forces applied by the user on the wheel, it is possible to determine the rolling direction exerted by the user. By orientating the wheel, it is then possible to allow user's movements by orientating the wheel according to the forces applied, or on the contrary to release the movements by steering the wheel perpendicular to the direction of the force applied. At last, if the steering angle is correlated to the applied force and the angular speed of the wheel, it is possible to constrain the user's movements to a predefined path on the plane.

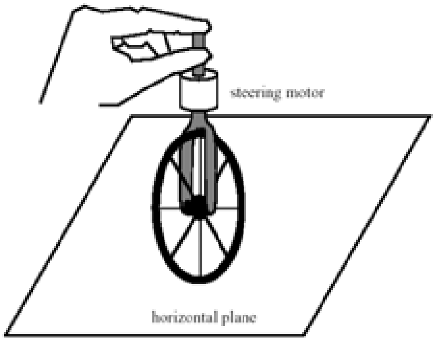

Figure 2-32 – An elementary example of CVT (from [Colgate, 1996])

Starting from the elementary CVT system of the steered wheel rolling on a plane, it is possible to extend the principle of constrained movement to a taskspace containing more than 2 dimensions [Gillespie et al., 2001]. [Peshkin et al., 2001] shows the simple example of the steering wheel, and its extension in the Scooter prototype, which is a three-wheeled cobot, able to implement unilateral virtual surfaces as well as free mode in its x-y-THETA taskspace. The added third wheel brings stability to the system, and allows for the reduction of kinematical singularity. This model has been implemented in General Motors cars factory [Peshkin et al., 2001], where the cobot helps the operator moving the door's car next to its body by supporting the door's weight, and constraining the door's movement to a predefined path, preventing the door marring the car's surface.

Towards active cobots

The part of the environment to which the CVT was mechanically linked (for instance the ground in the case of the steered wheel) is usually inert in the first devices presented. [Peshkin et al., 2001] and [Faulring et al., 2004] present active cobots, where a central rotative shaft linked to every CVT brings them motion, thus providing mechanical energy to the end-effector along each one of the degrees-of-freedom, depending on the angle position of each of the CVT.
Limitations of cobots:

It seems to the authors of this State of the Art that the main drawbacks of cobots are the fact that they cannot implement soft contact.

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2.3 Human-computer interfaces (Medialab, INPG)

2.3.1 General purpose HCI (MediaLab)

Human-Computer Interaction (HCI) is a well-defined academic discipline, with an extensive body of literature. For the general scope and state of this field we refer to the recent book by Jacko and Sears (2002) and book-in-progress by Buxton (2004). Our main concern here is with the relationship of sensors, actuators or generally transducers in the context of HCI. But before we progress with this specific task it is important to discuss the meaning of the term of HCI broadly and its meaning in our specific context. The problem of the meaning of HCI is two-fold: (1) what constitutes a computer and (2) what kind of interactions do we consider relevant.

A very broad definition of HCI includes every technological artifact that contains computational electronics in the form of processors. By this definition many everyday devices count as computers. This includes such commodities as dishwashers, washing machines, cars, answering machines, alarm clocks and telephones. Here we will not consider these devices. For our purpose HCI will be limited to situations where general purpose computations and software are at least in principle envisioned to be performed using the device and available through interaction.

Further, we will only consider interactions with these devices and of those interactions, only interactions that are relevant to input and output of some form, hence require sensors or actuators. Hence we do not consider mechanical aspects of interactions, like loading and unloading of removable storage media and the like.

While the modes of design of human-computer interactions are themselves varied and still widely debated.

Sometimes there is a well-established setting for an interaction. Probably the strongest of these is the type-writer paradigm, which is common to table-top general purpose computers. In these cases there may in fact be many types of sensor-actuator technologies in use, but this detail may be rather unimportant to the interaction paradigm itself. It may in fact be rather, the necessity of improving the interaction towards an envisioned ideal or reducing problems found in sustained use and human studies. Two further important examples are the screen display and also more and more the mouse, bringing together the pieces that most people will perceive as “a computer”, as has often been pointed out by Buxton (e.g. 1996). All of these have gone through an evolution of sensor and actuator technologies while changing little if anything of the interaction.

Even for less pervasive interfaces, a grouping by their interaction paradigm is often possible.
Additionally many interfaces are traditionally classified with respect to their main or design function in an input/output paradigm of interaction. The keyboard, for example, is conventionally seen as an input device for capturing discrete fine-grain (finger) movements, even though from an enactive point of view, the tactile “output” can not be cleanly separated from the input interaction. We will, as far as possible, retain the traditional separation and mention in a separate section examples when input also serves a distinct output function.

Additionally interactions can often be discerned by the setting of the device under consideration. While interactions between a desktop device, a large-group device (for exhibits or tele-conferencing) and mobile devices may share commonalities, the setting often also dictates specific aspects of the interaction and drives different developments of sensor-actuator technologies. In particular the recent revolution in mass-market hand-held computer commodities has broadened the state of affairs with respect to widely used interactions and interaction technologies. Moreover, an increasing number of interaction designs couple classes of devices previously thought of as independent – e.g. mobile phones and TVs (texting to interactive TV programs), so that previously well-defined forms of interaction are increasingly common in an effort to provide versatile, flexible designs. A review of the history of human-computer interaction technology before the explosion of mobile technology can be found in Myers (1998).

Human-computer interface design can draw from is vast pool of sensor and actuator technologies (see for example Fraden (1996)), yet new sensor and actuator technologies keep emerging.

Human-Computer Interfaces can be categorized in various ways. Human Computer Interfaces without qualifiers usually implies the standard desktop paradigm. Mobile HCI refers to mostly hand-held but also other devices that are not necessarily bound to a fixed workplace or location. The phrase computer-supported collaborative work is used for contexts that are collaborative by design and intent. Both of these fields have ties to ubiquitous and pervasive computing (Abowd and Mynatt 2000).

In particular with respect to mobile HCI there is good evidence that the interaction paradigm and hence the sensor-actuator use has not yet found a stable canonical form, as is the case for desktop HCI. This can be seen by even a cursory survey of the research currently ongoing within the mobile HCI community, where the design of novel interfaces ranks second after information visualization as a topic of research (Mohamedally et al 2003).

This taxonomy can then be refined with respect to sensorimotor modalities or utility/function. Even then it can be rather difficult to define such taxonomies for the categories of the taxonomy may not match the phenomenon of interest (Compare for example Buxton (2004) and Hinckley (2002)).

For our purpose of relating Human-Computer interaction to sensor and actuator technology one is faced with exactly this problem. If one chooses to classify by task or function, different sensor and actuator technologies may appear as options elsewhere, whereas when one classifies by sensors and actuators, important shared functions across different sensing technologies cannot be easily identified. Because of the length available here, we will emphasize the function over the sensors and actuators and hence group technologies by prominent uses. Secondly we will only consider technologies that have shown sustained interest. For a comparable classification of devices by use see for example Hinckley, Jacob and Ware (2004).

Input Modes and their sensor technologies:

Desktop Paradigm Input Type	Device/Technology	Sensor Technology	Physical Mechanism
Text Input	Keyboard	Rubber Dome	Mechanical
		Membrane	mechanical
		Capacitive	non-mechanical
		Metal contact	mechanical
		Foam element	mechanical
	Speech Recognition	Microphone	
Pointing Device	Mouse	LED/Photodetector	mechanical
		LED/CMOS Camera	optical
		Switches	
		Potentiometers	
	Light Pen	Photodetector	optical, CRT raster sync dependent
	Touch Pad	Capacitive	
	Trackball	See mouse	
	Joystick (digital)	Switches	
	Joystick (analogue)	Potentiometers	
	Touchpoint		
	Graphics Tablet		
	Footmouse	Potentiometers	
	Eye-tracking	See Digital Imaging	
Extended Navigational Devices	Multi-DOF devices (Spaceball, …)		
	Boom Chameleon		
	DataGlove	force sensing resistors	
	3-d mice	Gyroscope	
Motion/Position Sensing	Microscribe		
	The Monkey		
Haptic Force Feedback	Phantom	Motor	
	Mouse (Immersion,…)	Motor	
	Joystick	Motor	

As can be seen, the array of input options is large for desktop computers. The sensor technology for each type of input is usually rather well established, though evolutions between types of technologies still occur and new technologies are introduced. A typical example of sensor transition happened recently in the case of the mouse, where the opto-mechanical mechanism coupled to a rolling ball was replaced by a purely optical mechanism, which is in the process of replacing the mechanical predecessor due to it's desirable advantages of surface flexibility and resilience to problems due to dust accumulation.

A large array of interfaces have been developed which lie outside the widely distributed screen, keyboard, mouse setup. These are either specific to tasks that have limited appeal or simply haven't reached market acceptance yet. Which of the devices currently in development will persist remains to be seen.

Despite the long history of interface design for desktop computers, it is worthwhile mentioning that the available array of sensor-technologies far exceeds what is usually and frequently used in actual designs. For a review of sensor technologies we refer to Fraden (1996), where he gives a comprehensive survey of available sensor technologies.

Mobile/Handheld Paradigm

Input Type	Device/Technology	Sensor Technology	Physical Mechanism
PDA	Touch screen		
	Switches		
	MESH	Vibrotactile display	
		Gyro	
		Acceleration (accelerometer)	
		Electric field (capacitive)	
		Magnetic field	
Cell Phone	Microphone	various	
	Switches		
Digital Camera		CCD (charge coupled devices)	
	Digital Imaging		
	Switches		
	Microphone		
Digital Audio Recorder/Player	Microphone		
	Switches		

Mobile devices have seen a boom in the last ten years. However only a small portion of these devices are strictly general purpose computers. Special purpose commodity items like cell phones, digital cameras and digital audio players make a significant portion of the consumer success, and for this reason they are included here. Hybrid items do exist and there are signs of them becoming popular. Examples are hybrid cell phones and digital cameras, or cell phones with PDA style functionality.

The PDA has, however, by virtue of its flexibility the largest array of input modalities and hence utilized sensor technologies. Many aspects of the used technologies and modalities are still in development, however.

Large Space/ Collaborative Paradigm

Input Type	Device/Technology	Sensor Technology	Physical Mechanism
Pointing	Gesture Recognition	Digital Imaging	
	Sound Source Localization	Microphone Arrays	
	3-D Mouse	Gyroscope	
	Wand		
Text Input/Selection	Speech Recognition	Microphone	

Large space collaborative spaces differ from desktop and mobile paradigms in the sense that they not necessarily constitute individual work places (like desktops) or single-user items, like mobile devices, but are often stationary large displays with multi-user function. Examples are tele-conferencing setups or technology in common spaces (museums, …). The market outlook of this paradigm is so far rather different than desktop and mobile devices. Yet this field has a long academic research tradition and tele-operation do slowly find use outside research laboratories. (see for example Li et al 2000)

Experimental Input Technologies

Input Type	Device/Technology	Sensor Technology	Physical Mechanism

	Muscle Tension	Electromyogram

A number of devices are tried which either do not clearly fall into any of the above paradigms or have yet to be established.

Output modes and their actuator technologies:

Desktop Paradigm Output Type	Device/Technology	Actuator Technology	Physical Mechanism
Visual Display	CRT (Cathode Ray Tube)		
	LCD (Liquid Crystal Display)		
	PDP (Plasma Display Panels)		
	ELDs (Electro Luminescent Displays)		
	Laser		
	Electronic Ink and Paper		
	LEDs		
Auditory Display	Speakers		
Force Feedback	See Input charts		
Tactile Displays	Braille displays	Solenoids	Magnetic

Traditional display of a desktop computer consists primarily of a visual display and secondarily of auditory display. Further modalities, with respect to force feedback and other tactile displays are emerging only recently and don't yet belong to the commodity setup. Visual displays have seen an ongoing line of technological developments as can be seen in terms of the available actuator types. While speaker design does see evolution, this is far less driven directly by the computer but by consumer audio needs. It has to be seen if direct tactile display will emerge as a viable desktop commodity display option.

Haptic displays form a particularly new and important segment in this development for our purpose. Haptic display and interactions can relate to an array of body sensations. Oakley (2003) proposes the following terminology: haptic refers to all sensations relating to touch. Proprioceptive describes sensations describing the body's state including vestibular, kinaesthetic and cutaneous. Here vestibular refers to head orientation and motion, kinaesthetic the sense of motion including limb and tendon configuration. Cutaneous describes skin-based sensation of touch, temperature and pain. Tactile is the subset of cutaneous limited to the pressure aspect of touch. Force feedback specifically relates to technologically created states to be sensed by the Human kinaesthetic sense. We will also mean it to include tactile features as those can not easily be separated out at interaction points.

In the realm of haptic display, probably the best known concept is that of single-point force displays like the phantom. These use motors and lever-mechanical configurations, with additional sensors. A number of related devices have been proposed. We refer to Hayward et al (2004) for a recent review. Additionally, especially when the forces sought are smaller, one can also explore force-displaying (and usually also sensing) materials. There are, however, rarely used as of yet. For a review of such transducer technologies we refer to Fletcher (1996).

For tactile display, traditional technology displays mechanically, driven by miniature solenoids to lift and lower pegs of a display. Tactile display can also exploit force reflection in which case force-feedback technologies are used. A review of tactile displays can be found in Kaczmarek and Bach-y-Rita (1995).

Mobile/Hand-held paradigm

Output Type	Device/Technology	Actuator Technology	Physical Mechanism
Visual Display	Display	LCD/ELD	electro-optic
Auditory Display	See Desktop		
Tactile Displays	TVSS, MESH	Vibrotactile display	

Especially PDAs are closely modeled after the desktop paradigm with minor modification. The interface is still point-and-click following the mouse-screen interaction idea. Auditory display is unaltered. Yet due to ongoing research and the diversity of devices there is a current percolation of ideas and much exploration of interaction paradigms, and interaction technologies. In particular, new interface technologies is only second to information visualization in published research activities at primary mobile HCI conferences in recent years (Mohamedally, Zaphiris, & Petrie 2003).

Large Space/Collaborative Paradigm

Output Type	Device/Technology	Actuator Technology	Physical Mechanism
Visual Display	Projector	LCD DLP (Digital Light Processing) LCoS (Liquid Crystal on Silicon).	
	Screen Arrays	See Desktop Visual Display Technologies	
	Cell arrays	LED,…	
Auditory Display	Speaker		
	Speaker arrays		
	Beam steering		
	Audio Spotlight	Nonlinear ultrasound	

Collaborative technology focuses on technologies to provide large seamless and efficient display. A second concern, especially in tele-conferencing applications, is the auditory interaction. The control of noise and the selection of particular speakers, lead to the development of various technologies, mostly using traditional speakers but also alternative actuator technologies.

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2.4 Simulation (PERCRO, CEIT, INPG)

2.4.1 Training simulation. (CEIT)

The Large Haptic Interface for Aeronautic Maintainability (LHIfAM) is a floor-grounded force-feedback hardware, conceived for maintainability simulation in Aeronautics (see Figure 1). The system has been created by CEIT Applied Mechanical Department [Savall, Borro et al., 2002], [Savall, Borro et al., 2004]

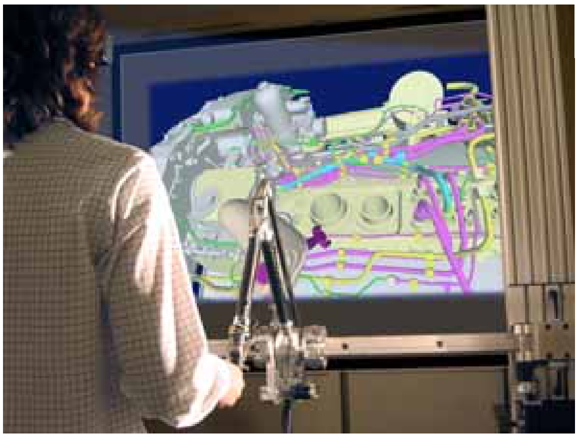

Figure 2.33: LHIfAM: The Large Haptic Interface for Aeronautic Maintainability

One of the most relevant aspects of maintainability in aeronautics concerns man and tool accessibility task analysis, which is undertaken in order to calculate paths and assembly-disassembly sequences and times.

Design based on electronic mock-up is widely used in the creation of engine externals (piping, harnesses and installations) by the aeronautics industry. Pipes and harness are routed over these parts and accessories are installed by means of a workstation network. This allows a group of designers to work quasi-concurrently over an assembly, copying and automating the original process. This technology is known in the industry as DMU/DPA (Digital Mock Up / Digital Pre-Assembly).

DPA/DMU technology has overcome the need for a hard mock-up for design purposes, significantly decreasing time-to-market and thereby saving money. However, nowadays the use of a physical mock-up is mandatory in order to evaluate the maintainability of externals during the development stage. Although these mock-ups can be used for other applications, the ultimate purpose of the construction is to check the maintainability. The expenses of these mock-ups led ITP to research an alternative using haptics.

ITP is the exclusive supplier of low-pressure turbines for Rolls-Royce engines of greater than 35,0001bs of thrust - primarily the Trent engine family. It is also the Spanish participant in the EJ200

engine for the Typhoon Eurofighter, and earlier in 2002 became a 13.6% shareholder in the TP400 engine programme for the A400M European military transport aircraft.
Dressings and Maintainability design areas have always aspired to do away with -partially or totally- the physical mock-up, at least during the development phase. During production, the first production engine serves as a physical mock-up.
The main aim of this project was thus to develop a haptic device that can be used as a tool to predict the maintainability of an aircraft engine. One of the main advantages of this development would be that mock-ups were no longer needed for this purpose, leading to important cost savings in the development of a new engine.

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2.4.2 Design simulation. (CEIT)

Rapid prototyping stations are new CAD (Computer-Aided-Design) systems and 3D design applications that aim to speed up the design process. Before manufacturing a product, a detailed 3-D model can be created inside a computer. A haptic device will enable the designer or customer to actually "touch" and assembly the parts of the model right inside the computer during design or inspection without fabrication of physical prototypes. Compared to conventional technology, significant boosts in productivity and comfort for engineers and designers using haptic input devices are expected, as well as a substantial diminution of financial costs on long-term.
As an example, the Sarcos Dextrous Arm Master[7], Figure 2, allows forces of contact to be simulated, such as surface tracing, assembly forces and grasping. It is a good example of what rapid prototyping means.

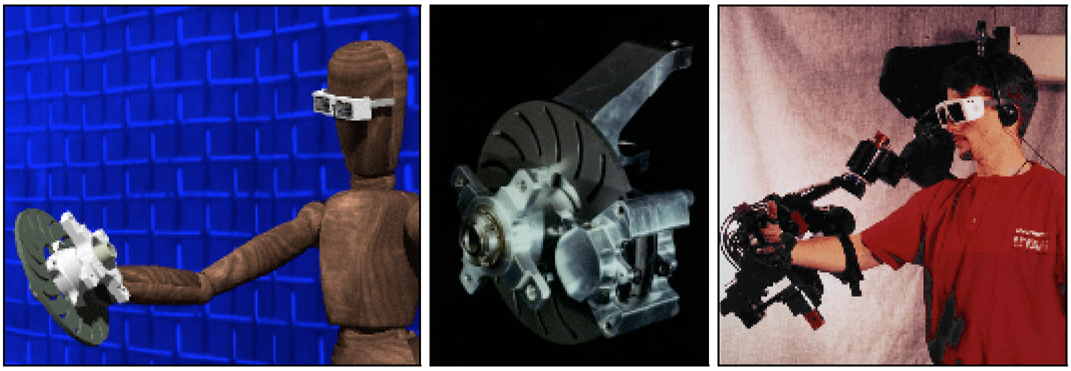


Figure 2.34: Virtual Prototyping for Human-Centric Design: The Sarcos Dextrous Arm Master (University of Utah, department Computer Science)

2.4.3 Haptic interfaces in Computer music (INPG)

(© Claude Cadoz, Jean-Loup Florens, Annie Luciani.)

This section deals with new musical instruments design, haptic interfaces in analysis of performer/instrument interaction and in a general way of *Artistic use of Haptics : Real-time artistic instrumental playing* Devices, hadware and software

Real-time CORDIS-ANIMA simulators

The CORDIS-ANIMA system can be implemented on any general-purpose computer but the real-time

[7] http://www.sarcos.com/

interaction implies two major conditions: obviously, a maximum of computing power to simulate models of sufficient complexity, but also a specific control of the input and output protocols. A real-time simulation loop is indeed complex: it is constituted of three nested loops at three frequencies: the sound sampling frequency (the higher), the image sampling frequency and the gesture sampling frequency. The two last being a sub-multiple of the first. The synchronization must be absolute and driven by an external clock. For each input (gesture) data, the computer has to run a complete simulation loop including the nested ones and to produce the output data (for sound, image and force-feedback control).

In the early stages of development in the laboratory, the very first simulators were in fact real-time in their principle: an analogical computer was used for the first force-feedback experiences, and a DEC LSI11 just after. The LSI11 processor was controlled by an external clock assuming a rigorous synchronization of the input and output. Of course, the simulated models were very simple, and sometimes simulated at very low frequency, but they were real-time.
After that, we adopted two consecutive solutions for real-time simulation:
In 1982, Talin Berberyan [DARS-BERBERYAN (T), 1982, 1983] built a dedicated processor, the CTR (CORDIS Temps-réel), with a hardware implementation of the CORDIS-ANIMA algorithms, that was probably the first real-time processor for physical modeling. It allowed to simulate models of strings (or others) with about 20 to 30 masses in real-time and with gestural control. It was replaced during the 80's by an Array Processor (AP120 from Floating-Point System inc.) that delivered approximately the same performance, but with more generality.

In both cases, the simulator was a specific machine exclusively dedicated to simulation process and driven by a host computer. The next step was centered on Silicon Graphics workstations (1993) that offered at that time the best compromise between computing power, graphical resources and general software environment (under Unix). In this last case, as in the case today of any non dedicated platform, it is not possible to overcome the real-time constraints without intervention at the basic hardware level (including the processor in a specific architecture allowing a complete control of the input/output dataflows) and at the basic software level (of the operating system itself in order to eliminate all operations not strictly involved in the simulation during the simulation process).

The TELLURIS portable platform, dedicated to real-time multisensory simulations with usual platforms, is at this time a major axe of development in the laboratory.

<u>The Retroactive Gestural Transducers (TRG®)</u>

One of the greatest difficulties in the design of such devices for artistic playing is to reach a high level of performance (in compacity, in dynamics, in accuracy) to be usuable for artistic instrumental playing.

The first force-feedback gesture transducer (TGR — *Transducteur Gestuel Rétroactif* in french), achieved in 1978, [Florens, 1978] permitted the validation of the force-feedback concept, and the first measures on action-perception gestures (figure (a)). This device, sensing forces and displacements at its manipulation stick, was able to produce a force-feedback of several tens of N with a time response of about 1ms, and with a displacement range of about 1m. It allowed for the first time to evaluate the importance of the force-feedback in the manipulation of simple virtual objects. It allowed also to highlight, from decisive experiences, the inter-sensory phenomenon and its importance (for example, the influence of the visual perception on a correlated tactile perception, and conversely).

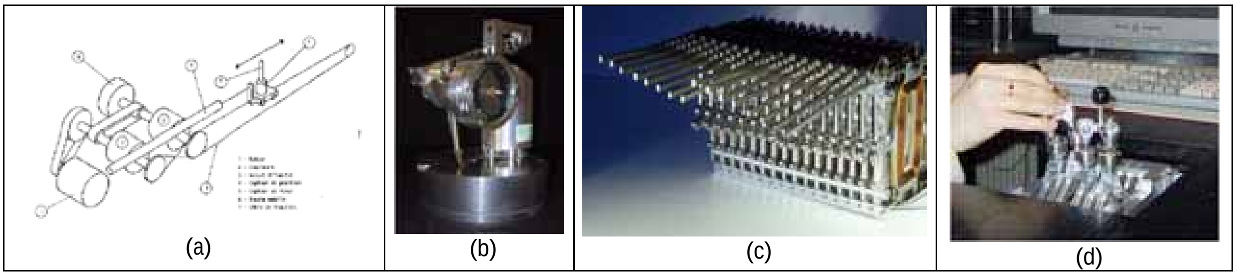


Figure 2.35 Haptic devices ACROE-INPG technology

The second TGR, achieved in 1981, named "la Touche" (Figure (b)), permitted higher compactness of the mechanism, the first tactile behavior synthesis, and digital physical interaction simulations with sound and animation [Cadoz, Luciani, Florens, 1984, 1989].

The third TGR, named ©*Clavier Rétroactif Modulaire* (Modular Retroactive Keyboard — CRM) presented in 1988 (figure ©), was designed to improve on compactness and to bring technically "limitless" degrees of freedom. Its associated principle, the *Slice Motor®*, is based on magnetic levitation technology, and allows for the gather of an unrestricted amount of separated 1-dof elements [Cadoz, Lisowski, Florens, 1987, 1989, 1990, Nouiri, 1994, 1995].
This concept solved the two crucial problems within the TGR: modularity in terms of number of degrees of freedom, and modularity in terms of manipulation morphology.

From this concept, ACROE designed the ERGOS technology (Figure (d)):
• by improving the mechanical and dynamical performance of the previous devices, particularly in the accuracy of the returned forces to be able to render accurate rubbing as in bowed instruments,
• by designing a set of parallel kinematic adapters (actually, added mechanical components) to truly exploit the versatility of the human gesture.

Haptics-audio chain in digital musical instruments

Nowadays, the action – audio relation is mainly implemented as shown in the following figure, as an open-loop system in which gestures are sensed by means of sensors (for example using conventional keyboard or more generally motion capture systems). Such organization is called "mapping process", in which the action controlled the sound parameters. The gestural parameters are mapped on the sound parameters. Such chain can by clearly cut in two non-retroactive parts (see figure). The sensors and the mapping process can run at a computation rate of about 1 - 500 Hz. The sound synthesis part has to be computed at a rate about 10 - 40 KHz. The link between the two parts is unidirectional, from the left to the right, gesture part *controlling* the sound part.

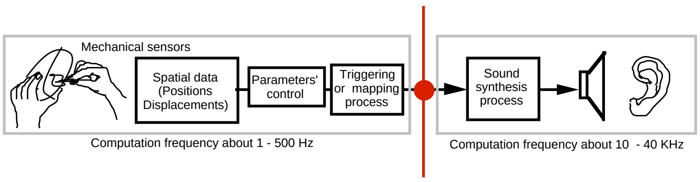


Figure 2.36 Action to sound Mapping architecture

The current improvement of such architecture is to introduce force feedback devices on the side of the human action by maintaining the mapping process. Examples of corresponding "mapping" implementations, eventually featuring haptic transducers, can be found in VR and in Computer Music [7,8,9,10,11]

The major remark that can be pointed out here is that, in such case, when a force feedback is used, it does not impact the sound quality.

What are the major properties of the real instrumental playing that render the sounds "so disembodied" when they are produced by computers or digital musical instrument?
The ACROE - INPG answer is:
The instrumental interaction generates a type of "complexity" that is not reachable otherwise, that is the complexity that emerges from complex dynamic systems coupling..

When one rubs a crystal glass with a wet finger, when one rub a cello string with a rosined bow, the sound is moldable by the physical interaction between the glass and the finger, between the hand and the bow and the bow and the string. These are coupled systems able too generate complex non predictable behaviors, bifurcations, transients, thresholds passing, critical points, etc. Such behaviors are emergent behaviors that cannot be produce by any open-loop action-sound system.
In the glass-finger playing, the sound becomes or not. In bowed string playing, the sound is sustained or not, the timbre changes or not, etc… The emotion in front of a virtuoso violinist or the annoying in front a friend who success in the production of the pure crystalline sound, is because, the sound engraved the management of such complexity. The sound expresses a know-how of controlling and mastering such system.

To obtain such characteristic effects we have to guaranty that the coupling will not be broken in any part of the instrumental chain, from the action to the sound. It expresses the difficulty of the instrumentalist, the resistance of the instrument to the dexterity of the instrumentalist, from the success or the un-success in the mastering of this complexity.

In the mapping concept, the instrument is cut in two parts, a part for the human body and a part for the sound generation, that are not coupled. With "haptic mapping", the part for the body is a closed loop system and the human feels the manipulated matter during the action, that is an essential property to drive the actions. But this interaction is not prolonged in the sound generator part. The part of the object that produces sounds is not coupled to the others parts. It seems as a siren button we push by feeling the button, but the sound produce does not feed by the gestural closed loop. Such situation is completely different that the "finger-glass" situation. The haptic devices are only used to feel with the body, not for their role in the sound production.
For ACROE-INPG, we don't use haptic interaction for itself, but for the very, incommensurable consequence that have on the properties of the sound:
The embodiment of the sound by the gesture

The digital instrument we have to implement can be simple or complex, but the first conditions we have to guaranty is that there is no in the dynamical (physical) coupling between each part of the instrument, that are the minimal conditions to trigger the emergence of such complex phenomena. If we have to cut this instrument in two (or more) parts, for computational reasons for example, then, as shown in the figure, the communication between the two parts must not be unilateral and have to represent a dynamical coupling.

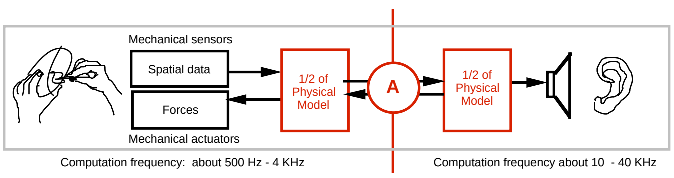
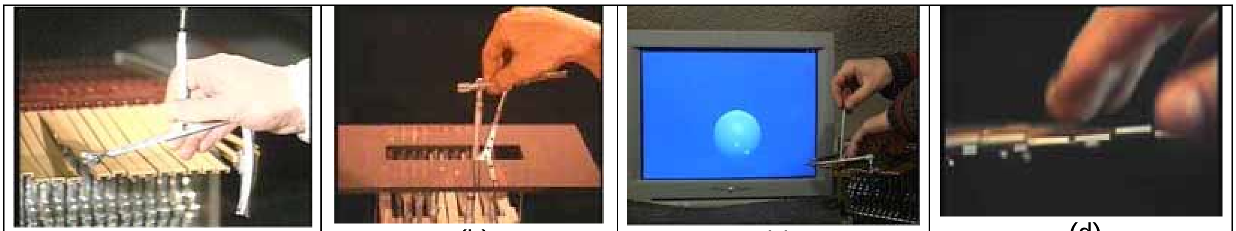


Figure 2.37 Action to sound interaction based architecture

That is the conditions implemented in several musical instrumental playing with the real-time TELLURIS platform and ERGOS force feedback technology.

Typical implemented instrumental playing situations
From a typology of instrumental situations, four typical cases have been implemented:
- the finger-on-a-glass (a)
- the bowed string playing (b)
- the maracas playing (c)

• the piano playing (d)
each of them bringing to overcome typical bottlenecks: type of the coupling between the non-vibrating and vibrating part, frequency rate for each parts, latency between each part, position, velocities and forces ranges.



(a) (b) (c) (d)

Figure 2.38 Instrumental playing situations

<u>Haptics-image chain in Dynamic Visual Arts</u>

A. Puppet *animation with physically-based simulation and force feedback manipulation*

Figure 2.39 Model of a puppet

B. Animation of complex deformable and articulated rigid objects with CORDIS – ANIMA physically-based formalism

On the left, simulation of a mobile evolving on a plastic soil, which is deforming in a non-linear way according to plastic behavior and the motion of the vehicle. On the right, real time 2D force feedback control of a similar model.

Figure 2.40 Physically-based models and real time simulation of complex phenomena (plasticity of the soil and complex rigid-deformable articulated and motorized body

C. Real time molding of a simulated plastic paste with gestural feeling [Luciani & al., 1991]

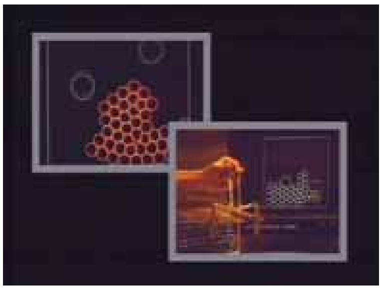


Figure 2.41 Feeling the matter: real time molding of plastic material by means of force feedback pliers

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3 FUNCTIONAL ANALYSIS OF RETROACTIVE HAPTIC INTERFACES

3.1 Introduction

This section deals with the functional aspects of Haptics devices.
The point of view of this second analysis is intermediate between the previous section (part II) that concerns application and uses in which only high level task analysis is evoked, and the last analysis section that deals with the technological realization of the devices.
The functional approach presents both technical aspects and human science related ones. For this reason and compared to the two others point of view for analysis it is the most difficult and only very introductive work on this topic could have been achieved during the 1rst WP period.
The objective is to establish from existing concepts a sufficiently general framework that allows to describ the functional properties of analysed haptic systems.
There are two questions in this approach: (1) characterize the functional properties the application requires, at a modelisation or metaphoric level; (2) characterize the limitations drawbacks and constraints induced by various aspects of the technology.
This duality is due to the fact that basically haptic interface is a component of a representation medium that means that its caracterization has normally to refer to two systems, firstly the thing represented and secondly the real substrate used for this representation. In the 1rst field will be situated the functional aspects related to application or tasks to perform. In the 2nd field will be situated the very important works that have been carried out and that concern in particular the stability problem which arises in a specific and difficult to apprehend form.

A complementary field of knowledge would also be necessary and concerns the low level of human systems that means the bio-mechanics and low level sensori motor loops study. The basic material for such investigation has to be gathered and this work will be carried on in following steps of the project eventually in collaboration with other Wps.

We try to identify global properties, independent from the domain of application and global criteria from the analysis of the different points of view related to these questions. The functional approach excludes the technological details of the device and forces to precise its relations with the systems in which it works. Although the concept of Haptic Interface is intuitive, generally well understood when defined in a close relation with a given application its function remain still multiform and somewhere elusive.
As an interface between human gesture and remote or computed objects through data paths as defined in §1 an haptic device is basically a two “port” system, the trivial definition of an interface, but it is not an obvious interface since the two ports do not belong to the same categories of things. One side is a mechanical coupling the other side being signal input output port. Compared to other human media interfaces it works in close contact with the human body that means that differently from vision and audition its basic function cannot refer to any signal transmission through a natural medium, and consequently not objective signal or “data” exists at the interaction point between the human and the device.
While in the case of traditional sound and image interfaces the functions and performance criteria can be seen in the conceptual framework of signal encoding and filtering similar approach cannot be directly applied to haptic interfaces.
3.2. The first set of question concerns consequently (a) the basic principles on which the two ports of the device may be characterized and (b) in which way the device will link its two ports. This addresses the question of coupled actuation sensing, the configuration of the mechanical port, and the relation

between the physical characteristics data at the mechanical port and the type of data signals that are transmitted or received at the data port.

3.3 A second level of question is related to the specificities of *the human side* and the adequacy of the device that takes in account the complexity and diversity of the human gesture or mechanical behaviour. These questions could be analysed according to two levels :
3.3.1 --The task related aspects. In which are considered more or less generic situations for example prehension or free motion to reach a target. Considering such elementary situation allows to define typical requirements in terms of workspace, number of degrees of freedom, forces and speed scales.
3.3.2 --The basic task independent, human factors. In particular the low level of human bio-mechanical properties and their implication concerning some of the haptic device morphological and dynamical properties.
3.4 A 3rd topics is related to the *data system side* (connection with the data treatment system that supports a Virtual objects scenes or environment (generic case of Artificial Reality) or the virtual coupling with a remote real environment (generic case of teleoperation)) .This part includes :
3.4.1 General technical methods for task related metaphors realization. This point includes in particular real time simulation software and their implementations, algorithmic shemes and related parameters like computing rate and numerical data representation.
3.4.2 Hardware data path and simulation hardware architectures.

3.5 The above structuration considers separately the components of the chain, human, haptic interface, computer or remote teleoperated system. A last set of questions that concerns the efficiency must consider this chain in its globality. This last part may be structured according the following issues:
3.5.1.The means in which the function of the device are specified. This may refer to a metaphoric system like physical modelling.
3.5.2 The spatial and morphological constrains introduced firstly by the mechanical configuration of the device. Classical devices are made of articulated rigid solid whose shape and motions, delimitate the working space.
3.5.3. The dynamic (in the sense of spatio-temporal properties) limitations. The dynamics limitations are caused by each component of the chain . The mechanical system introduces parasitic inertial and damping forces and its natural oscillating properties (eigen- modes) may contribute in control loop unstabilities. The sensor and actuator present also inherent bandwidth limitation and it is the same for all the data path and data treatment system.

3.5.4. The relation between the spatial limitations and dynamic ones.
3.5.5. Transparency and Fidelity are frequently used in the haptic community and may be used as performance criteria in relation with the 3 previous points.
These properties whose quantitative definition may be found in [Lawrence 94] and [Cavosoglu,01] mainly refer to the teleoperation situation but they may be extended to virtual environement coupling.

[Lawrence 94] Lawrence D., “Stability and transparency in Bilateral Teleoperation”, *IEEE Transaction on Robotics and Automation*, vol 9,pp. 624-637, October 1993.
[Cavosoglu 2001] Cavosoglu and Tendick, “Bilateral Controller Design for Telemanipulation in Soft Environments”, in *Proceeding of the IEEE International Conference on Robotics and Automation*, 2001.

3.5.6. The stability
As active control system an haptic system is non stable in some conditions of human / virtual object configuration. The stabilization issue for an haptic system is more difficult than for classical systems as servo-controlled systems or more complex robots for the following reasons : the mechanical load that is the human hand or body behaves in non predictable way and is difficult to model. Symmetrically the virtual or remote environment present generally complex evolutive or unknown local dynamic properties. In other words the global environment system of the haptic device cannot be modeled and

consequently the traditional methods for close loop system stabilization that are based on correctors whose tuning depends on the whole system are relatively not efficient.
Facing this situation several strategies have been developed, which consist in assuming that the haptic device and its link with the virtual/remote environment constitutes a passive link. According to the passivity theory it was then possible to tune the device and control loop parameters, like gains and corectors parameters or physical damping and with the only hypothesis of passivity on the human system so that stability criteria were always satisfied. This approach leaded to over-contrain the systems and create some distosions in the restitution of the remote/virtual environment.[3]
More sophisticated approaches have been proposed which tend to reduce the above drawbacks [4] by using more sophisticated passivity criteria. But these methods were still based on fixed parameter approach (that means a compromise in tunning parameters to obtain stability).
More recent work [4] have consisted in introducing a system that automatically tunes the coupling parameters by a continuous monitoring of the power flow that circulates through the haptic interface. The system is made of a “Passivity Observer” and of a “Passivity Controller” that maintain in permanence the passivity of the link.

We have to study more deeply the important amount of work that has been carried on these issues. These works are generally coupled to theoretical developments from other disciplines. It is the case of passivity theory that was introduced by Colgate and Schenkel in 1994 [Colgate and Schenkel,94] as a general conceptual framework to deal in more efficient way with stability problems.

It seems necessary to examine the following:

- It is important to examine more precisely in which way the classical definitions of stability are applicable to an haptic system (Interface and simulation or teleoperation). For example the virtual environement may present normal behaviours that may violate any usual stability criteria (for example a mass falling in a deep potential valley). That means that there are “normal” instabilities that must be distinguished from “abnormal” ones.
- The abnormal instabilities are not originating only in the coupling between the human and the virtual environment but also in the way in which the virtual environment is computed. And they result from the combination of the temporal limitations of these two systems (bandwidth, computation rate…)
- The abnormal instabilities can also be seen as a critical configuration of the global distorsions that are also induced by the same temporal limitations of the chain : for some parameter configuration the system is instable and for neighbor configuration it will be stable but highly distorded (under damped) etc…
- Instead of focusing only on strict unstatbility it would be useful to research a more precise characterization of these global distorsions (how they depend on model and system parameters) as a structural distorsion of the reference model that may be represented either as a parameter distorsion or as a structural complexification (for instance adjonction of parasitic masses or strings as metaphoric effects of delays)

Such an approach has been proposed in [5] and explicated for an elementary system. It will be exposed in the future version of this document.

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3.2 A non obvious "two-port" interface.

To be completed.

3.3 Functional analysis related to human.

3.3.1 Task analysis.

To be completed.

3.3.2 Task independent, human factors.

Two different aspects are treated in this section, the first is related to the inertia tensor issue and the second to the human parameter for tactile stimulation system design.
Other topics that will be developed later concern the human properties related to the most exigent temporal requirements. That concerns the low level sensori-motors loops and the pure mechanical properties of the human body.

Haptic Interfaces and Specification of Inertia Tensor (UPS IX)

From an applied perspective, developing an enactive approach to perception and action relies, (not exclusively) on the understanding of the invariants in the dynamics of sensory motor couplings that can be used to improve the sense of reality. Haptic interfaces usually generate structured mechanical signals that stimulate the human kinesthetic and touch channels (Hayward et al., 2004). Two main functions of haptic perception are usually distinguished, exteroception and proprioception. Exteroception relies on the specification of objects properties such as weight, length, and shape in the haptic structure during *active* manipulation and exploration. Proprioception relies on the specification of body properties such as the direction of our moving limbs. In the context of action, essential information is often an emergent property of the interaction between the observer and the environment and, thus is available not in the observer or the environment but only in the interaction between the two (Gibson, 1966). The understanding of haptic specification in psychophysics could contribute to the considerable engineering effort (Blake Hannaford) that is currently invested to reproduce and simulate the (haptic) sensory information allowing accurate and efficient control of arm and body movements, such as in pointing, manipulating, reaching, standing, walking, and so on.

Proprioceptive control or arm movements and the inertia tensor

From a fundamental perspective, pointing at a target with the hand or reaching for an object in the extra-corporal space requires the spatial mapping between the endpoint of the arm and the target/object located in an external frame of reference. In the field of motor control and computational neurosciences, classical approaches have analyzed the control of arm movements as a series of sensory-motor coordinate transformations, from a direction in a visual space to a direction in a motor space. More specifically, it has often been assumed (Kalaska and Crammond 1992; Soechting and Flanders 1992) that the central nervous system (CNS) performs a major computation in the conversion from a kinematic space (i.e., spatial target, hand displacement, or joint motion) to a kinetic space (i.e., joint torque or muscular activity). When the arm's movements are out of sight throughout the progress of reaching towards a still visible target, the pointing task requires to rely mainly on kinaesthetic cues and efferent commands. It is widely recognized that proprioceptive information from muscles, joints and other receptors play an important role for accurately controlling both the spatial and temporal features of the movement, as well as the final orientation of the hand (Sainburg et al. 1993). Patients deprived from proprioceptive feedbacks, due to large fiber-sensory neuropathy, show large errors in movement direction and curvature (Sainburg et al. 1995). It is well established that deafferented subjects have no ability to adjust their movements in the face of unexpected loads, or to maintain a steady joint angle without vision (Rothwell et al. 1982; Sanes and Shadmehr 1995). Precision in muscle timing, a known key factor for controlling limb interaction torques, is also dramatically impaired (Sainburg et al. 1993). For these patients, vision partially improves performance (Ghez et al. 1995). A significant aspect of this inaccuracy in the absence of vision is the inability to take into account the variation in inertia of the limbs during the reach. Despite extensive research in animals and human subjects, the precise contribution of proprioception to motor control still remains poorly understood. The recurrent question is about the identification of the kinaesthetic invariants that are genuinely used for directing the arm toward the target. Some experiments strongly support the notion that the CNS uses intrinsic criteria based on the arm's dynamics in the planning of the movement (Hogan 1984; Flash and Hogan 1985; Viviani and Flash 1995), including inertial properties of the arm (Sabes et al. 1997, 1998). In healthy subjects, it has been established that transient inertial loads, unexpectedly added or subtracted symmetrically from the spatial axes of a moving limb, leave the movement end-point unaffected. Nevertheless, contrasting with the above experiments are numerous investigations providing evidences that the control of the final hand position is affected when loads are affixed away and asymmetrically from the spatial axis of the forearm (Pagano et al. 1996; Sainburg et al. 1999), thereby leading to alterations in mass distribution. According to Pagano and Turvey (1995), our ability to perceive the spatial orientation of a limb or an object via kinaesthetic inputs is tied to a mechanical parameter, the limb or object's axis of rotational symmetry, i.e., the eigenvector (e3) of the inertia tensor. The inertia tensor can be defined as an invariant, which quantifies the mass distribution of a segment or a rigid limb, i.e., a quantity with the dimension of mass x length_ (Ayra, 1990). This mechanical parameter is considered as time-independent and coordinate-independent.:

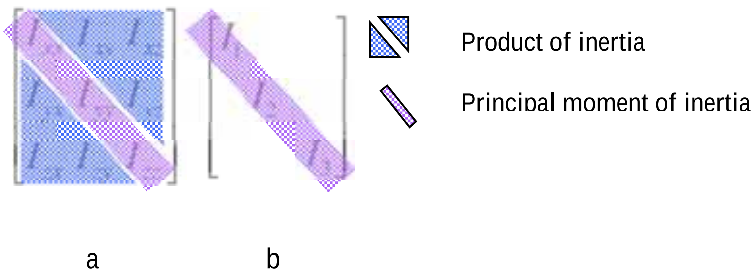

Figure 3.1**: a) Inertia tensor is a 3x3 symmetric matrix with moments of inertia on the diagonal and products of inertia off the diagonal. The symmetry axes are called eigenvectors or principal directions (ek) and their lengths are given by eigenvalues or the principal moments of inertia (Ik). b) When the tensor is diagonalized, the products of inertia go to zero leaving only the principal moments of inertia (Adapted from Carello 2000**)

In the last two decades or so, many psychophysical experiments have been performed in order to test the contribution of e3, often consisting in wielding a handheld object without sight. The results indicate that many object properties such as length, weight, or shape, can be extracted from the inertia tensor. These studies have also revealed, following Gibson's (1966) insights in his description of the dynamic touch system, that inertial eigenvectors can be used in pointing the whole occluded arm toward a visible target (Pagano and Turvey 1995), in aligning the posture of the forearms (Pagano et al. 1996), or in matching the position of the hand with the position of another part of the body, such as the shoulder or nose (Riley and Turvey 2001).

Generalization to unconstrained multi-joint arm movements

Up to now, these questions have been investigated in pointing tasks involving arm movements limited to only a single degree of freedom. The generalization of the inertia tensor hypothesis to unconstrained poly-articulated pointing/reaching/manipulating arm movements still remains to be performed. In single-degree-of-freedom reaching, this mechanical parameter is time-independent and coordinate-independent. In 3D multi-joint reaching, however, the continuous modification in the angular limb configuration leads this physical parameter to be coordinate dependent. Pagano et al.' studies (1996; Garrett et al. 1998) indicated that (perceptual or motor) performance can be reliably biased by the manipulation of the limb eigenvectors. One function of I_{ij} consists of revealing the direction of the principal moments of inertia by the eigenvectors (e1, e2, e3). The authors have suggested that understanding movement control and coordination should be addressed in terms of the relative directions of the segmental inertia ellipsoids, rather than in terms of joint angles. However, they have equally concluded that the observed bias when manipulating e3 is consistently less important than predicted. These contrasting results may suggest the existence of several strategies for the control of multi-joint arm movements. As indicated by Adamovich et al. (1998), human subjects can use diverse perceptual information to achieve comparable final accuracy, but the details of the strategies employed may differ with the kind of information available.

(No-)Example of specification of simulated object properties with haptic devices using the inertia tensor

These now classical psychophysical results are of importance for the development of haptic interfaces and haptic devices. It is clear that the capacity of humans to acquire implicit knowledge about the physics of a task and to exploit that knowledge for the control of the movement extends beyond the control of limb movements alone (Dingwell 2004). Indeed, coupling a haptic interface with human properties requires the knowledge of the body characteristics and of the dynamics of the performed movements, but also of the properties of wielded (simulated) objects. Humans generally have a great ability to manipulate hand-held objects in everyday life.

A haptic interface is a device that enables manual interaction with virtual or remote environments (Durlach & Mavor, 1994). The device feeds back information to the operator about the consequences of interaction in the remote world. Although the feedback modality is unspecified in principle, it can take the form of haptic feedback, which indicates the forces and vibrations that are imposed on the effector in the remote or simulated world. This type of feedback has been used in two contexts. One is "*teleoperation*," that is, when a human operator controls a remote device. The other is *virtual haptic environments*, in which contact with computer-generated objects and surfaces is simulated. In either case, haptic feedback enhances a sense of "telepresence," the feeling that the operator is in a physical environment. As developed by Klatzky & Lederman (2002), three types of information are potentially provided by a haptic display. One is directional force feedback, indicating forces that the remote or simulated effector encounters in the environment. Commercial force stimulators are available, such as the PHANToM, and new laboratory models have been developed (e.g., Hollis & Salcudean, 1993). Another type of information is the sustained, distributed spatial pattern of local forces that generates skin deformation across the finger tip. To generate this information requires a stimulator in the form of a matrix of pins; such devices have been difficult for engineers to implement, although there are some examples (Kontarinis & Howe, 1993). Another promising display for immediate application is one that produces vibrotactile stimulation (Cholewiak & Wollowitz, 1992). Vibratory stimulation can be produced relatively cheaply, and the frequency and amplitude can be set to optimally activate human mechanoreceptors. An example of this type of display is the OPTACON. A more recent development is the vibrating mouse – although that does not present a spatial array of forces. Haptic displays promise to be useful in many applications where conveying a sense of physical interaction is important. Haptic feedback has already been found to be essential for performing some tasks, and it is highly useful for others (e.g., Kontarinis & Howe, 1995; Sheridan, 1992). Vibrations, in particular, have been shown to improve performance in industrial teleoperation (Dennerlein, Millman, & Howe, 1997), where a human operator controls a remote robot. Vibratory signals are effective cues to the moment of puncture in medical applications (Kontarinis & Howe, 1995), and they can aid remote manipulation by conveying the forces encountered by a robot effector. Other potential applications of haptic displays are to electronic commerce, where the quality or aesthetic value of produces could be displayed, and haptic augmentation of visual displays of complex data sets (Infed et al., 1999). (see Klatzky & Lederman, 2002, for a general review).

This rapid survey of classical and customized haptic force feedback devices indicates that, although the technology is there to produce it, the sensitivity to (and the manipulation of) rotational dynamics is rare. All these interfaces have a poor level of believability in terms of the incorporation of inertia tensor information. The direction and orientation of simulated objects, normally (although not exclusively) perceived by mean of the inertial rotation, are not specified. The sensory feedback is principally exerted with the fingers. Rotation about shoulder, elbow, and wrist joints, naturally present when an object is manipulated, are absent and therefore rotational acceleration is rarely extracted during object manipulation. Consequently, exteroceptive information such as shape or length that are naturally specified by eigenvalues and eigenvectors of the inertia tensor are usually not detected with these devices.

One exception, however, is worth mentioning. Swindells (2003) has exploited the idea that people perceive the length of a rod via the change in its moments of inertia (with unchanging overall size and mass) in the development of the TorqueBAR. The TorqueBAR is based on the psychophysics of rotational dynamics, and has been developed to improve the sense of reality of simulated object properties. It is conceptualized as a coupled input-output prototype intended to explore novel interactions with dynamic inertia. The specification of (simulated) object properties is obtained by the manipulation of the inertia tensor components (eigenvalues, eigenvectors, inertia products, etc…). Possible applications emerging out of the TorqueBAR are new videos games and real-time robot navigation systems using kinesthetic inertial feedbacks.

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4 TACTILE INTERFACES

4.1 Introduction

A tactile interface is a device which produces virtual touch sensations by delivering a time-varying spatial distribution of mechanical disturbance at the surface of the skin, usually at the fingertips (see Fig. X). Spatial control is achieved by using an array of contactors on the skin, each with its own channel of computer control. The intention is to produce, within the various populations of mechanoreceptors in the skin, activation patterns that correspond to those experienced during “real” touch perception. Spatial distribution of touch sensations is important for representation of edges, corners and surface features of real or virtual objects.

Tactile interfaces that are both effective and practical have yet to be fully developed in the context of RGIs. Consequently, the currently available generation of RGIs is deficient in terms of providing tactile information to the user. This has implications for the effective use of RGIs in various applications. For example, accurate manipulation during teleoperation may be hindered by inadequate spatial representation on the fingertips of touch sensations from edges, corners and surface features. As a second example, in the area of RGI-aided creativity, fingering of a virtual stringed instrument may be difficult if the user cannot feel where/how the string lies on the fingertips. For reasons such as these, development of an effective tactile interface for incorporation into RGIs will provide a significant enhancement of these systems.

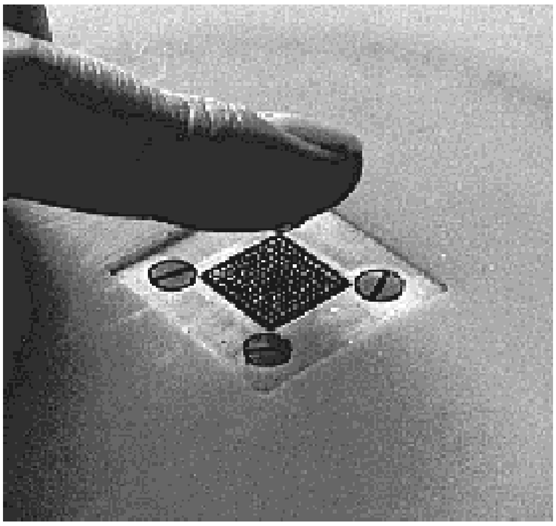

Figure 4.1 A tactile interface (UNEXE device) with 100 contactors over 1 cm^2 on the fingertip

4.2 Human factors

A tactile interface typically takes the form of an array of moving contactors on the skin, driven by electromechanical transducers, e.g., see Fig. X. When using such a device, the intention is not to reproduce the topology of "real" surfaces – rather it is to deliver vibratory stimuli to produce an appropriate excitation pattern over the various populations of mechanoreceptors in the skin. The functional specification of tactile interfaces thus relates to the properties of these mechanoreceptors. [There is an alternative design strategy, using a contactor array to display gross features of the surface topology – such “shape displays” are described in an interesting review paper by Howe (2004).]

This strategy for producing virtual touch sensations relies on two fundamental assumptions:

- It is possible to use vibratory stimuli to produce the appropriate excitation patterns. In practice, this assumption requires that the mechanoreceptors are not sensitive to the directions of the stresses and strains in their mechanical environment, but only to their magnitudes. [It is impracticable to produce a vibratory stimulator which distorts the skin in an arbitrary direction – designs are generally limited to providing forces normal to the skin only (e.g., Summers and Chanter, 2002) or tangential to the skin only (e.g., Fritschi et al., 2004).] This assumption may not be strictly true, but it appears to be a useful working hypothesis.
- It is possible to specify stimulation patterns in software to produce realistic touch sensations. This assumption requires an understanding of the transduction processes which link real objects and the excitation patterns produced when these objects are explored by the sense of touch. In practice, there is very little understanding of these processes – a significant gap in the knowledge base – and hence the “recipes” for stimulation patterns to produce realistic sensations are in many case produced by trial and error.

4.3 Psychophysics

Glabrous (non-hairy) skin contains various populations of mechanoreceptors: pacinian receptors and three types of non-pacinian receptor (Johnson et al., 2000). These differ in terms of their frequency response (Gescheider et al., 2001), and in order to evoke a wide range of "realistic" touch sensations an interface must operate over a significant fraction of the tactile frequency range of, say, 10 to 500 Hz. Vibratory stimulation in the upper part of this frequency range (approximately 100–500 Hz) is expected to stimulate pacinian receptors predominantly. Stimulation at lower frequencies is expected to stimulate non-pacinian receptors predominantly.

The detection threshold for vibratory stimulation varies significantly with frequency, with a minimum value of around 1 micron at 250 Hz, rising to around 10 microns at 50 Hz. (In fact, threshold values depend to some extent on contactor area.) In order to produce comfortable, easily detectable levels of stimulation, a tactile interface must deliver vibratory stimulation at 10 to 20 dB above threshold, i.e., over an amplitude range of perhaps 3 to 10 microns at 250 Hz and 30 to 100 microns at 50 Hz.
The spatial resolution required for stimulus presentation is related to the density of receptors, and is effectively determined by the spatial acuity for tactile perception – around 1 mm on the fingertip for "real" stimuli such as gratings (Johnson et al., 2000). Summers et al. (2001) show that stimuli presented at 2 mm resolution can be perceptually similar to stimuli presented at 1 mm resolution (see Fig. Y), suggesting that 2 mm resolution may be adequate for a practical device. Considering typical scanning speeds by the user of around 100 mm s^{-1}, we see that the temporal resolution required for modulations within each channel is around 20 ms at 2 mm resolution.

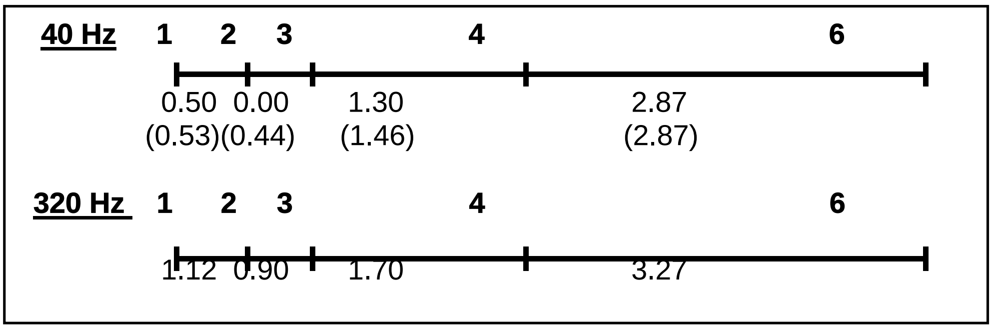

Figure 4.2. Discrimination index *d'* between five stimulus resolutions, for vibratory stimulation at 40 Hz and at 320 Hz (scanning of virtual lines over the fingertip). The labels above the tic marks indicate the resolution in mm. The numbers below each line indicate *d*'. A 2nd set of data at 40 Hz is shown in brackets. For more details, see Summers et al. (2001).

4.4 Actuators and mechanical considerations

In order to produce comfortable, easily detectable levels of stimulation, a tactile interface must deliver vibratory stimulation over an amplitude range up to approximately 100 microns. The mechanical force and input power required to produce such levels of mechanical disturbance are determined by the mechanical input impedance at the skin surface, which depends on the contactor area. (The mechanical load on a 1 or 2 mm contactor may be roughly estimated as: mass 10^{-5} kg, resistance 0.1 N m^{-1} s, stiffness 100 N m^{-1}.) However, in practice the power consumption of tactile interfaces is generally dominated by losses in the electromechanical transducer mechanism.

For use in a multichannel tactile interface, the actuators must be small and efficient, with a working bandwidth of around 10 to 500 Hz. Piezoelectric actuators appear to be a good choice (Summers and Chanter, 2002), with advantages of size and power consumption over electromagnetic devices. In order to obtain sufficient displacement amplitude from a piezoelectric device without excessive drive voltage, some form of mechanical leverage is necessary, e.g., use of the piezoelectric material in a bimorph configuration.

Both Hasser and Weisenberger (1993) and Taylor *et al*. (1998) describe arrays based on shape-memory-alloy (SMA) actuators which operate over a range of stimulation frequencies. However, waveform control in such devices is difficult because of the inherent on/off nature of the actuator mechanism. In addition, operation at stimulation frequencies above 100 Hz is problematical because of the inherent time constant associated with heating/cooling of the shape-memory alloy – Hasser and Weisenberger achieved operation at frequencies up to 200 Hz by designing for only partial relaxation of the system between heating pulses.
Several other actuator technologies have been investigated:
Pneumatic systems appear to be more suitable for haptic displays on a larger scale. They are difficult to implement at the size required for good spatial resolution and their temporal response is limited.
Electrorheological systems require mechanical input from the user to obtain information, i.e., they are perhaps more suited to a static device which is palpated by the user.
Electromagnetic systems are difficult to engineer with high efficiency. This has led to the use of existing commercial devices (solenoids, loudspeakers, etc.) to drive research prototypes, and these have often been too large or too heavy to achieve the required performance.

4.5 Sensing issues

There are two distinct aspects of sensing for tactile interfaces:

- sensing of position within the workspace, so that the tactile information to be delivered is appropriate to the location which the user is exploring;
- sensing of the movement of the tactile actuators in response to computer-generated drive signals.

Regarding position sensing – in the context of an RGI the tactile interface will be only one component of the interface and hence it will rely on the overall position sensing of the entire system. An additional constraint imposed by use of a tactile interface is that the spatial resolution of position sensing within the workspace should ideally be better than the spatial resolution of the actuator array (i.e., perhaps 1 or 2 mm).

Regarding movement sensors for the tactile actuators – in principle, error correction can be implemented by using such sensors within feedback loops, but the added cost and complexity would seem to prohibit this for a practical, commercial device. (In the context of research device it is possible to instrument contactors in a stimulator array with miniature accelerometers or optical sensors, in order to monitor the tactile signals delivered to the user.)

4.6 Software issues

When using software to specify tactile aspects of a representational virtual environment, i.e., "tactile rendering", the issues are similar to those in visual rendering. The 3D virtual objects are covered in essentially 2D virtual surfaces, whose tactile properties must be specified.

A significant problem for the operation of an array stimulator is the need to specify multiple parallel waveforms when creating a stimulus. In an attempt to provide a user-friendly system, UNEXE use an interface which specifies a spatiotemporal distribution of vibratory output at 40 Hz and a spatiotemporal distribution of vibratory output at 320 Hz. The 40 Hz output is intended to stimulate primarily non-pacinian receptors and the 320 Hz output is intended to stimulate primarily pacinian receptors. This two-frequency system may be considered as analogous to a 3-colour video display – the stimulator produces a sequence of frames in two tactile "colours".

Psychophysics experiments at 40 Hz and 320 Hz produce different results (Summers and Chanter, 2002), suggesting that different receptor populations have been targeted as intended. For stimuli at 40 Hz and 320 Hz to have the same subjective intensity, stimulus amplitude at 40 Hz must be around 10 times greater. For stimuli with components at both 40 Hz and 320 Hz, measurements have been made to determine the component amplitudes required to achieve constant subjective intensity as the amplitude ratio is varied – see figure 4.3.

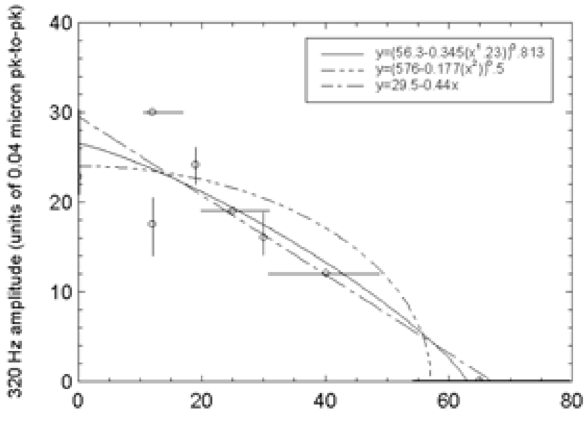

Figure 4.4 Component amplitudes at 40 Hz and 320 Hz for constant subjective intensity. Data averaged over 5 subjects, from a comparison between various 2-component test stimuli and a 2-component reference stimulus. The data have been fitted with an expression of the form $[(x/a)^n + (y/b)^n]^{1/n} = 1$, where n = 1.23 gives the best fit. Also shown are best-fit lines for a linear model (n = 1; addition of normalised component amplitudes) and for an elliptical model (n = 2; addition of normalised component powers).

4.7 Overview of existing devices

Several tactile interfaces have been developed in recent years, generally as research tools. In addition to the STReSS, VBD and UNEXE devices described elsewhere in the technical sheets (Chapter 6), other devices include:

- The tactile shape display from Harvard University (Howe, 2004). This uses stacks of commercial servomotors to drive a 6 × 6 array of contactor pins at a spacing of 2 mm. Maximum displacement (2 mm) is high but frequency response (7.5 Hz) is low, although response up to 25 Hz is obtainable at lower amplitudes.

- The SMA-based array of Taylor *et al*. (1998). This uses shape-memory-alloy actuators to drive a 64-pin array. Waveform control in such devices is difficult because of the inherent on/off nature of the actuator mechanism. However, in this design resistive feedback is used to give closed-loop control, providing a significant improvement to performance.

There are also several tactile array stimulators designed use with a passive subject, i.e., the array is fixed in position and presents stimuli which are not under subject control. Such devices may involve mechanical systems which are too heavy or too bulky to be adapted for active use in RGIs. However, this type of device has provided significant psychophysics data for perception of virtual touch stimuli. Such devices include:

- The stimulator of Szaniszlo *et al*. (1998), which uses piezoelectric bimorphs to drive an array of 288 contactors over an area of 400 mm^2, with a fixed stimulation frequency of 220 Hz and a fixed stimulation amplitude. This device has been used to investigate spatial and movement aspects of tactile perception (particularly on the face, where pacinian receptors are absent).

- The stimulator developed in the mid 1990s by James Craig (Indiana University) and Kenneth Johnson (Johns Hopkins University). This is a high-density array with 400 contactors over an area of 1 cm^2 and a design bandwidth of 0-500 Hz. Each contactor in this array is controlled by a purpose-built linear motor, allowing very precise specification of the displacement output. This device offers considerable scope for novel psychophysics and neurophysiology investigations, with independent targeting of both pacinian and non-pacinian receptors (Vega-Bermudez and Johnson, 1999).

4.8 Conclusion and future possibilities

The current generation of RGIs typically provides an inadequate representation of touch sensations. Development of an effective tactile interface for incorporation into these interfaces will provide a significant enhancement. Some research prototypes may be too sophisticated for direct development into commercial devices, because of cost limitations, but “cut down” versions offer exciting possibilities. There is clearly room for improvement in some aspects of existing designs.

In relation to human factors, there are several possibilities for improving the mechanical layout:

- use of a curved contactor surface to match the shape of the fingertip, in contrast to the planar surface used in most existing devices; this would offer lower contact pressure in the quiescent state
- positioning of the tactile actuators so they do not lie beneath the contactor surface; this would allow thumb and fingers to be brought close together for manipulation of thin virtual objects
- provision of retractable contactors which are held away from the skin in the quiescent state and individually move to contact the skin when stimulation is delivered; this would remove all tactile sensation in the quiescent state.

In relation to basic technology, since existing devices are often too large and too heavy, micro-electromechanical systems (MEMS) offer exciting possibilities. When designing a stimulator array, if the footprint of the actuator mechanism could be reduced to the area of a single contactor, it would then be possible to construct large arrays by simply stacking individual actuator/contactor units side by side. For this to be practicable for a commercial device, however, the unit cost would have to be small.

To complete this section, it is interesting to consider a completely different aspect of spatially distributed sensation – that of temperature perception. This is an important aspect of the perception of objects via the skin. If the contactor array of a tactile interface were able to provide a controlled distribution of temperature as well as a controlled distribution of mechanical stimulation, this would open up exciting possibilities. For example, it would allow exploration of the affective aspects of touch, such as the “feel” of human skin or animal fur.

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5 TECHNOLOGY OF RETROACTIVE HAPTIC INTERFACES

5.1 Introduction

According to the previous analysis this section deals with the four macro components identified in the generic scheme of haptic interfaces :

1. The mechanical structure of the device.
2. The Actuation system.
3. The sensing devices.
4. The signal treatment system that includes : local control loops, data communication paths and computer treatment systems.

The Retroactive Haptic Interface (RHI) technology is related to several fields : mechanics for the human interacting part, computer science and more particularly real time and reactive systems, physical modelling and simulation, control, electronics.

5.2 Mechanical structure of a device (Percro)

5.2.1 Kinematics

Introduction

Haptic interface presents a difficult mechanical design problem. The main challenge in their design is the combination of requirements such as of high stiffness, low inertia, force isotropy, high backdrivability and combined with large enough workspace. These features are clearly high dependant from the kinematic structure. This makes the kinematic design very important in the realization of an haptic device.

There are some important parameters able to show the effectiveness of a kinematic structure :

- Work-space volume and workspace shape: The workspace is the volume of space which the end-effector of the mechanism can reach. It is quite difficult to define effective measure of the workspace of a mechanism, in fact, a possible measure of workspace could be its volume, but this value is quite meaningless without considering also the geometrical shape.
- Perceived inertia and inertia isotropy: The perceived inertia is the force perceived by the user of the haptic interface when a unit acceleration is applied to the end-effector. The perceived inertia is represented by the inertia tensor, which is generally a 6 by 6 matrix whose elements are function of the position. The inertia isotropy is the measure that indicates how the inertia value varies with the direction of movements. The isotropy is measured with the Condition Number of the inertia tensor, high isotropy means Condition Number close to the unit.
- Force isotropy: Force and torques are transmitted from actuators to the end-effector with a relation expressible with a matrix: the Jacobian matrix. The inverse of the Condition Number of such matrix indicates the isotropy of the force and torque transmission. Small value of condition number lead the systems to control instability. This measure is generally dependant on the position than it has to be calculated in every point of the mechanism-workspace. A possible extensive measure of this feature is the integral of Jacobian Condition Number within the workspace of the mechanism ([1,2]).
- Structural stiffness: Structural stiffness is the ratio between applied force or torque at the end-effector and the obtained displacements, when the motors are considered blocked. The stiffness is completely represented by a stiffness tensor which is generally a 6 by 6 matrix. A simplified representation is to give the maximum displacement under a given load (the worst case).

Structural stiffness is an important parameter for an haptic device because it determines, combined with control gain, the maximum stiffness of simulated objects [3];
- Singularity position: The singularity of the mechanism are particular position where there are lacks of mobility or controllability of some degrees of freedom. These positions depends on the kinematic structure and the actuator placement and they have to be avoided during because they lead to control instability. The kinematic design have to take in account this issue with the aim of locating the singularity position at the boundary of the workspace of the mechanism.

The design of an haptic interface always involve the optimization of such measure of kinematics, but it has to be taken in account that this is not sufficient to achieve an effective kinematic design. There are, in fact, many “variables” that depends on the kinematic design but can’t be expressed with any quantitative parameter. Some example of them are the shape of workspace and the encumbrance of links in the visual space.

Classification

Many haptic devices are able to exert on the user either force and torque. The kinematic structure of such haptic devices can be often divided in a Positioning stage and a rotational stage. The first stage is responsible of the spatial positioning of the end effector, while the rotational stage is able to orientate the end effector.
By the actuation point of view, the first stage is responsible of exerting the forces on the user and the second is responsible of the torque-feedback.
In serial mechanism is almost always possible to distinguish this two stages. When the haptic interface’s design is based on parallel kinematics there are two possibilities:
- A mixed parallel-serial structure: The kinematics is constituted by a series of two parallel stage or a parallel mechanism jointed with a serial stage.
- A fully parallel kinematic: The mechanism is completely parallel (for example a Stuart platform kinematic).

Positioning stage

Positioning stage is the part of the kinematics responsible of the translational displacement of the end-effector of the mechanism. It is possible to distinguish between pure translating positioning stage and mixed roto-translating positioning stage.

Serial

A Serial mechanism is composed by an open chain of rigid link and every link except the first and the last (end effector) is connected with at least and no more than two other links. In such mechanisms the kinematic issue is less relevant respect to the transmission and actuation design. Actuators able to exert the needed force or torque are generally too heavy and encumbering to be placed directly on the joints. Than the choice of the location of the actuators and the design of the appropriate transmission is very important for achieving a low perceived inertia.

The main limitations of serial kinematics are:
- Low stiffness: the links are most of the times long and thin structures and a load on the end effector can cause quite large deformation in the structural components. Moreover if the actuators are located away from the joints (to reduce moving masses) the length of the transmission could contribute to increase the compliance of the structure.
- Low peak-forces: when rotational joints are used a force applied at the end effector cause high torques on the first joints of the mechanism (the joints located closer to the base),
- High perceived inertia: The requirements of high stiffness combined with large workspace lead the structural components to assume heavy weights and high rotational inertia. Moreover serial kinematics are, in many cases, subject high variations of inertia tensor with the position.
- Narrow bandwidth: As consequence of high inertia and low stiffness the frequency response is upper limited.
- Non-isotropic behavior:

On the counter part serial kinematics show the following advantages:

- Large workspace
- Naturally adaptable to human arts kinematic: design of anthropomorphic devices
- Computationally easy to treat: Forward kinematics solution is very simple and can be solved with standard method, for example using Denavith-Heartenberg parameters. Inverse kinematic is solved for almost all the possible serial combination of joints. The differential kinematic is solvable with standard method [3].

The possible combination of achieving a positioning stage with a serial kinematics are limited. The most used joints are rotational and prismatic. The last one is less employed because the use of prismatic joints lead large perceived inertia. And moreover the actuation solution are more complicated. Spherical joints are not used because they are very hard to actuate (in serial mechanism all the joints have to be actuated).

Examples of serial positioning stage

3R with four bar mechanism : Freedom_7

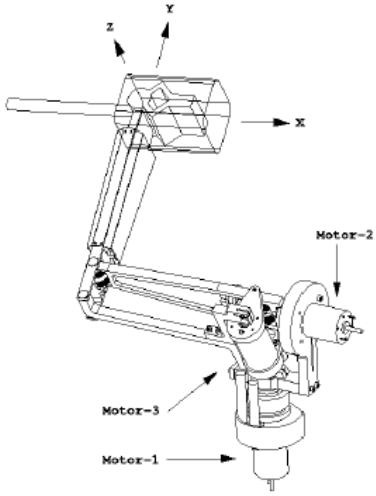


Figure 5.1 Freedom Seven positioning stage

Freedom 7 is a 7 dof haptic device developed by Prof.Hayward in McGill University of Canada [5,6]. The positioning stage is a classical serial mechanism made of three rotational joints. The third joint is actuated by means of a four bar mechanism in order to locate the motor closer to the base. The study of the motor position lead to a self gravity compensated behavior. Orientation stage in this case is obtained with a parallel kinematics.

A very similar kinematic for the positioning stage is adopted by Phantom, the very well known haptic interface commercialized by Sensable technologies [7].

<u>RRP – Grab</u>

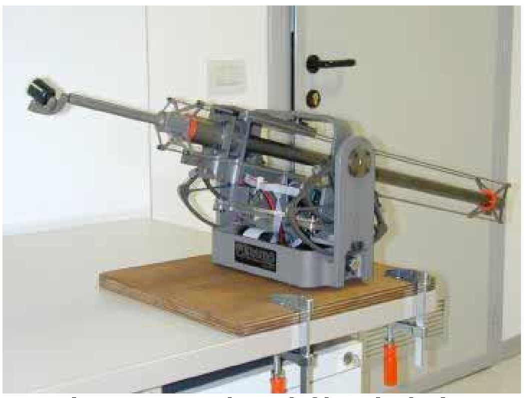


Figure 5.2 Grab a 3dof haptic device

Grab is a device designed at Percro Laboratory [8]. This is serial kinematics haptic device designed to achieve high isotropy and low inertia. It a RRP structure. This choice was made for achieving a better force isotropy, in fact, the condition number of the Jacobian matrix is independent by the rotation of the first two joints, but varies only with the position of the prismatic joint. A high structural stiffness was achieved by using the prismatic joint as last.

RPP Haptic master

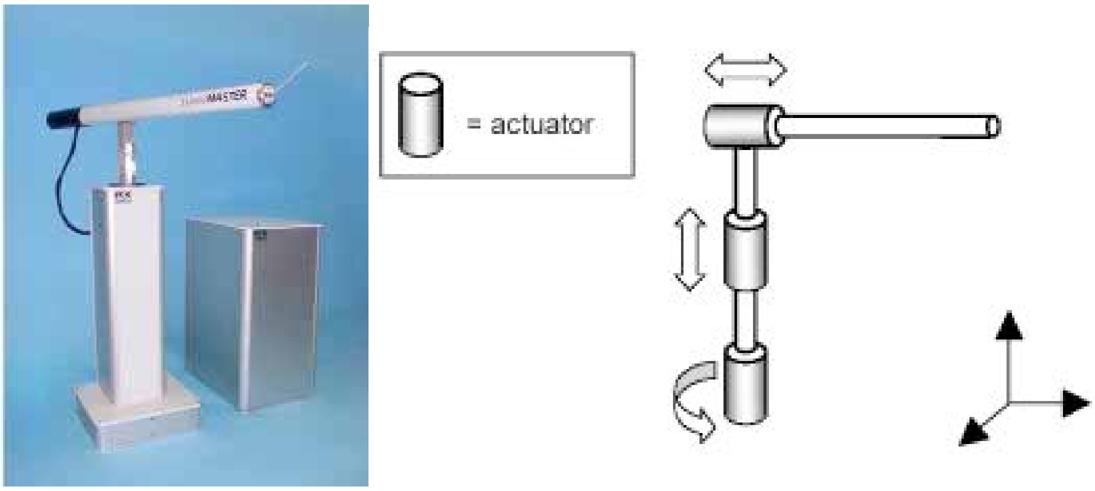


Figure 5.3 FCS Haptic Master

Haptic master is a admittance control haptic device commercialized by FCS Control System [10]. The kinematic structure of the mechanism is a RPP. The length of the path from the base up to the end-effector imposes the design of very stiff and heavy structural components, but in this case masses of moving parts is a little concern, in fact, this haptic device is admittance controlled so the dynamic perceived by the user in free space moving is a totally virtual.

PRR-LHIfAM

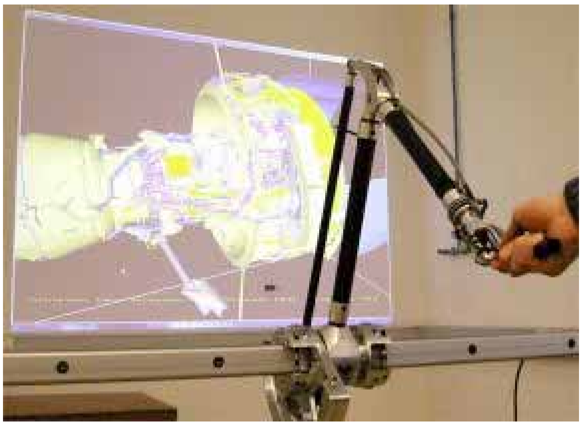


Figure 5.4 Lhifam Haptic Interface

LHIfAM is a very large workspace haptic device developed in the Department of Mechanics in CEIT (Spain). This haptic device has a particular kinematic structure designed to achieve the requirement of a very large work space. The particular design lead to the choice of a prismatic joint at the beginning of the kinematic chain, followed two rotational joints. This solution introduces a big amount of moving masses and impose an inertia compensation on the prismatic axis direction.

Parallel

A Parallel mechanism is composed by one or more closed kinematic chains. In many of the kinematic designs the layout consist in a set of “leg” (serial kinematic chains) that connect the end-effector with the base of the mechanism.

Generally parallel kinematics shows the following limitations:

- Small workspace: The workspace of a parallel mechanism is given by the intersection of the workspace of all the serial links that connect the end-effector with the base of the mechanism. The design of parallel mechanism, in fact, always require an optimization of the workspace volume.
- Computationally hard to treat: Inverse kinematic is solvable, in fact, it consist in solving the inverse kinematics of each serial link that connect the end-effector with the base. Forward kinematics is often hard to solve in closed form and there are no standard methods. This lead to increase the computational load to calculate end-effector position by means of numerical methods [4], using inverse kinematics and differential kinematics.
- Encumbrance: Multiple kinematics chains can reach high encumbrance around the workspace of the mechanism.
- Control stability: The convergence of many kinematics chain on a single end-effector creates coupling between actuators. In some cases this phenomena can lead to instable conditions.

On the contrary parallel designs shows the following positive characteristics:

- High stiffness: Forces and torques are distributed on the multiple chains of the mechanism, so each link is low charged. Moreover the possibility to locate motor at base of the mechanism allow to design very short transmission that have a small contribute to the global compliance.
- Low inertia: The possibility to reach high stiffness structure with quite thin and light link’s structures lead to a low perceived inertia.
- High bandwidth: the high stiffness and low inertia lead to a large band of frequency response.

Examples of Parallel positioning stage

Parallel positioning stages can be classified as pure translating and non-pure translating. Non-pure translating is rarely used.

Pure-Translating Haptic devices:

Pure translational parallel mechanism were largely studied within the field of robot for manufacturing. Their main capability is to have only translational degrees of freedom. This means that the mechanism is able to carry a generally oriented torque applied at the end-effector without activating any of the actuators. This feature is exploited to design multiple stage mechanism with translational stage and serially connected rotational stage.

<u>DELTA</u>

The basic idea behind the Delta [11] robot design is the use of parallelograms. A parallelogram allows an output link to remain at a fixed orientation with respect to an input link. The use of three such parallelograms restrain completely the orientation of the mobile platform which remains only with three purely translational degrees of freedom. The input links of the three parallelograms are mounted on rotating levers via revolute joints. The revolute joints of the rotating levers are actuated in two different ways: with rotational (DC or AC servo) motors or with linear actuators.

Figure 5.5 The Delta Haptic Interface

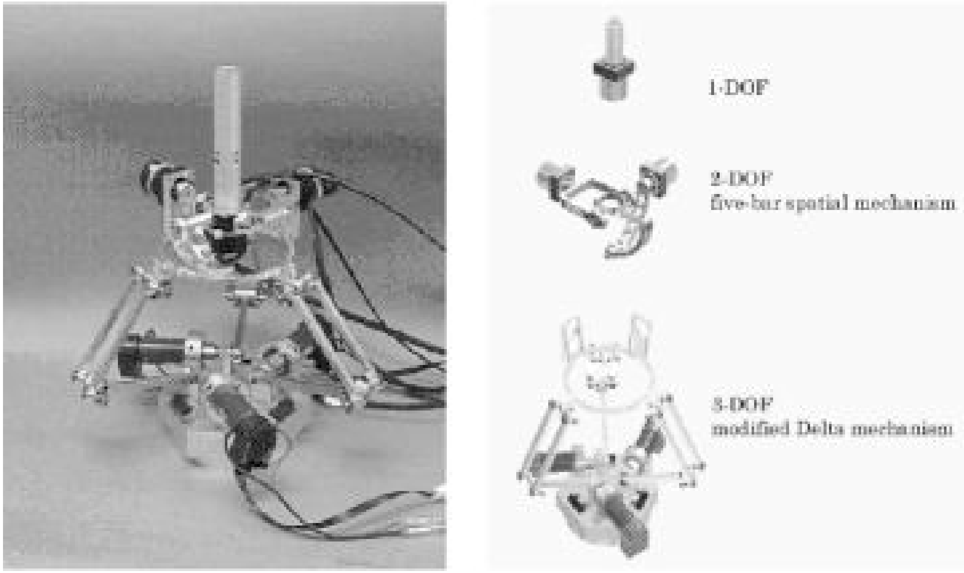


Figure 5.6 Delta kinematics in a 6DOF haptic device

There are other haptic devices that make use of Delta kinematics. For example in Tokio University in the department of Aerospace and Space Engineering, a Delta based haptic device was developed [10].

3DOF (Percro)

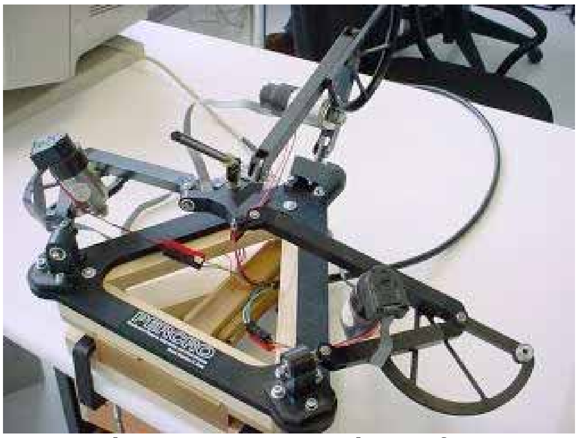


Figure 5.7 5DOF Haptic Interface

A mixed serial-parallel kinematics was developed in Percro Laboratory. This haptic device is a 5DOF mechanism composed by a translating platform and a 2DOF rotational serial wrist. The kinematic of such device was studied to achieve high Force Isotropy within the workspace volume [12].

3P- Excalibur

Excalibur is developed in the Biorobotics Lab in Washington university [13]. This haptic device has mixed serial-parallel kinematics. The first two degrees of freedom are a parallel mechanism that allow the movements on a horizontal plane. The third degree of freedom is a vertical prismatic axis. The kinematic scheme is represented in following figure.

Figure 5.8 Excalibur System

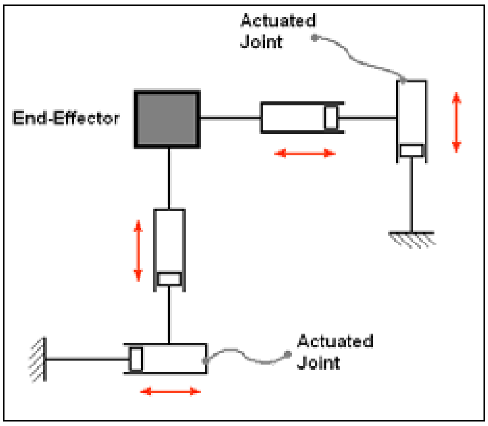


Figure 5.9 Positioning Stage of Excalibur HI

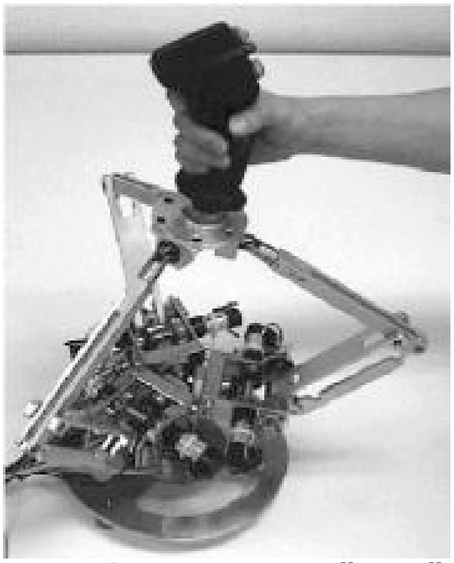
In this case a parallel kinematics was employed for the first two degrees of freedom in order to achieve a higher stiffness.

Fully Parallel

Fully parallel kinematics are parallel mechanism were the end effector is connected to the base through a set of serial chains. No serial connection between different stages are present. There are several examples of haptic devices based on such kinematics but the high degrees of design freedom in this kind of design makes impossible to classify them in rational ways. Among all these devices it is possible to identify only some common feature. The main limits of this kind of kinematics is the lack of angular workspace, in fact, in many cases allowable angular displacements hardly reach 10°-15° in every direction. This limitation makes fully parallel haptic devices useful mainly for desktop application .

Pusan National University:

In South Korea in Pusan National University in the Intelligent Robotic Laboratory department a fully parallel haptic device was developed [15]. In this case the six DOF are achieved by means of only three legs (on the contrary Stewart Platforms has six legs) in order to increase the workspace of the mechanism. Clearly two motors on every leg are needed to achieve 6DOF behavior. In the following figure is represented a prototype of such mechanism and its kinematical structure.



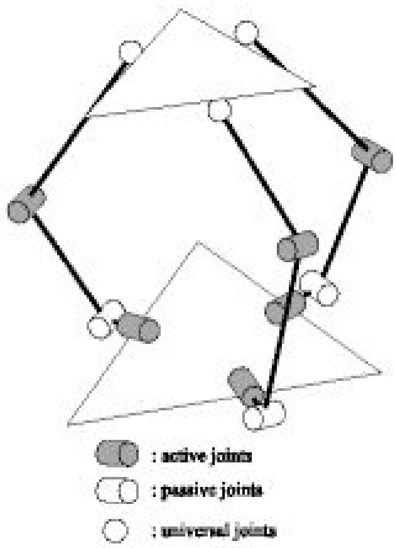


Figure 5.10 6DOF Fully Parallel Haptic Device (IRL) K-Joystick

In K-JIST in the Human-Machine-Computer Interface Lab. another 6DOF device has been developed and realized [16]. Also in this case it was used a three leg design in order to maximize the workspace volume.
In the following figure is represented a picture of the device and its kinematic structure. In this case a four bar mechanism was employed to achieve the actuation of the legs.

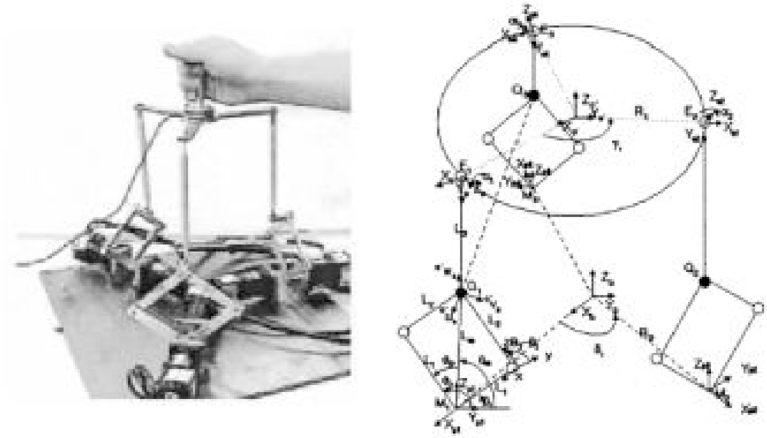


Figure 5.11 6DOF Fully Parallel Haptic Device (HuMaCoIn)

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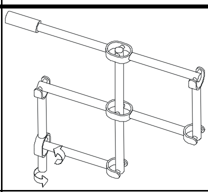
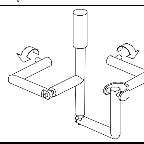
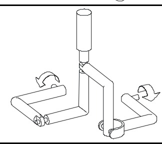
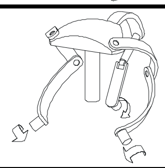
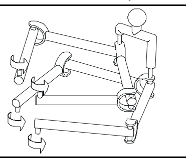
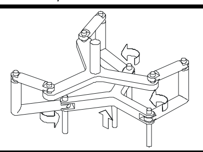
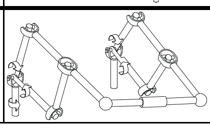
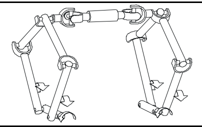
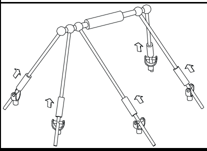
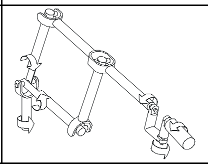
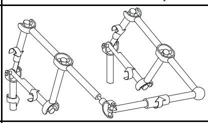
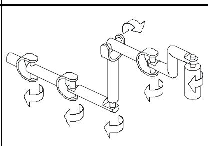
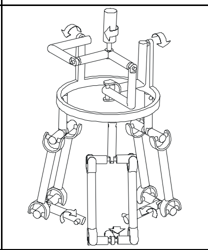
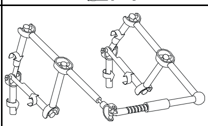
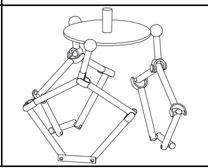
[16] *Design, Fabrication, And Evaluation Of A New Haptic Device Using A Parallel Mechanism* **Jungwon Yoon and Jeha Ryu.**

Orientation Stage

A state of the art in torque feedback mechanisms has been carried out by CEIT Applied Mechanical Department as a preliminary study for our force/torque device design. The survey comprehends a variety of haptic and teleoperation master devices stretching from 1-dof rotary knobs to redundant 10-dof mechanisms, all of them providing either pure torque or force/torque feedback. Encountered devices have been classified by number of degrees of freedom (dof) with force/torque feedback, and in this manner they are presented in Table 1.

dof	Device	Ref	Kinematics	type[8]	Workspace[9]	Force/Torque[10]	Purpose
1	Immersion Haptic Rotary Controllers HPRC	[Grant, 2004]	-	L	Unlimited	T = 0.12	Provide infrastructure for Human-Computer interaction task studies
	Aladdin Haptic Door Knob	[MacLean,Roderick, 1999]	-	L	Unlimited	T = 0.25	Haptic door knob for conveying information about environments
	Rotary Haptic Knob for Vehicular Instrument Controls	[Badescu, Wampler et al., 2002]	-	L	Unlimited	T = 0.146 (1.1 with brake)	Emulate conventional knobs and produce new effects in motor vehicles
2	Spherical Remote-Center-of-Motion Manipulator for MIS	[Spaelter, Moix et al., 2004]		L	±50 / ±50	T = 0.5	Surgery simulator for training of MIS with Virtual Reality
	PERCRO Haptic Gearshift	[Angerilli, Frisoli et al., 2001]		L	-	-	Reproduce the mechanical behavior of an automotive manual gearshift
	Immersion Impulse Engine 2000	[Rosenberg,Jackson, 2002]		L	-	-	Feedback joystick for research
3	ShaDe	[Birglen, Gosselin et al., 2002]		L	P±45 Y±90 R±45	-	Master of the Agile Eye
	University of British Columbia Planar 3-dof Haptic Interface	[Sirouspour, DiMaio et al., 2000]		L	Unlimited rotation	-	Simulation of virtual dynamic environment
4	Northwestern University 4-dof Force-Reflecting Manipulandum	[Millman,Colgate, 1991]		L	∅200 L90 90º rotation	F = 44.5 T = 1.36	Micro-teleoperation, human manipulation, human limb mechanics
5	Two PHANToM Configuration	[Wang, 2001]		L	-	-	Research on the role of torque in haptic perception of virtual objects

8 Device type: L = Link, M = Magnetic levitation, S = Stringed.
9 Distances in mm, angles in degrees. For spherical workspaces diameter (∅) is given, for ellipsoidal workspaces the three axis lengths, for cylindrical workspaces diameter and length (∅, L), and for prismatic ones, width, height and depth (W, H, D).
10 Forces in N, torques in Nm.

	University of British Columbia Twin-pantograph Haptic Pen	[Stocco, Salcudean et al., 2001]		L	W75 H75 D120 ±45 / ±45	Cont F = 3.3 T = 0.34 Peak F = 21 T = 3.24	Surgical training, teleoperation system, force feedback excavator control stick
	University of Colorado Haptic Interface	[Lee, Lawrence et al., 2000]		L	∅400 60 / 60	F = 8	Scientific visualization applications
6	HAPTION Virtuose 6D35-45[11]	-	-	L	450 (not specified)	Cont F = 10 T = 1 Peak F = 35 T = 3	Assembly simulation, ergonomic studies, maintenance training
	MPB Technologies Freedom6s[12]	-	-	L	220 / 240 / 220 P100 Y100 R320	Cont F = 0.6 T = 0.08 Peak F = 2.5 T = 0.125	Animation, 3D Modelling, CAD, Medical Simulation, Telemanipulation
	SensAble Technologies PHANTOM Premium 1.5/6DOF	[Chen, 1999] [Cohen,Chen, 1999]		L	W260 H460 D120 P335 Y260 R335	Cont F = 1.4 T=0.188(P-Y) 0.048(R) Peak F = 8.5 T=0.515(P-Y) 0.17(R)	General purpose
	Two PHANToM Config. + actuated rotation about handle	[Iwata, 1993]		L	-	-	-
	Cybernet Systems Corporation CyberImpact 6-dof hand controller[13]	-	-	L	W102 H102 D102 ±45 / ±45 / ±45	-	Advanced joystick or flight-yoke for the whole hand
	Salisbury/JPL Arm	[Bejczy,Salisbury, 1983]	-	L	300 (not specified)	F = 10 T = 0.5	Hand controller for use in space telerobotics
	ViSHaRD6	[Ueberle,Buss, 2002]		L	W310 H860 D310 P90 Y360 R360	Cont F = 33.5 T = 20(P-Y) 0.2(R) Peak F = 178 T = 54(P-Y) 1.2(R)	Various applications with different interface tools on its end-effector
	Compact 6-dof Haptic Interface	[Tsumaki, Naruse et al., 1998]		L	∅75 P70 Y70 R70	F = 10	Teleoperation
	Northwestern University 6-dof Haptic Interface	[Burns, 1996]		L	W300 H300 D300 P±90 Y±90 R270	F = 44.5 T = 4(P-Y) 1.36(R)	Virtual reality and teleoperation. Astronaut training in 0-gravity environment
	ForceDimension 6-dof DELTA Haptic Device	[Grange, Conti et al., 2001]	-	L	∅360 L300 ±20 / ±20 / ±20	F = 20 T = 0.2	General purpose
	University of California Pantograph Linkage Parallel Platform Master Hand Controller	[Long,Collins, 1992]		L	-	-	Generalized teleoperator master for remote handling of toxic debris

[11] "Virtuose™ Family at HAPTION," http://www.haption.com

[12] "Freedom6s at MPB Technologies Inc.," http://www.mpb-technologies.ca

[13] "CyberImpact 6-DOF force feedback hand controller by Cybernet Systems Corporation at NASA SBIR," http://sbir.gsfc.nasa.gov/SBIR

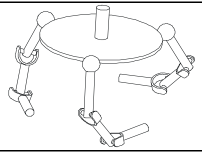
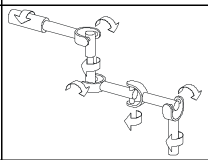
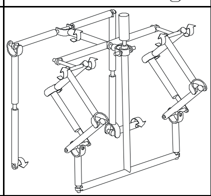
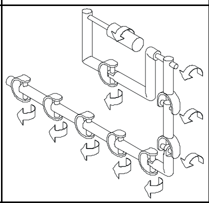
	University of Tsukuba HapticMaster[14]	-		L	∅400	Cont F = 12 T = 0.56 Peak F = 21	Virtual reality, scientific visualization and 3D shape modeling
	9-string 6-dof force-feedback joystick for telemanipulation	[Agronin, 1987]	-	S	-	-	-
	University of British Columbia 6-dof Magnetically Levitated Haptic Interface	[Salcudean,Parker, 1997]	-	M	∅6 ±5 (no specified)	Cont F = 16 Peak F = 34	Virtual emulation of simple mechanisms and teleoperation master
	Carnegie Mellon University Hemispherical Magnetic Levitation Haptic Interface Device	[Berkelman, Butler et al., 1996] [Berkelman, Hollis, 1995]	-	M	25 (not specified) 15-20 all directions	Cont F = 50 T = 6	-
	6-dof Force-Feedback Device Based on the DLR Light-Weight Robot II	[Preusche, Koeppe et al., 2001]		L	-	-	Teleoperation
	Freedom-7	[Hayward, 1995] [Hayward, Gregorio et al., 1997]		L	130 / 160 / 180 P90 Y100 R120	F = 5 T = 0.6	Surgical training with virtual environments
	MIMIC Technologies Inc. SPIDAR-G	[Kim, Berkley et al., 2003]	-	S	-	-	Engineering design
	ViSHaRD10	[Ueberle, Mock et al., 2004]		L	∅1700 L600 P360 Y360 R360	F = 170 T = 13(P-Y) 4.8(R)	Test bed for the development of novel haptic applications.

Table 1: Observed Parameters for the Selected Devices

Focusing on the challenge of coupling a torque feedback wrist to a 3-dof force reflecting haptic device, the first problem appears with the kinematic choice for the torque feedback wrist. There are several possible solutions:

Parallel and hybrid wrists [Tsumaki, Naruse et al., 1998]. The main advantage from the haptic viewpoint is a higher stiffness, but this advantage does not apply to the device as a whole unless the positioning device is at least as stiff as the wrist. The major disadvantage of these wrists is their limited workspace and their complexity.

Serial wrists [Chen, 1999]. These mechanisms provide a large rotational workspace with a less complex design. Morover they tend to be more compact and light weight than the parallel and hybrid ones. The disadvantage is that always there’s at least one singularity inside the workspace.

In order to avoid singularities inside the workspace it arises the choice of a redundant mechanism [Hayward, 1995]. On the other hand it introduces a more complex control and a heavier device and accordingly a higher mechanical impedance.

[14] "HapticMaster at University of Tsukuba, VRLab," http://intron.kz.tsukuba.ac.jp/vrlab_web/hapticmaster/hapticmaster_e.html

Another problem of the torque reflecting mechanisms is the spatial coincidence of the hand and the endpoint of the positioning device. In any of the aforementioned devices, if the endpoint is fixed the user must translate his hand to make rotations around it. This happens due to the stylus-like handle of this haptic devices. The consequence of it is a kinematic coupling between rotations and translations. This implies a more complicated computation of the Jacobian matrix. If we want to avoid this coupling from the mechanical design we should place the hand “inside” the torque mechanism, and this implies taking the pieces of the torque mechanism “outside” the hand. This solution has the drawback of increasing the volume, mass and inertia of the torque mechanism. An example of this is the Haptic Workstation™ at Immersion[15].

As a result of this work, a paper has been submitted to Worldhaptics’05 [Martin,Savall, 2004]. In this paper, different found devices are discussed from the human-device interaction viewpoint in terms of kinematics and in order to get a perspective of the torque feedback problem as a whole.

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Computation of kinematics

One important aspect that determines the interest of a kinematics configuration is the complexity of the computation that must be associated to a given configuration. As a general rule the basic control and observation signals that are defined by the nature and the diposition of the actuators and sensors cannot be treated directly by the virtual object computation. Scaling and coordinate changing transforms are necessary to provide and accept signal that refers to the workspace coordinates instead of actuated/sensed joints coordinates. The corresponding transformations are necessary and they must be done in real time at adequate computation rate. It consists at least of a position transformation and of a force transformation. The general characteristics are :

The position transformation is generally non linear.

The force transformation is a linear transformation whose coefficients depend on the position. The flow diagram in the case of a simple impedance control system is represented Figure Figure 5.12.

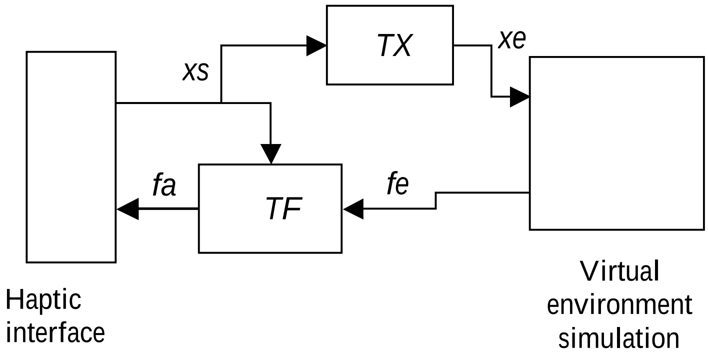

Figure 5.13 The data-flow diagram of kinematic transformation for an impedance mode control. It shows in particular that the actuators control forces *fa* prensents a direct dependance on the sensed positions *xs* through TF.

5.2.2 Transmission (PERCRO, CEIT)

Haptic devices comprise a particularly demanding application for the mechanical transmissions. A haptic device is conceived for two principal purposes: Allowing a user to freely move into a virtual environment and realistically rendering the forces that would be derived from the interaction between user and virtual environment. The fulfilment of the first purpose demands the device to be structurally transparent, for what it needs to have high reversibility, low friction and low inertia. With regard to the second purpose the device must be highly stiff and backlash free.

Direct drive consists in directly driving the joints with the motors. Thus, many of the problems of power transmissions vanish, stiffness between the actuator and joint is essentially infinite, and no cables, gears or pulleys are required. However, direct drive imposes two restrictions.

Joint torques are limited by the output torque of the motor because there is not a speed reducer (or increaser) between the motor and joint.

Mass and bulk of direct-drive motors must be placed at the joints they drive. The heavy outermost joint motor must be supported and accelerated by a stronger and heavier supporting link. The next motor down the chain must then be yet larger to support and accelerate the outermost heavy motor and links and so on to the base where motors and joints are very large. The result is a heavy, power-inefficient robot with wide links which interfere with much of the manipulator's own workspace making it less capable of reaching between and around objects in its environment.

On the contrary, the use of a transmission removes the actuator bulk from distal joints towards the base (decreasing the inertia). Through the speed reduction, the output torque is also increased by the transmission reduction ratio, hence a small but high-speed motor can meet the joint-torque requirements. Consequently, at the end, actuator size and power consumption are reduced. This makes the use of transmission a suitable practice in haptic mechanical design. However, the use of mechanical transmission implies additional problems, such as compliance and backlash.

Overview

The torque-to-weight ratio of the actuators is particularly important for haptics. High speed reduction ratios result in high reflected equivalent inertias as viewed from the joint, which worsens reversibility. Low speed reduction ratios lead to insufficient output force and torque values. Thus, a compromise needs to be achieved for the torque-to-weight ratio of the actuators.

Requirements of low backlash and compliance, relatively high output torque, and large speed reduction in a compact, light-weight package have resulted in wide use of several types of transmission which are subsequently discussed from the haptic viewpoint. Cable transmissions and harmonic drives are separately studied because their interest for our research lines is bigger.

Gear train

Gear trains consist of two or more gears meshed for the purpose of transmitting motion from one axis to another.

Figure 5.14: Gear train

Several reductions may be needed to achieve an adequate overall ratio, so straight trains tend to be bulky. Furthermore, transmission-ratio change is rather difficult because of the high cost and because of the needed precision housing, which makes it hard to design a moveable driving shaft.

The use of high-quality, accurately cut gears can minimize backlash. Normally, these solutions introduce additional friction in the transmission and require costly precision housings to support the gears. Compliance can be reduced by using larger gears than are needed to carry the torque.

An important advantage of a gear transmission is the unrestricted range of motion of 360 degrees.

<u>Cycloidal drive</u>

Cycloidal drives (Figure 4) offer similar one-stage reduction ratios to harmonic drives with lower compliance and higher mechanical efficiency. However, robot applications tend to come in at the bottom end of the size range for cycloidal drives, and so they tend to be relatively large and heavy. Nevertheless, they are an attractive alternative in situations in which their weight can be handled.

Cycloidal drives have high shock load capability and are available with zero backlash. Their efficiency is about 94%. Transmission ratios between 5:1 and 180:1 can be achieved in one stage.

<u>Worm gear</u>

Although relatively cheap for large reduction ratios, worm gears (Figure 5) are not popular in robotic applications, because of their relatively high backlash and low mechanical efficiency. Moreover the non-coaxial geometry often creates packaging problems.

On the other hand, worm gears can be designed to be self-locking, which removes the need for brakes, but this often implies problems with reversibility. As seen in chapter, reversibility is an important factor in a haptic device.

Ball Screw

Ball screws (Figure 6) are one of the most elegant solutions to the problem of obtaining a large speed reduction in a compact, light-weight package without backlash and with low compliance. Eliminating backlash (by spring-loading) can easily be done using a preloaded double nut. They have relatively high mechanical efficiency (90%) and compared with other transmission types, ball-screw drives are very stiff.

When a rotary joint is powered in this manner, the system effectively has two speed-reduction stages: the first reduction stage is the conversion from rotary to linear motion via the screw; the second is in the conversion from linear back to rotary motion via a lever arm. The result is a very compact and efficient high ratio reduction.

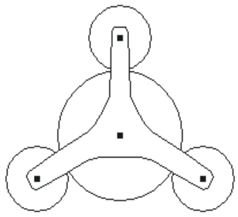

Figure 5.15: Cicloidal drives

Figure 5.16: Worm gear

Figure 5.17: Ball screw

Roller-Chain Drive

Roller-chain drives (Figure 7) can also be used to transmit power. Because the direct speed reduction obtainable is very limited, a speed reducer must be placed between the motor and the drive sprocket of the chain transmission.
Important disadvantages of roller-chain drives are their backlash and torque and velocity ripples. The transmission ratio can suffer from the climbing of the chains onto the teeth. Moreover, vibrations can be present during working due to the polygone effect. Transmission ratios until 120 can be achieved.

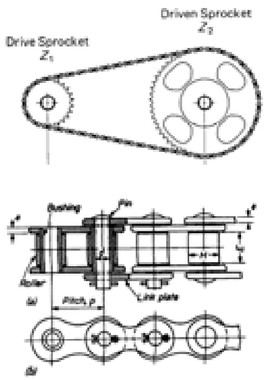

Figure 5.18: Roller-chain drives

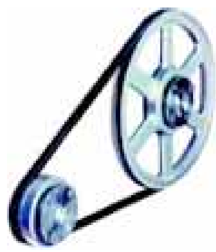

Figure 5.19: Belt transmission

Band mechanism

In band transmissions, a thin metal band, connected at both ends with either of the two shafts, is used to transmit power. When the transmission is located in one end position the band is rolled up entirely round the driving shaft, while in the other end position the band is totally unrolled from the driving shaft.
In general, the band is only wound in one layer. As a consequence band transmissions have a very limited movement, which is their main disadvantage.
Advantages are: high accuracy of transmission ratio, low mass, stable parameters, high strength and high transmission stiffness. Moreover, there is no friction between band and pulley.

Belt Transmission

Metal or rubber belt transmission's working principle is based on friction between belt and shaft. One way to aument the friction, in order to be able to transmit more power, is increasing the pre-tension in the belt. Nevertheless, this causes higher bearing loads and as a consequence more bearing friction.
Advantages are an unlimited range of motion and its ability to change the transmission ratio provided that the belt changes too. Belt drives (Figure 8) also are easy to design, are relatively cheap and can reach high efficiencies (98%).
The use of rubber belts implies relatively low stiffness, while metal belts require higher pre-tensions. Besides, problems can occur when reaching the resonance frequency. Besides their limited transmittable power, also their maximum single stage transmission ratio is only about 20.
Rubber belts exist also in synchronous form (positive belt drives, toothed belts). Their advantage is that slip can not occur, which can occur in non-synchronous belts.

Cable transmission

Pretensioned capstan cable

The same as belt transmissions, the working principle of cable transmissions is the friction between the cable and a driving capstan Figure 9 while both ends of the cable are attached to the driven pulley. A study on the design of cable transmissions for force-controlled manipulators can be found in [Townsend, 1988].

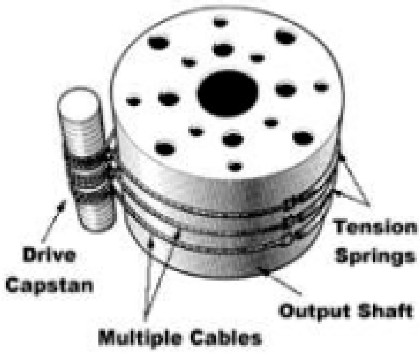

Figure 5.20: Cable transmission

Cable transmission offers several advantages such as: low friction, low weight, high strength, high stiffness, no backlash (due to the cable preload), low velocity and torque ripple, low cost, they do not leak, do not require surface lubrication, and can be guided over long distances around pulleys through complex geometries, allowing to bring the motors down to the ground and thus reduce the moving mass. Nevertheless, they require a more complex design and their range of motion is limited. The latter feature is not always a real disadvantage, since workspace in haptics in many cases is limited. For the aforementioned reasons, cable transmission is the type of mechanical transmission which best fits the requirements of haptic devices. This statement is especially applicable to impedance controlled haptic devices, since they need to be as mechanically backdrivable as possible.

Tendon cable

In contrast with pretensioned capstan cable, tendon cable has one of its ends fixed to de driving capstan. Very low pretension is needed for this transmision and therefore, friction will remain low. The same as in pretensioned capstan cable, the main disadvantage in tendon cable is the limited workspace.
Depending on the number of actuators to number of actuated dof ratio, tendon transmissions can be classified into the N, N+1, and 2N configurations [Jacobsen, Ko et al., 1989], where N represents the number of actuated dof.

Push-pull cable

This system is used to fix a certain orientation in which the tension must be exerted by the cable. It also helps when reaching the moving parts from the actuator is complex. The main disadvantages of this system are backlash and friction. Some haptic devices, like the Cybergrasp and the JPL Generalized Master, use this sytem succesfully.
A push-pull cable is made of a housing inside which runs a steel cable. If the cable is stiff enough to push without bending, then it is a push-pull system and only one cable is needed. When the cable is flexible, then it is a pull-pull system. Those systems can have only one cable that works against a spring or have a pair of antagonist cables.
Disadvantages of this transmission system are backlash, friction and the pretension on the wire rope caused by the diferences on length between the conduit and the wire rope as they bend.
Backlash appears on the push-pull systems as a consequence of the core moving from one side to the other inside the conduit, because the core bends when pushing and becomes tense when pulling. But not neccesarily in pull-pull systems: if the curvature radius is always in the same direction and cables remain always under tension, then, there will be no backlash.

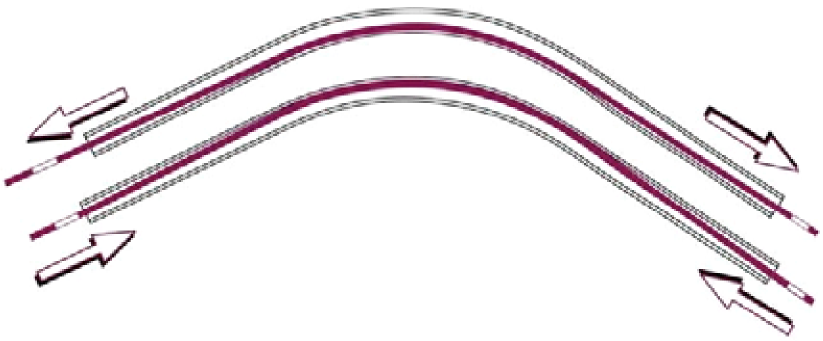

Figure 5.21: Backlash in push-pull systems

Concerning friction, manufacturers usually give some factors as guidelines to aproximate the efficiency of the core-conduit system as function of the number of turns and degrees of curvature.

Harmonic drive

Harmonic drives (Figure 12) use a flexible splined intermediate member. Advantages are a large speed reduction capability in a single stage (50:1 to 320:1), with consequent light weight and compactness, and backlash-free operation. For these features, harmonic drives have a special interest for the research lines described in paragraph 1. On the contrary they display a relatively high compliance as a consequence of the flexible spline member (mechanical efficiency is only of the order of 70 to 85%) and they suffer from lack of backdrivability. For the latter feature, the use of harmonic drives forces to use an admittance control scheme.

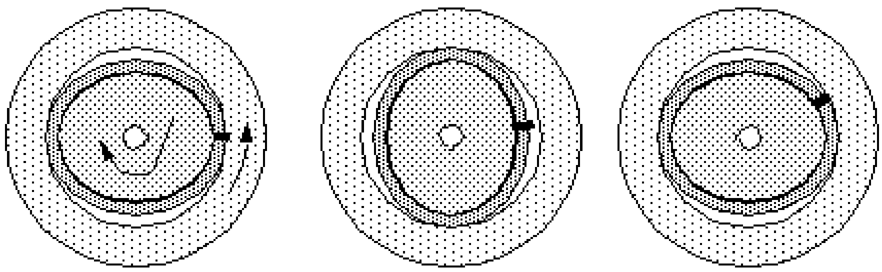

Figure 5.22: Harmonic Drive

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5.3 Actuation (DLR, PERCRO, CEIT)

Our interest is to find compact light-weight actuators with a sufficient torque capacity. With that aim, a search is being carried out through the last advances in electromagnetic compact motors.

5.3.1 Introduction

Choice or design of actuators is a very critical step in the design process of an haptic device. The characteristics of the actuation system reflect on the performance of the whole device. As most of advanced robotic application, the specification of actuators for haptic devices are very strict.

General characteristic of such actuators are:

- High force (or torque) to weight ratio: This feature is very important in order to allow the possibility of using actuators in direct drive configuration. The force to weight ratio of current actuators (especially for electric motors) is far from allowing their use without any reduction stage. Moreover the feature of light weight is very important for portable haptic device to avoid non ergonomical working condition for the user.

- High bandwidth: Several application of haptic interface, such as simulation of friction effects, surface texture, require high frequency force stimulation. In this kind of application actuators bandwidth must be very large.
- Large stroke: For rotational actuators in most of the cases the requirement is the continuous rotation. In almost every case the rotation of the joint is not continuous, but due to the speed reduction ratio, required to achieve higher forces, the rotation of the motors exceed 360°. For linear axis the length of the stroke varies from few millimeters to some meters.
- Low internal friction: The friction of the actuators reflects on the user multiplied by the factor of the inverse of the speed reduction ratio of the possible transmission.
- Low inertia: Inertia of the moving parts of actuators reflects on the user multiplied by the square of the inverse of the speed reduction ratio.
- High level of Safety: The haptic devices for their own nature are robotic systems that have to interact directly with the human body. This consideration lead to the specification of high reliability and safety for the actuation of this devices.
- Easy maintainable: The maintenance of the actuators must be cheap and simple because haptic devices are addressed to common people that have no experience in maintenance procedures.

5.3.2 Electro mechanical actuators (DLR)

Electric Motors for Haptic displays

The role of an actuator inside the haptic display is to produce a precise, smooth and programmable torque with a large bandwidth so the device can display various contact types.
The electric actuators more often used in haptic displays are brushed or brushless DC motors. The specific issue for a drive in a haptic display is the torque production at stall conditions. From the functional theory of electric drives is known that not every electric motor is suited to work at maximum stall torque in a repetitive cycle (brushed DC motor).

The quality of the displayed forces and torques depends in the highest grade of the quality of the used drives and the current control environment. Based on an accurate mechanic design of the device (low friction, no backlash), the force commands can be converted in a simple current command. This implies an in system calibration of the current commands in each axes of the haptic device.

To fulfil the demand of a low inertia of the device, once have to look for the best motor solution reported to the torque/weight ratio. This criteria lead directly to the choice of a brushless DC drive solution. The major disadvantages of this drives represent the higher prices and the additional efforts for the current commutation and control. For the current commutation a special commutation sensor for the detection of the rotor position is needed (Hall-, MR- sensors, Encoder). The resolution of the sensor signal is an important factor in the accuracy of the current control and directly to the quality of the commanded torque.

Brushed DC Motors

Following the anterior ideas, the advantages of the brushed DC motor technology is the lower price and the easy handling in current control schemes. The choice of motors with ironless and sloped windings will grant the damping of the cogging torque, which has a major disturbing effect in haptic displays. This technology is applied by motor manufacturer like maxon motor or Faulhaber (see picture1 and 2).

Figure 5.23 : 20 W brushed DC motor from maxon motors

Figure 5.24 : 30 W brushed DC motor from Faulhaber

A lot of the tested devices during the visits at the haptic laboratories rely on the product qualities of these manufacturers (e. g. maxon: LifHaM-CEIT, morpheon-McGill University, Faulhaber: -PERCRO, Force Feedback Joystick- DLR).

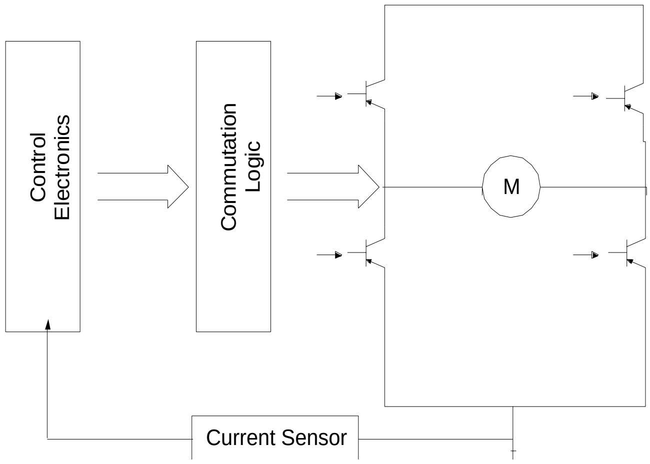
A major disadvantage of this motor type related to the usage in haptic devices is: they are not designed to work at zero speed with maximum torque (current). This due to the mechanic commutation by a collector system which connects the rotor windings (electric excitation) to the motor contacts during the mechanic revolution of the rotor. When small movements occur the electric caused sparkles, cause the deterioration of the collectors and so the limitation of the device lifecycle.
Taking a closer look at the data sheet of a brushed DC motor once can see that the stall torque is much higher than the torque produced by the continuous current (current which can be permanently applied to the motor whitout causing thermal dammage of the motor).
The formula which describes this realtionship is:

Tcont = kT x Icont ;
- where - kT – motors torque constant in Nm/A,
- Icont – continuous current in A

To reduce the weight of the device, a lot of device designers are choosing smaller motors and enable higher currents than the continuous current. As a result the calculation and observation of a thermal model (integration like I2xt) is needed to avoid the dammage of the drive. Another possibility is to measure and observe the temperature of the motor and switch off the current when the critical value is reached. In the case of haptic devices this causes a discontinuous and disturbing behaviour in force-feedback interaction. This solution is unacceptable when controlling critical and very precise tasks (telerobotic applications in medicine, nuclear plants, space robotics).
The question which origins from this point of view is: which is the maximum current I need to command my desired torque or otherwise and can I specifie the time cicle of a force exertion in my haptic based interaction?
The answer for this question is mostly given by the specific application and this fact is limiting the general use of a haptic device.

Current control schemes for brushed DC motors

To control the current of a brushed DC motor a current sensor, a transistor H bridge configuration and commutation logic are needed.
The current sensor is in most of the schemes a precision resistor situated in the bottom branch of the transistor H-bridge between the source- (N-channel MosFET) or emitor-pin (NPN bipolar transistor) of the bottom-transistors and ground (see picture 3). The best results can be achieved with special resistors with 4 pins (Manufacturer: Vishay, Welwyn etc.). The value of this resistor is kept small (3 mΩ up to 100 mΩ) to reduce the influence in the current limitation caused by the power dissipation and the noise influence of the sensor.



Picture 5.25 : H-bridge Configuration with current flow modalities and motor rotation direction (A = motor rotates clockwise -cw, C = ccw)

This allows also the use of resistors with smaller case dimensions (size R2010 or R2512 in SMD case with 1W or 2W power dissipation capacity). The value of this resistor is also used for the current limitation in schemes with integrated current controllres (smart power modules). The current limitation is based on a fixed, internal generated voltage comparation limit for the current control comparator (see also e. g. datasheet of L6506 from ST Microelectronics).

The value of the current proportional voltage on the pins has to be amplified and filtered to be compared with the reference (commanded) value. The amplifier scheme must have a good linearity over the whole temperature range and also assure low noise amplification in the entire frequency bandwidth.
The edge frequency of the implemented filter in the current sensing path is depending on the choosed chopping frequency (non-linear power stages) and is ment to avoid the influence of noise from the measuring resistor and other noise sources.
The transistor H-bridge allows applying current on the motor pins in both directions, enabling in this way to move the motor bidirectional (cw and ccw). For this purpose the diagonal top- and bottom-transistors have to be enabled by the commutation logic. The commutation must also assure that the transistor in the same branch can't be enabled simultanuosly. This is equivalent to a sortcicuit in the branch causing high current flow trough the transistors and the dammage of the power stage. Smart power modules with integrated logic automatically avoid this malfunction by using internal invertors for the transistor command in the same branch. Anotehr important control possibility in this scheme is the fast brake of the motor by enabling both bottom-transistors causing a discharge of the induced current trough these transistors to the ground pin. This causes implicit a fast brake function on the motor.
The H-bridge can be constituted by four N-channel transistors or pairs of P/N- channel transistors. In case of the P/N channel half-bridges the maximum current is limited by the current of the P-channel transistor (smaller than for the N-channel transistor). These bridges have the advantage that the transistors can be controlled by logic level signals (TTL for example) and the top-side transistors don't need a bootstrap scheme to be enabled.
Drives which need smaller currents can be controlled by linear stages as known from audio amplifier schemes. The limiting factor for the use of the power stages is the maximum current which causes the heating of the bipolar power transistor and needs a heat dissipation unit (additional space required).
The commutation logic enables and disables the transistors in the H-bridge and is commanded by the PWM signals from the controller or the discrete current limiting device.
Due to the small electric time constant of the Dc motors winding given by the resistance and the inductivity (tel = L/R) the current will rise very quick even at very short 'on'-times of the transistors. This effect will cause a current ripple with high amplitudes which can cause noise and the heating of

the motor and the power transistors. This effect can be eliminated by higher chopping frequencies and by connecting an additional inductivity in line with the motor terminals.
Most of the power electronics manufacturer (Vishay / Siliconix, ST Microelectronics, International Rectifier) have in their device program several so called ‘smart-power’ devices which include the commutation logic with additional functions like cross-conduction-, over-current- protection and high-side transistor charge pumps (e.g. Si9986, L6206) and the power transistors H-bridge. When the control logic is remote (not integrated) from the device, the connection wires to the motor pins are very long. For the reason of EMC (electromagnetic compatibility) this connection wires have to be twisted and shielded.

Brushless DC motors and their control

The haptic applications based on drives with brushless DC motors require additional efforts in finding the best motor – gear combination for quality force-feedback. The strong permanent magnets (mostly NdFeB, SmCo, RECo –rare earth) which generate the magnetic excitation of the brushless DC motors generate also a higher torque ripple. A solution to reduce this ripple is to shape the magnets in helical form along the rotor.
Another cause for the torque ripple can be the insufficient resolution of the commutation sensor (digital Hall sensor for six-step commutation) or the wrong circular alignment on the rotor.
The torque ripple is not indicated in the data sheets of the motors and must be demanded from the manufacturer. As a design indication: in use with gears with small reduction ratio the torque ripple should not exceed 1% of the nominal torque.
The commutation sensor can be as well as an encoder system (optical or magnetic) or digital respective analog Hall sensors.
In the latest versions some brushless DC motors have integrated MR (magneto-resistive) based commutation sensors with higher resolutions (maximum 512 lines / revolution) as for example the Digital MR – Encoder from maxon motor AG or the IE – 2 from Faulhaber GmbH.
Brushless DC motors have mostly 3 connection terminals and need therefore three transistor half bridges or six discrete power transistors in the power stage. The manufacturer of power devices offer integrated half bridges or 3-phase driver for a six-step commutation based on digital Hall sensors (Si9979).

Picture 5.26 : Brushless DC motor from Faulhaber

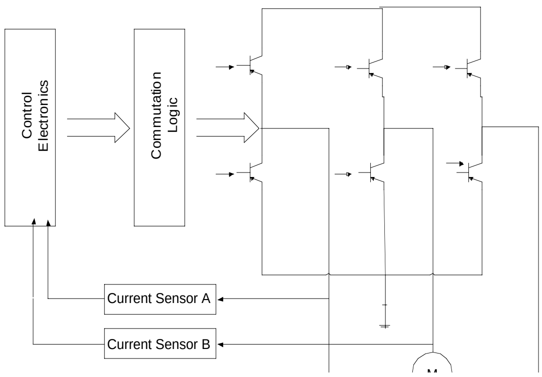
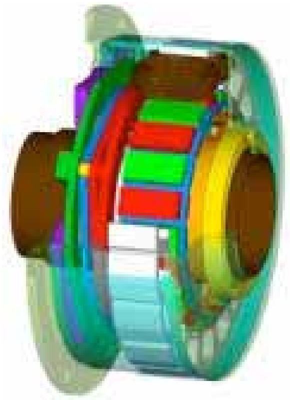


Figure 5.27 Control scheme of a three phase brushless DC motor

In combination with gears with lower reduction ratio the six-step commutation is not precise enough for a haptic feedback with low torque ripple. The best results are achieved with a sinusoidal commutation based on analog Hall sensors or encoder sensors (DLR light-weight robot or SENSO-wheel products from Sensodrive – a DLR spin-off company).
For the torque control of the drive the current control loop of the controller has to be accessible. The motor manufacturer companies offer to their motors control boxes with sinusoidal commutation like Faulhaber’s MCBL- or maxon’s LSC or ADS controllers.

The newest developments of Elmo Motion Control (motion-control company from Israel) offer good servo control features which allow an easy integration of different motors and sensors in a flexible control environment.
A special version of the brushless DC drives represents the so called torque motor. These are motors with higher number of poles and a winding design which generates smaller torque ripple and allow higher currents. These drive solutions are thought to be used without a gear box and find their application for example in steer-by-wire related subsystems. The commutation sensor needs higher resolution and the sinusoidal current control must be more accurate as in case of the use with a gearbox (DLR new motor technology with MR commutation sensor).

Figure 5.28 : Integrated controller from Faulhaber (enables sinusoidal current control)



Picture 5.29: DLR's RoboDrive (brushless DC servomotor)

The efforts for current control and additional commutation sensing and the higher prices for this drive solutions result in a limited use of this drive in haptic devices. But, due to their positive torque – weight balance, they offer the best solution if the drive has to be integrated in the kinematical chain of the device.

5.3.3 Electro-dynamic actuators (INPG)

The electro-dynamic actuator is the simpler actuation system that is based on the Lorentz force principle. Unlike the DC motor it has not any commutation system and consequently it cannot provide an infinite (rotation) displacement. The most know electrodynamic structure is the voice coil that is made of a soleinoid coil moving in a radial induction fied. This structure is used in electroacoustical transducers like loudspeaker motor, electrodynamic microphones or actuators employed in some acoustical measurements.
The solenoid configuration presents an optimal force / moving mass ratio since the whole mass of the moving conductor contributes in the force generation. However the advantage is balanced by the large size of the magnet and this kind of actuator may be heavy and bulky.
To take advantage of the properties of the voice coil in haptic system actuation it is necessary to use it as a direct drive with the lighter mechanism.Some early prototypes of haptic devices were made of big hard disk head actuators that provided a few newtons for about 5cm displacements.
As examples of voice coil haptic devices there is the two axis experimental device of University of Washington presented in section 6.3 that has been developed by Venema and Hannaford., the INPG shared flux multi-axis devices described in 6.2 and the levitation systems like Maglev that have been developed especially by Pr. Hollis at CMU (described in 6.5)

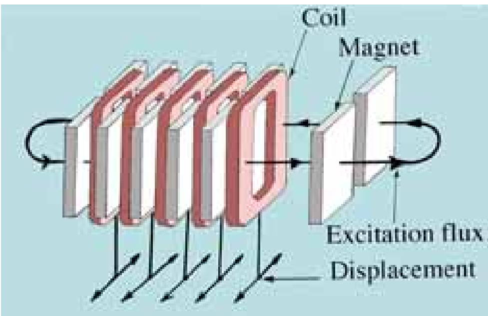


Figure 5.30

The shared flux multi-axis principle (Picture 5.31) introduced by ACROE in a force feedbackmodular keyboard (Cadoz &al. 1989) allow to obtain a modular multiaxis actuator in a very compact form.

5.3.4 Hydraulic actuations.

An hydraulic actuator works by changes of pressure. The pressure is generally convey by a liquid fluid (special oils). This system can be used in both linear and rotary actuation. In the case of rotary actuation, the power unit is a set of vanes attached to a drive shaft and encased in a chamber. Within the chamber the actuator is rotated by differential pressure across the vanes and the action is transmitted through the drive shaft to the external world. The rotary configuration is very hardly used due to its complexity and its extremely low efficiency.
The general linear mechanism consists of a piston encased in a chamber with a piston rod protruding from the chamber. The piston rod serves as the power transmission link between the piston inside the chamber and the external world. There are two major configurations of this actuator: single or double action.

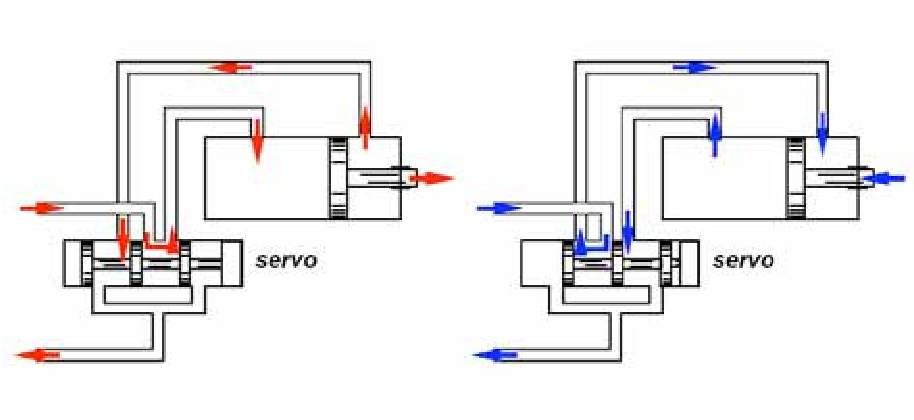


Figure 5.32 - Double action hydraulic actuator

The single action configuration can exert controllable forces in only one direction and uses a spring to return the piston to the neutral or un-energized position.
The control of the force can be realized by means of a two kind of valves which regulates the pressure in the chambers: a servo-valve or a proportional valve. The servo valve is
The hydraulic actuators present many interesting characteristics:

- High forces: the pressure can be raised at very high values (70-200 Atm), allowing to exert very high forces;
- Low inertia: the moving part of the actuator is a piston that can has a very light weight structure respect to the force performances;
- High stiffness: the liquid fluids have very low compressibility factors so the stiffness of the system with closed valves is very high;
- High bandwidth: all the previous characteristics lead to a very high bandwidth, up to 5-6 kHz;

On the contrary they shows some disadvantages that makes them very hardly used for HI actuation:

- Safety: They exert very high forces able to hurt causing injury of human operators;
- Encumbrance: Hydraulic systems needs a very high pressure pump which is a very big, bulky and noisy component.
- Maintenance: Hydraulic systems have several components that need to be checked often. Servo-Valve and sealed systems are very critical components and their failure can cause extreme hazard for personnel and equipment .
- Backdrivability: Hydraulic systems are clearly not backdriveable, so they can be used only in admittance control mode.
- Control: the behavior of the servo-valve last component is strongly non-linear and requires at least a second order modeling.

Application in HI:
There are some examples of hydraulic actuated haptic interfaces realized in some research laboratories.
Sarcos Inc. commercialized the Arm Master with 10 degrees of freedom constituted of a spherical shoulder joint, a hinge elbow joint and a spherical wrist. It is equipped with a two-fingered gripper that can apply forces to the three fingers on a single phalanx only. It is based on a hydraulic actuation that allows a compact but responsive design. The robot includes an optical encoder angular position sensor, a rotary variable differential transformer for analog position measurement and a strain gauge full-bridge joint torque sensor.

Figure 5.33 Master Arm by Sarcos Inc.

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[1] *Development Of A Hydraulic Master-Slave System For Telerobotics,* **Shigeki KUDOMI, Hironao YAMADA, Takayoshi MUTO**
[2] *Sending A Robot To Do The Man's Job (Sarcos Dextrous Arm)* **Korane K.J.,** Machine Design vol.63 No.22 1991.

5.3.5 Pneumatic actuators.

These type of actuators are the direct descendents of the hydraulic systems. The difference between the two is that pneumatic systems use a compressible gas (i.e. air) as the medium for energy transmission This makes the pneumatic system more passively compliant than the hydraulic system. With pneumatic actuators, the pressure within the chambers is lower than that of hydraulic systems, because of water condensing phenomena, resulting in lower force capabilities.
The control of the exerted force is commonly done using one or more voice coil actuated valve. A pressure sensor is normally located into the pressurized chamber in order to control the force in closed loop.
Pneumatic systems are used in robotic systems when lightweight, small size systems are needed with relatively high payload to weight ratio. Examples of applications include walking machines. Their application in Haptic interface are restricted to portable haptic devices such as Hand-Exoskeletons and Arm-Exoskeletons.
The pneumatic actuators presents characteristics that are very similar to Hydraulic ones. Anyway there are some advantage in using pneumatic actuators:

- Safety: Operates at lower pressure (4-15 Atm) respect to hydraulic actuators. The used fluid is not flammable;
- Reliability : the systems do not require a return line for the fluid; the air is simply exhausted through an outlet valve on the actuator; the result is a more simple fluid circuit that means less maintenance and higher reliability;
- Light weight: The components of the active part of the actuator can be designed to achieve a very light weight. The ratio between force-weight is about 16:1 [1]. This feature makes them suitable for portable Haptic Interfaces.
- Backdriveability: This kind of actuators can be passive backdriveable due the low friction of fluid in the circuit; this is the main feature that makes this kind of actuator much more used than the hydraulic ones.

On the contrary the following disadvantages make the pneumatic actuators ineffective respect to other choice of actuation (electrical for example):

- Maintenance: Pneumatic actuation maintenance is less onerous respect to hydraulic actuators but not comparable to the maintenance needed by electrical motors;
- Encumbrance: They require a pump to provide air at high pressure; this component can be very big, heavy and noisy. The result is that the whole system is not easily transportable and can't be used in many environment.
- Friction: They are not self lubricated, like the hydraulic, so the friction between cylinder and piston can assume relevant value. In case of linear actuators, dry friction is hard avoidable. The use of rolling bearing is more difficult to design and expensive to built.

Application in HI:

The RM II Hand Master

The RM II is an hand exoskeleton developed by VRHL in Rutgers University [2]. It is a glove able to provide 1DOF force feedback on every finger (excluding the little finger). The actuation is devolved to a pneumatic system in direct-drive configuration. Pneumatic pistons were chosen in this application because it was possible to reach the higher Force to Mass ratio. Special carbon fiber for cylinder and graphite for pistons were used in order to obtain a light portable, assembly. The internal walls of the cylinders are coated by a layer of Pyrex that reduce the friction forces.

PHI (Pneumatic Haptic Interface)

PHI is an arm exoskeleton developed in Southern Methodist University [1]. The kinematic of such HI is a serial chain of four rotational joints. The actuation is achieved by means of four linear double acting pneumatic cylinder. A proportional voice coil actuated valve, combined with pressure sensors into the pressurized chambers are used to control the exerted force.

Figure 5.34 The RM II Hand Master

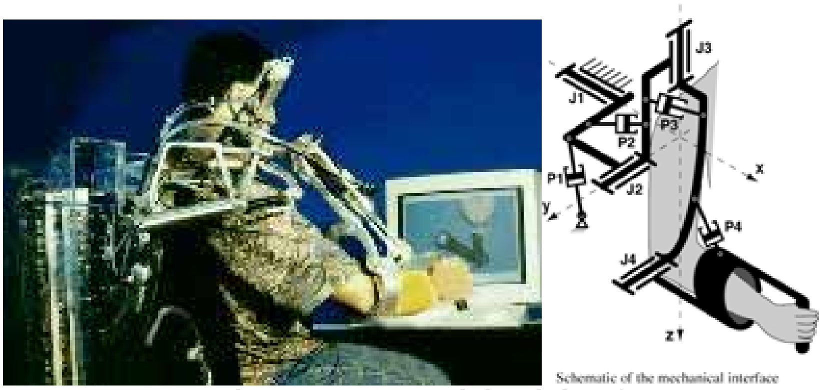

Figure 5.35 Pneumatic haptic interface

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[2] *The Rutgers Master II-ND Force Feedback Glove*, **Mourad Bouzit, George Popescu, Grigore Burdea and Rares Boian,** Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002.

5.3.6 Piezoelectric actuation.

Piezoelectric materials are materials able to change contract and expand under strong electric fields. This principle is well known since many dozen of years and it has been exploited for realizing several kind of actuators. The actuators that uses piezo-materials can be divided in two main categories :
Micro/Nano actuators
They are used in ultra high precision positioning system, exploiting the very small, but very precisely controllable displacement of a piezoelectric element, film or stack;

- <u>Ultrasonic Motors</u>
  They exploit the vibrations induced by the high frequency excitation of the piezoelectric elements to transmit motion and forces by means of somehow controlled friction. They find application for low force positioning, such as for example the motion control of the optical components of the modern automatic cameras.

This type of actuators are not effective in the field of haptic interfaces. The first ones have very high force to weight ratios but they produce too small displacements. The second ones are very difficult to control and generate low forces. In several research laboratories there are new ideas of exploiting the piezo-electric materials properties that can have compatible characteristic with some haptic interface. These new concept actuators are based on two main principles:

- Inchworm actuators:

The principle of actuation of a linear inchworm is shown in the figure below

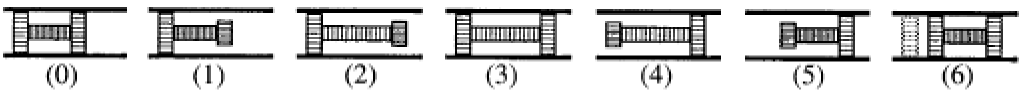

Figure 5.36 Inchworm principle of working

The three represented strips are piezoelectric ceramics able to expand and contract. The actuation is achieved with the following phases:

1- the distal, vertical piezoelectric strip contract;
2- the intermediate piezoelectric strip expands moving ahead the vertical strip;
3- the first strip that was contracted expands and fix itself on the wall of the cylinder;
4- the other vertical strip contract;
5- the same vertical strip is pulled by the intermediate horizontal strip;
6- a step is completed.

This principle of working is different from traditional piezo-motors because in the contact between piezoelectric material and the surfaces there isn't slipping movements.

The achievable forces with this actuation principle are extremely high respect to the weight and encumbrance, but the main lack up to now is the limitation to speed.

- Harmonic piezo-drive servomotors

The working principle of Harmonic piezo-drive servomotors is very similar to an harmonic drive transmission. The difference between them is in the mean of deforming the flexible spline. As represented in the figure below, the elliptical shaped shaft of the harmonic drive transmission is replaced by a rotating wave of deformation generated by several linear piezoelectric ceramics oriented along the radius of the circumference.

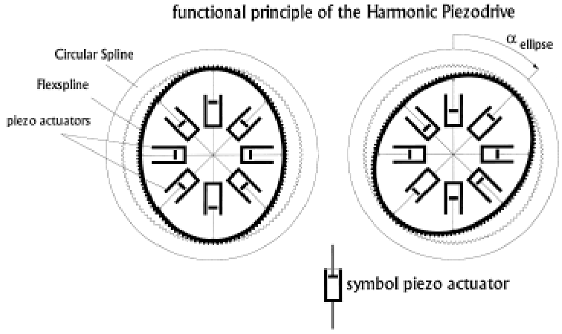

Figure 5.37 Harmonic piezo-drive servomotors principle of working

Unluckily this kind of actuators are not yet usable in the haptic field because of the low maximum speed they can reach, but several researchers are working on the possibility of increasing improving such characteristics.

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[3] *Development of a Piezoelectric Inchworm Motor*, **Mark Vaughan, Donald J. Leo**
[4] *Piezoelectric electromechanical translation apparatus*, **A. May, G. William,** United States Patent 3 902 084.

5.3.7 Magneto-Rheological actuation.

Magneto and electro rheological fluids

Magneto (electro) rheological fluids are liquid materials that change to solid state in few milliseconds when a magnetic (electric) field is applied through them. In particular the value of yield stress of the solid state is proportional magnitude of the applied field. This characteristic allow to use this kind of fluids to realize fine torque controllable clutches. The control of the output torque is made by controlling the magnitude of the applied fields. In the case of magneto rheological clutches the control is achieved by means of a current generated magnetic field. In electro-rheological fluids the controlled variable is the applied voltage needed to create the wanted electric field.
Magneto rheological fluids present higher performance than electro-rheological ones because they achieve higher values of yield stress . Commercialized magneto-rheological fluids reach a yield stress of 60-70 kPa [1] while electro-rheological ones reach 6-7 kPa [2].
On the contrary electric fields are obtainable with lighter structure because of the weight of iron components needed to convey the magnetic flux.
The physician are still investigating on new kind of fluid able to achieve higher performance in terms of higher yield stress, linearity, frequency response and long time stability.
These smart fluids have been exploited commercially for the realization of controlled clutches and breaks, but their application in the haptic interface field are quite bright:

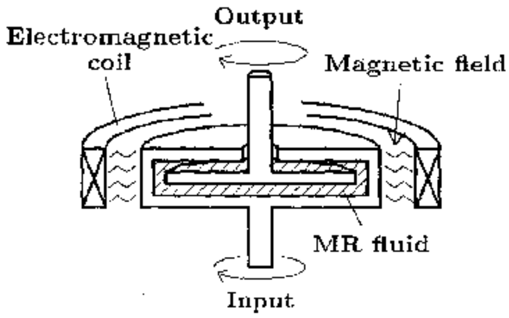
Passive bi-directional

Magneto (electro) rheological clutches can be employed to actuate passive haptic interfaces. In this case the clutches replace the traditional actuators achieving a lighter weight structures. In this mode of application the haptic device is intrinsically limited by the passivity.

Active Mono directional actuators

In PERCRO laboratory there is the idea to realize an active mono-directional actuators using magneto rheological clutches. In this case a low cost hardly controllable electric motor is used coupled with a

clutch. The motor run at constant speed coupled with the input shaft of the clutch. The output torque is controlled by the clutch decoupling the motor from the load.
This kind of solution is clearly effective only when mono directional actuation is needed (for example in tendon driven haptic interfaces). The effectiveness of this kind of actuation reveals when the haptic device needs several actuators located at the base and close to each other (typically in parallel mechanism devices). In this only one motor is needed to drive several clutch's input axis. The use of only one motor allow to achieve very high force to weight ratios, and reduce the total cost of the device.



Active bi-directional

In PERCRO laboratory there are some researchers that study the design of a new magneto-rheological bi-directional clutch. This clutch is constituted by two input axis that moves in opposite direction and one output axis that is able to exert torque in both directions by coupling itself, by means of a magneto-rheological fluid, to the first or second input axis.
This kind of actuation completely replace traditional rotating actuators and can be applied to several haptic mechanisms.
As in the Active mono-directional case, this actuation system is very effective if it's possible to use only one motor for driving all the input shafts of the clutches.

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5.3.8 Mechanical amplification.

The mechanical amplification consists in using a direct electromechanic device as "relay" to control the mechanical energy flow instead of the combination electric amplifier / electromechanic transducer (DC motor or electrodynamic device) . The major advantage of this solution is to reduce the additional impedances introduced by the transduction link in the energy path. As exemple a minimum intrinsic inertia exists in all Lorentz force based actuator which is at least due to the mass of the active moving conductors.

The electromechanical relays are continuous controlled clutches. Such systems were made of two coaxial rotating cylinders between which a magnetic powder could produce a variable friction depending on a magnetic field that was created by a coil presented in the figure below. When the difference of speed rotation between the cylinders was sufficient the transmitted torque was only depending on the command current.

Figure 5.38 Magnetic powder controlled clutctche. Electromechanic transducer schematic.

These devices that were currently used in some electromechanical peripheral like printers and teletypes in the 70s were employed to build a low inertia actuator (Figure 5.39) for a 1 dof haptic system [Florens 78].

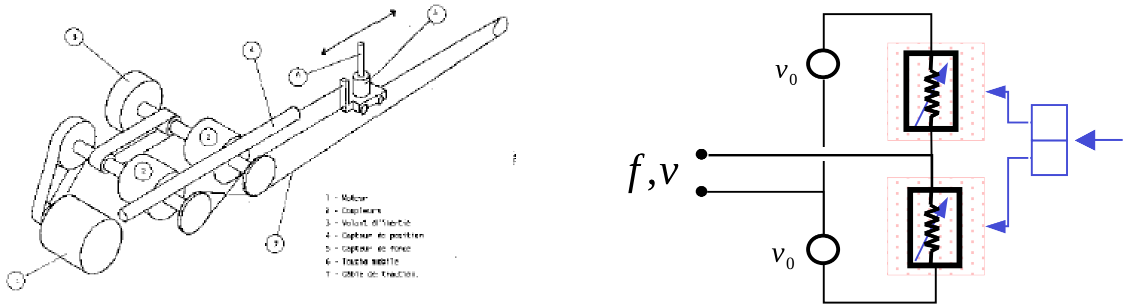

Figure 5.40 Mechanical amplifier stage using two magnetic powder clutches working in push pull.

This device was able of high accelerations thanks to its low inertia and high power. The devices could produce several KgF for a displacement of 50cm.

One of the drawbaks of this kind of actuation was the residual vibrations due to the continuous rotation of the primary shafts. Other limitations are the relative mechanical complexity and the size, however very high accelerations could be obtained thanks to the weak inertia.
The basic principle of some active cobots [Colgate,91] could be compared to the mechanical amplification with the difference that CVT provide a speed control instead of force control.

[Colgate,91] Paul A. Millman and J. Edward Colgate, « Design of a Four Degree-of-Freedom, Force-Reflecting Manipulandum with a Specified Force/Torque Workspace », Proceedings of the IEEE International Conference on Robotics and Automation, 1488-1491, 1991

Cobots actuation technology (PERCRO)

Introduction

COBOT means COllaborative rOBTtics. This term was conceived by Prof. Edward Colgate of Cobot from the Laboratory for Intelligent Mechanical Systems (LIMS), Northwestern University.
Cobots are passive robots able to generate passive constraints on the user movements. The user defines the moving direction. Non-holonomic joints such as wheels, instead of servos, are steered in order to allow this movement with the least effort for the operator. Electric actuators are present but they work in passive mode controlling only the orientation of an idler wheel. Constraints are software defined and lead to two different modes in which the cobot can move: The Virtual Caster and the Virtual Wall mode. In the former one, the wheel moves like a caster and its motion is unconstrained. Forces perpendicular to the actual moving direction of the cobot are minimized by steering the wheel in the new direction. Thus, the human collaborator can move the cobot in any direction wanted. In the latter, the wheel is no longer steering to minimize perpendicular forces. The cobot is now in virtual wall

mode. The wheel is steered tangent to the virtual wall and forces hat tend to penetrate the constraint are ignored. Thus, the user has two possibilities: Moving the cobot along the wall or pushing it back to the unconstrained area.
The aim of realizing haptic passive haptic devices based on this new concept are :

- Safety: Cobots are intrinsically safe devices because they are passive so they moves if the operator applies forces on them. The force of interaction they can exert are simply equal to the force that operator is applying.
- Power consumption: Theoretically the power consumption could tend to zero, in fact electric motors that control the wheels orientation make no positive work on the system. In actuality the electric motors use energy to exert the low torques needed to control the wheels orientation.
- Low Inertia: Generally the main cause of an high perceived inertia in haptic interfaces is imputable to the actuator mass. In this case the requirements for the actuators performances, in term of maximum forces and peak forces, are really low. The force exerted by the whole devices don't came out from the actuators, but from the constraints generated by non-holonomic systems. In Cobots design smaller and lighter weight actuators can be used. This lead to a reduction of the perceived inertia.
- Stability: The system is passive and it is intrinsically stable (energy is only dissipated).

On the contrary there are several limitations that makes these kind of actuation ineffective for many HI application: passivity: could be a value but it is also a limitation for the possible application. A passive system is not able for example to simulate elastic surfaces, gravitational force or more general force fields. This basic principle of working is exploited for realizing different devices.

2DOF Planar mechanism: UNICYCLE COBOT

Figure 5-41 -Unicycle cobot

The simplest device that can implement virtual constraint surfaces and has the added benefit of being physically passive, is the unicycle cobot shown in figure above. It consists of a rolling wheel in contact with a planar working surface. The wheel is attached to an upright handle. A motor is used to steer the wheel about the handle. The motor cannot cause the wheel to roll; it can only change the wheel's rolling direction. The entire apparatus is held upright using a pair of x-y rails which are equipped with linear potentiometers that measure the device's position. A force sensor on the handle measures forces perpendicular to the wheel's rolling direction.
The Unicycle cobot operates as follows. A user applies a force by pushing on the handle The computer monitors the force perpendicular to the wheel's rolling direction and attempts to minimize it by directing the motor to steer the wheel parallel to the applied force direction. Using this technique the wheel instantaneously reacts to user force inputs and is free to roll in any direction; in effect it behaves like a caster wheel. As the user is pushing the device around its position is monitored using the x-y rail potentiometers. If the user brings the wheel up to a programmed virtual constraint surface, the computer ceases to steer the wheel in a direction that minimizes the perpendicular force. Instead the

wheel is steered tangent to the constraint surface so that the only allowed motion is along the constraint. The computer does continue to monitor the user applied forces. Forces that would cause the wheel to penetrate the constraint are ignored. Forces that would bring the wheel off of the constraint surface and back into the free space are interpreted as before and the wheel again behaves like a caster.
The operation modes can be described as follows:

Virtual caster mode.

When a cobot is not in contact with a constraint surface it permits the full dof orientation and translation allowed by the device. In the Unicycle cobot example, the device is free to move in x and y axis directions only, no axis torques are interpreted. Therefore, at any particular instant the Unicycle has only 1 dof. When not in contact with a constraint the cobot simulates 2 dof motion by steering the wheel to minimize user forces. In virtual caster mode, the cobot's goal is to appear transparent to the user by permitting any desired motion.

Virtual wall mode.

When a cobot is in contact with a virtual wall it does not allow arbitrary motion by the user. Instead, its joints only permit translation parallel to or away from the wall. When in contact with a virtual wall, user forces are categorized as those with a component into the wall or away from the wall. Components of force away from the wall switch the cobot out of virtual wall mode and into virtual caster mode. Thereby the user can easily push the cobot along the virtual wall or pull it back into free space. In contrast, components of force into the wall are ignored, and the cobot continues to direct motion tangent to the wall.
One important distinction between cobots and other virtual constraint systems is that cobots are inherently 1-dof and simulate higher degrees of freedom using computer control. Most traditional robotic systems are inherently multi-dof and generate constraints by computer-reducing the perceived degrees of freedom. The fact that cobots are kinematically 1-dof and use control to simulate higher degrees of freedom is a function of their nonholonomic elements. In the unicycle example, the nonholonomic element is the wheel.

Switching between modes

The manner by which a cobot switches from virtual caster to virtual wall mode enables it to redirect user motions that would violate a constraint surface. For example, consider exploring a virtual wall using the Unicycle cobot. The computer is always monitoring the orientation and speed of the Unicycle's wheel. This information is used to draw a virtual perimeter in front of the virtual wall. The distance between
this perimeter and the wall is proportional to the wheel's velocity perpendicular to the wall. If the user continues on a collision course with the virtual wall and crosses the virtual perimeter, computer control switches from caster to virtual wall mode. Now, the wheel is steered such that if the user continues to approach the wall, the wheel will follow a line of approach that brings it smoothly from its current orientation to one that is tangent to the wall. Figure 3.2 is a diagram of the changing wheel orientation as the virtual wall is approached. The line of approach is drawn as an arc such that the transition in orientation from the virtual perimeter to the wall boundary is gradual.
Actually, the line of approach is itself a virtual constraint surface. Before the user realizes what has happened, the motion that he was enforcing has been redirected so that now the Unicycle glides along the virtual wall. One aspect of a successfully implemented virtual wall is that there is no resistance to motion tangent to it. In effect, a virtual wall acts as a real wall made of ice; when brought up against it, the cobot's end point immediately starts to slide along it. The user must really concentrate if he wants to apply a force component perpendicular to the wall without being overcome by motion tangent to it.

Constraint violation

When in contact with a virtual wall, it is possible for the user to apply a force into the wall that is large enough to cause the wall to collapse. The virtual wall's strength is related to the mechanism by which the cobot resists perpendicular forces. For example, in the Unicycle forces perpendicular to the rolling direction are resisted by a coulomb friction force between the wheel and the working planar surface (see Figure 3.3). If the applied force component perpendicular to the virtual wall becomes greater than this friction force, the virtual wall crumbles and the cobot enters the restricted area.

Non planar kinematics

The solutions adopted for Unicycle are very hard to extend to other kinematics configuration. It's possible to achieve a 3DOF planar device by adding a wheel and the rotational degree of freedom to the handle. It is also possible to realize a 3DOF rotational wrist by simply using fixed axis wheels and a movable sphere constrained by the wheels orientation.
Other kinematics (for example 3DOF anthropomorphic arms) are very difficult to be actuated by this kind of systems. For these reason, other solutions were studied and optimized in [3]. In particular we can notice that creating a constraint between two degrees of freedom can be seen as realizing a 1DOF mechanism with continuous variable ratio of transmission. In fact at LIMS it has been realized a CVT (Continuous Variable Transmission) with the same basic principle of the Unicycle with the aim of actuating a 2DOF serial mechanism In this case the nonholonomic constraint is generated by the rolling movements of a wheel on a spherical surface.

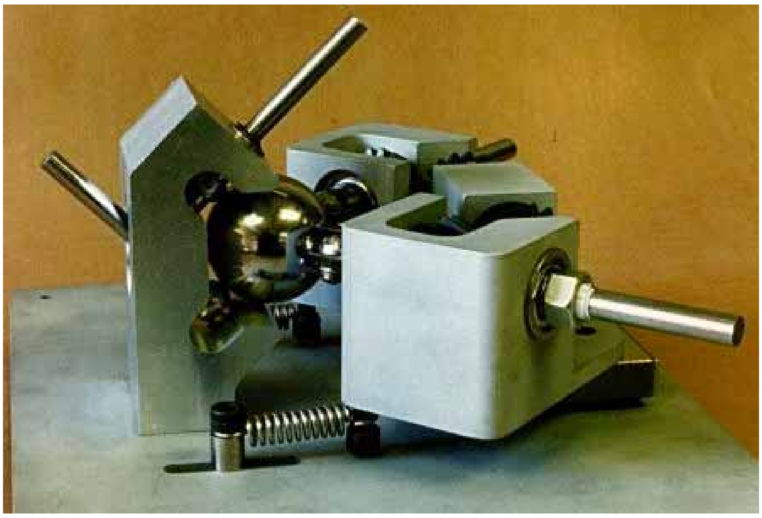

Figure 5-42 CVT- Continuous Variable Transmission

In Figure 1 is represented the first prototype of such device. It consist in a sphere caged by 4 wheels. Two of them called "drive roller" (on the left in the picture) have fixed axis of rotation and their rotation are the output (the DOF to be constrained) of the whole system. The two other wheels are the "steering rollers" that are responsible of the regulation of the transmission ratio between the "drive roller". These wheels have no-fixed axis, they can be oriented in a plane orthogonal to the straight line between the center of the spheres and the center of the wheel. The steering wheel axis are not independently movable but they rotate in opposite direction of the same angle as shown in Figure 2. In this way the kinematic constraints are always respected. The orientation of the steering wheel is controlled by an electric motor.
The ratio of transmission between the "drive roller" is given by the rotation of the angle θ (Figure 2).

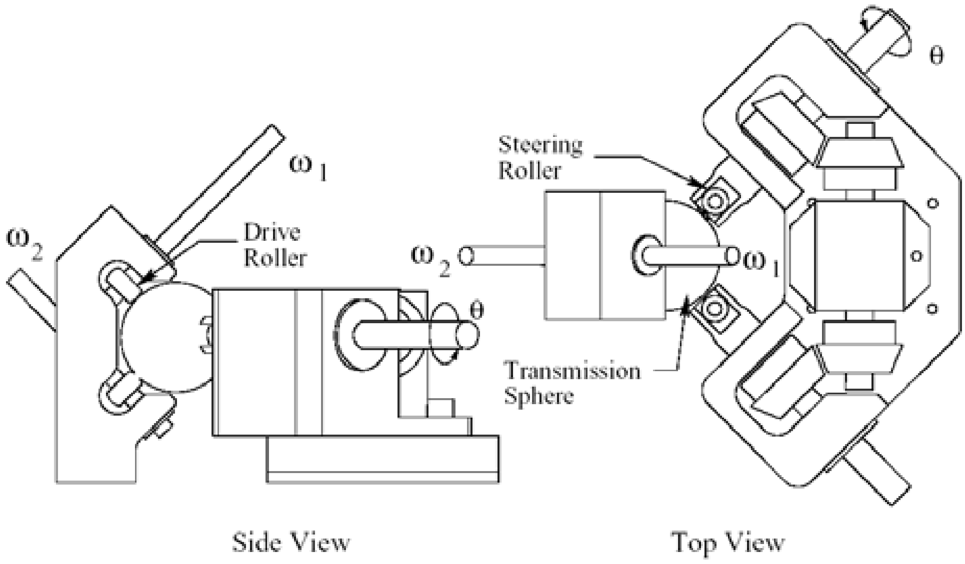

Figure 5-43 Continuous Variable Transmission Scheme

The control strategy of such a mechanism is the same as described for the Unicycle.
With CVT a 3DOF cobot Arm was realized. A prototype of such mechanism is represented in the following figure.

Figure 5-44 Arm Cobot

Six dof parallel mechanism

A 6DOF Cobot was realized by using a parallel kinematics (invented by Merelet) [4]. This kinematic require six linear actuators at the base.
These actuators are realized with a nonholonomic system. In this case the system not passive. There is a big cylinder that rotates at constant speed around an axis which is parallel to the translating joints. The nonholonomic constraint is created by six wheels rolling on the cylinder. The wheels axis's orientation is controlled by electrical motors.

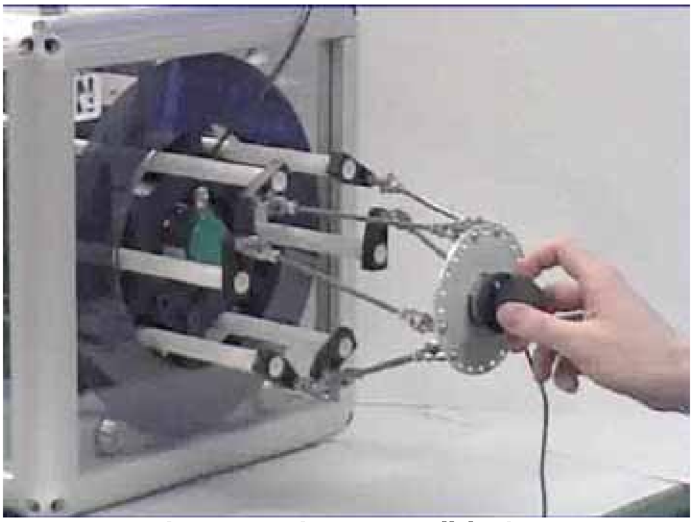

Figure 5-45 Six DOF parallel cobot

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5.3.9 General actuation issues.

The size / bandwidth / power compromise.

The mechanical drawbacks : backlash, dry friction inherent to the actuation system.
These drawbacks are the same as in the general mechanical parts of the system. However depending on the actuation process the mechanical joints of the actuator may have to satisfy to additional constrainsts.

The geometrical or size constraints.

The dynamic constraints, if the actuation process generates transversal forces. It is the case in many rotative actuators where the load (gear, belt, or direct cabstan) is not a balanced torque (ex the belt or cobble tension).

Material constraints.
The actuator evolution, especially in the case of electromagnetic type of actuators depends strongly of the material evolution (for example, the magnets evolution have had a great influence on the improvement of the electric motor performances).
History of technical developments on magnets

Years of evolution	Type of magnets	Density of maximum energy [kJ/m^3]
1880-1920	Steel magnets	2-10
1930-1965	AlNiCo	7-80
1950	Hard ferrites	7-80
1960-1980 Late 1960 1970	Samarium-cobalt $SmCo_5$ $Sm(CoFeCuZr)_{7-8}$	20-220
1985-2000	Neodyme-Iron-bore (NdFeB)	120-320
2000-in the futur	Superconducting oxydes at high critical temperature $(La\text{-}TR)MnO_3$	

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5.4 Sensing.

5.4.1 The Sensed data

Sensors for haptic devices (DLR)
For the functionality and the quality of haptic devices the implemented sensor systems play an important role. For example, to implement impedance control on a device the position detection of the devices endeffector is essential. Other sensors are needed for the current control of the motors like current sensing resistors or position sensors for the detection of the rotor position for the current commutation of brushless DC motors. In case of admittance control or inertia compensation with feedforward commands the systems demand the use of force or torque sensors.

5.4.2 Current sensor

For haptic devices the current sensor and the accuracy of the sensor signal is very important since many torque command schemes are based on the direct current control. The most common sensor type is constituted by resistors inserted between the bottom transistors and the ground pin of the power stage. These resistors have very low values (mΩ) to have minimum influence on the value of the current flowing through the motor windings. These resistors should have very low value tolerances and also low thermal linearity drifts. The sensed current value is represented by a proportional voltage which has to be amplified and filtered (mostly to avoid the noise influence of the resistor and the chopping of the motor currents). In schemes with more than one resistor a special attention has to be accorded to the balanced layout of the board to achieve the same behavior of the different amplifiers concerning linearity and thermal drift. With the resistor as current sensor the polarity of the current through the motor windings can't be detected. This has to be determined from the command issue of the transistor stage.

A lot of current controllers use decoupled current sensing devices (LEM sensors, Allegro, etc.) based on Hall or MR sensors inserted in a magnetic detector coupled with the magnetic field produced by the currents in the motor terminals. These sensors offer the possibility of the polarity detection and also thermal compensation of the sensor linearity and are decoupled from the high energetic, noisy part of the power stage.

5.4.3 Strain-gage force sensor.

Figure 5.46 Torque sensor in the robot joint of the light weight robot II

5.4.4 Optical sensors

Encoders versus Potentiometers (DLR)

The sensor systems more often used for the position detection in high fidelity haptic devices are definitively optical encoders mounted on the motor shaft. The motor manufacturer (maxon motors and Faulhaber) offer their motors with the option of a mounted encoder on the shaft. The optical encoders produce normally an incremental position signal. The standard resolution in this combination is mostly 512 lines per revolution which figures out to be quite low for a quality force-feedback. In this case the advice goes toward the option of a higher resolution of at least 1000 (or 1024) lines. The choice of the resolution depends also on the reduction ratio of the gears. Using a quadrature interpolation in the interface electronic the resolution can be risen up to 4000 lines per revolution. To interface the sensor to the control electronics most of the integrated solutions offer a special interface for the encoders (RS-422 Standard or single TTL interface) as seen at the dSpace systems or the motor servo controller from maxon or Faulhaber. This is also offered by the majority of the common motor control dedicated DSP's (Digital Signal Processor) , but here the right termination for the encoder cables has to be foreseen (for example pull-up resistors when the cables are longer than 1m and the encoder has no integrated line driver). For controllers without a dedicated interface the encoder has to be connected using an interface chip like for example the LS7266 or other. For FPGA (Field Programmable Gate Arrays) based solution the interface could be a state machine with a dedicated timer unit, which enables the high sampling rate demanded by the encoder interface.

Sometimes the position detection can be done using potentiometers attached to the back drive side of the joint or for example the joystick axes. Actually most of the commercial available force-feedback joysticks detect the position by using potentiometers, since this solution is much cheaper then any encoder solution. The position proportional voltage on the potentiometer slider pin has to be amplified and filtered in order to avoid noise influence of the potentiometer resistance. Important characteristics for the potentiometers are the linearity and value errors due to heating and manufacturing and also the maximum number of cycles. Good values for this characteristics offer the conductive plastic potentiometers (Greenpot, metallux, Novotechnik etc). The errors of the potentiometers and the amplifier circuitry allow resolutions of only 8 or maximum 9 Bit.

Figure 5.47 Agilent optical Encoder

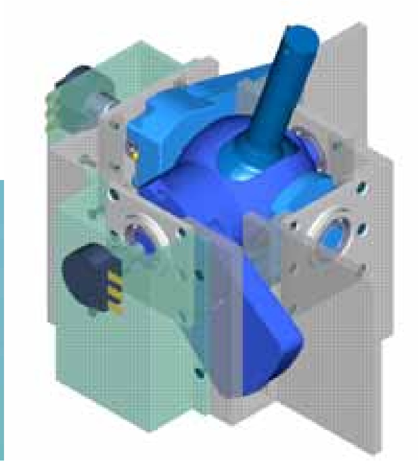

Figure 5.48 Potentiometer on a joystick axes (DLR force-feedback Joystick)

Figure 5.49 Commercial and Customized Potentiometer

The potentiometers have the advantage to offer a absolute position signal and for this reason they are often used as redundant sensor in security related application or to avoid for example a calibration of the joystick working area during every start-up sequence.
Different mechanic solutions with narrow space offers allow only the use of customized potentiometer solutions like the light-weight joint of the DLR robot. In this configuration the resolution of the potentiometer can be increased by a laser trimmed linearization.
In case of the haptic drive solution based on brushless DC motors additional sensors for the detection of the rotor position are needed. These sensors are mostly based on digital or analog Hall detectors or in newer products magneto resistive (MR) type sensors. For the Hall sensor based commutation of the motor the sensors have to be applied on the motor windings in the right position above the air gap in order to detect the right phase of the induced Back-EMF. The motor manufacturers offer the Brushless DC motors with integrated Hall sensor solutions. Based on digital Hall sensor only a six-step commutation of the motor is possible. In case of haptic application this solution is acceptable only in drive combination with gears with higher reduction ratios since the current vector can be set only in 18 positions per revolution for a three phased motor or respective for motors with a higher pole number.
The solution of commutation sensor based on analog (linear) Hall sensors is suited for the sinusoidal commutation of the motor which is the premise for a field oriented control of the motor. In this control configuration the direct control of the motors torque and the intensity of the magnetic excitation in the air gap are possible.
A common problem of the linear Hall sensor is the nonlinear behavior at temperatures higher than 80° C (temperatures which occur quite often close to the motor windings). This problem can be avoided by using MR based sensors. This solution demands the use of an additional commutation ring with magnetized sectors. The number of sectors determines the resolution of the sensor. With additional discretization and interpolation terms the resolution can be risen up to 18.000 lines per revolution. Some motor manufacturer offer their brushless DC motors with integrated MR encoders (Faulhaber’s IE-2 or maxons digital MR Encoder).
The latest versions of integrated brushless DC servo controller accept also solutions with optical encoders as commutation sensors (Maccon SWM controller, ELMO controller).

PSD-LED optical sensor for Magnetic levitated devices

A specific position sensing was developed for the MagLev haptic device [Hollis, 91], [Berkelman,97] The LEDs and position-sensing photodiodes are used for reaching an active area in the range of motion of the device. The position is sensed by three LEDs on the flotor, the motion of each LED is demagnified by lens and three planar position sensitive photodiodes are placed mutually orthogonal on the outer stator to maximize position accuracy and simplify the geometric calculations.

This system provides six independent variables (x and y on each sensor) constituting the Jacobian. Starting from it, the transformation from sensor data to flotor displacement vector (position and orientation) is done by picking one out of a 36 entry lookup table calculated beforehand for the flotor vector. This procedure is chosen because calculating the inverse Jacobian at run-time using a modified Newton-Raphson method in six dimensions is too computationally expensive since there is no closed-form solution to inverse kinematics (the forward kinematics from flotor position to sensor data is known analytically).
The optical system used for position sensing in the MagLev device has been tested to see if the nonlinearity of the photodiode output is a repeatable phenomenon. The short-term repeatability of the sensor was ±3µm.
The flotor displacement calculations are done using a DSP in a real time control system, resulting in a feedback sample rate of 1kHz. The non-linear output of the photodiode has been treated by additional software that aims to automate the creation of loockup tables for the sensor linearization.
After the device assembly, the position sensor resolution is limited to 10µm due to sensor noise. Another problem appeared: the casings of the LEDs situated on the flotor were slightly ferromagnetic, which resulted in large attractive forces on the flotor as the LEDs approach the high magnetic fields of the actuators. So, the infrared LEDs were replaced with high-brigthness red LEDs with no casings and much lower ferrous metal content in the leads.

Among the developed optical sensors, a special one using 3 linear position-sensing diodes and multiplexed planar infrared light beams is described in [Salcudean,97], [Salcudean,00]. This development was needed by the geometry and the physical principle of functioning (magnetic levitation) of the haptic device.
This optical sensor is composed of 3 linear position-sensing diodes (PSD) placed on a horizontal plane. Three light planes are generated by wide-angle infrared emitting diodes projecting infrared light through narrow slits toward the centre of the PSD plan. The position of the moving part of the device is computing as the point of intersection of 3 spheres of known diameters with respect to a fixed coordinate system. The translational workspace of the sensor at null orientation is the union of two symmetrical pyramids, and becomes smaller as finite rotations of arbitrary axis are allowed (with PSDs with active areas of 24mm each, the horizontal side of the pyramid is roughly 22mm at null rotation). The semi-dextrous volume shows the achievable translations for arbitrary axis rotation of up to 3°.
The advantages of this sensor are the linearity of the PSD, there is not need to use a 2-dimensional PSD, the facile alignment and manufacturability in a single printed circuit board.
The optical sensor range limits the angular motion of the maglev 6DoF joystick.

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[Hollis,91] R.L. Hollis, S. Salcudean, A.P. Allan, "A six degree of freedom magnetically levitated variable compliance fine motion wrist: design, modeling, and control", IEEE Transactions on Robotics and Automation 7, pp. 320-332, June 1991
[Berkelman,97] P. Berkelman, R. Holis, "Dynamic Performance of a Magnetic Levitation Haptic Device", Proceedings of SPIE, Telemanipulation & Telepresence, 1997

5.4.5 Electro-magnetic sensors

Principles and general properties

The displacement which is to be expressed electronically is imposed to of the magnetic circuit's element, causing a variation of the flow in a measurement coil. When the moving element is a ferromagnetic core in translation or rotation, its movement can be seen

- either in the variation of the auto-induction factor of a coil (variable induction)
- or in the variation of the coupling between the primary and secondary coils of a transformer (differential transformer, Microsyn) causing the variation of the secondary tension.

When it is coil, which rotates with regards to another fixed coil, one playing the inductor role, the other the induced, then it still is a variable coupling transformer. The primary is the inductor, the secondary which is unduced, delivers a tension which is a function of the rotation angle (inductive potentiometer, resolver).
The variations of the auto-induction factor L or of the mutual induction factor M as a function of the core displacement are generally of mediocre linearity ; this can be remarkably improved by associating two coils in opposition, the factors L and M varying in opposed directions for the same movement, thus achieving a partial compensation of the non-linearities (push-pull functioning).
The inductive sensor is placed in a circuit whose input is a sinusoidal tension of which the frequency is generally limited to a few tens kilohertz, so as to reduce the magnetic losses and those by current of Foucault, as well as the influence of the parasite capacitances. The measured tension v_m is the result of the amplitude modulation of the input tension $E_s \cos \omega_s t$ by the displacement x(t) :

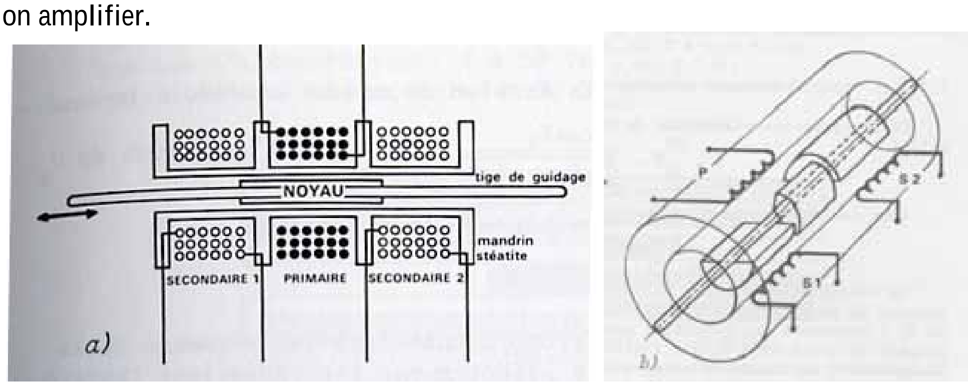
$$v_m = k \cdot x(t) \cdot E_S \cos(\omega_s t + \phi)$$

More rarely, the variations of the inductive element can be used to modulate the frequency of an oscilator proportionaly to the displacement. In any case, and whatever type of modulation, the frequency f of the displacements must be much smaller than the carrier frequency f_s, so as to facilitate the detection : $f < f_s/10$
By way of their own principle, inductive sensors are sensible to parasite electromagnetic fields and are also likely to induce some. That is why it is necessary to place them inside magnetic shielding.

Differential transformer

A differential transformer is a sensor with remarkable linearity, resolution and accuracy; in addition, it is appropriate for use in highly hostile environments.
Compared with a push-pull association of two inductive sensors with plunging core, which is similar, a differential transformer has the following advantages:

- greater setting-up simplicity, since it doesn't require the construction and balancing of a bridge
- the impedances of the excitor circuit and of the measurement circuit, which offer a galvanic isolation simplifying the rejection of common mode tensions and avoid in some cases the use of an isolation amplifier.



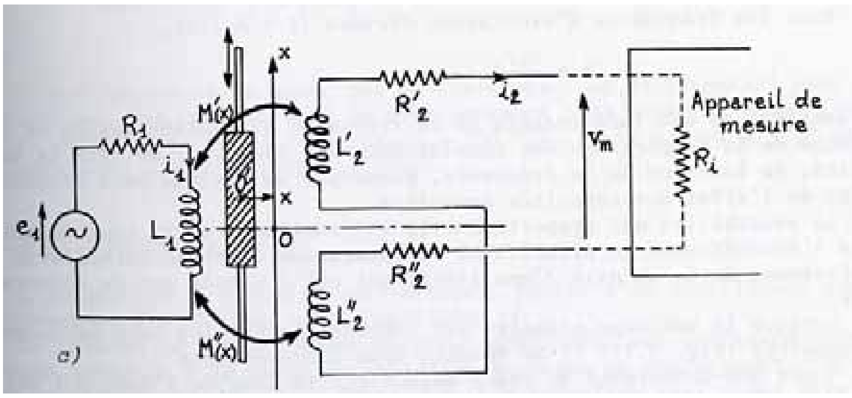


Figure 1 LVDT (Linear Variable Diferential Transformer)

Basic principle

The differential transformer is composed of a primary coil, whose input is a sinusoidal electro-magnetic force, $e_1 = E_1 \cos \omega t$, and of two secondary coils which are placed symmetrically to the primary. The displacement of the ferromagnetic core modifies the coupling between the primary and each of the secondary coils (Figure 1 a & b). The secondary coils are bound in opposition so that the electro-magnetic forces induced by mutual induction with the primary cancel themselves. A simplified electric circuit, where the parasite capacitances (those between spirals of a coil, and between coils) as well as the leakage inductances are ignored is shown in Figure 1c with the same notations as in the formulas.

The equations of the primary and secondary circuits are respectively :

$$e_1 = (R_1 + jL_1\omega)i_1 + j\{M'(x) - M''(x)\}\omega i_2$$

$$\{R_2' + R_2'' + R_i + j\omega(L_2' + L_2'')\}i_2 + j\omega\{M'(x) - M''(x)\}i_1 = 0 \quad ;$$

These equations allow to compute the tension $v_m = R_i.i_2$ on the terminals of the measuring device connected to the secondary coil as a function of e_1.

$$v_m = \frac{j\omega R_i\{M''(x) - M'(x)\}e_1}{R_1(R_2 + R_i) + j\omega\{L_2R_1 + L_1(R_2 + R_i)\} - w^2\{L_1L_2 + (M'(x) - M''(x))^2\}}$$

where : $L_2=L'_2+L''_2$ and $R_2=R'_2+R''_2$

In principle, v_m cancels itself when the core is in an intermediary position (identical with regards to each of the secondary coils) ; this is the initial position x = 0 , where M'(0) = M"(0)

Effectively, it is observed that that the tension v_m usually reaches a minimum but does not cancel itself ; there are two reasons for this :

- the harmonics produced by the non-linearities of the magnetisation curve of the core,
- the capacitance coupling between primary and secondary coils.

The importance of the harmonics is generally reduced by avoiding to expose the core to a strong induction flow.

The capacitance coupling produces a tension which is quadratic with the one resulting of the core's displacement : it can be minimized by careful and adequate grounding. Thus, when it is possible, giving the primary coil a symmetric input to that of the ground to which is connected a secondary coil is often an effective solution.

The use of a high resistance R_i (R_i > 50 kΩ) allows to make the tension v_m linear in terms of M"(x)-M'(x) and independent of the value of R_i :

$$v_m = \frac{j\omega\{M''(x) - M'(x)\}}{R_1 + jL_1\omega}e_1$$

The difference between the mutual induction coefficients which vary in opposed directions as a function of x allow for a good compensation of the non-linearities around x = 0 ; indeed :

$$M'(x) = M(0) + ax + bx^2 \ ...$$

and $$M''(x) = M(0) - ax + bx^2 \ ...$$

so: $M''(x) - M'(x) = -2ax$ *and* $v_m = \dfrac{-2j\omega ae1}{R_1 + jL_1\omega} \cdot x$;

so the output tension v_m varies linearly left and right of the initial position x = 0.

Metrological characteristics

From the above equation of the measure tension can be deduced the sensibility :

$$S = \frac{\Delta V_m}{\Delta x} = \frac{2\omega aE_1}{\sqrt{R_1^2 + L_1^2\omega^2}}$$, where V_m is the amplitude of v_m.

For low excitation frequencies, ($f < R_1 / 2\pi L_1$) :

$$S = \frac{2\omega aE_1}{R_1}$$

In this case, the sensibility is proportionnal to the frequency of the primay tension : it can be influenced by the thermic variations of R_1 ; however this can be reasonably compensated by serially placing R_1 and a resistance r'_1 whose thermic variations are opposed to those of R_1, or by giving the primary coil input from a power source.

For high excitation frequencies ($f > R_1 / 2\pi L_1$) :

$$S = \frac{2aE_1}{L_1}$$

the sensibility is independent of the input frequency and the influence of temperature is considerably reduced : in fact, the sensibility, in terms of frequency, goes through a maximum and then decreases as a consequence of the parasite frequencies.

The sensibility is proportional to the amplitude of the primary coil's tension, but the heating of the primary and the saturation of the core do not allow to increase E_1 beyond a limit indicated by the constructor.

When the primary coil is placed between two secondary coils two drawbacks arrise :

- a non-uniformity of the magnetic field along the axis outside the primary coil, causing linearity deterioration ;
- a limitation of the range of measurement of core displacement, from its central position to its output from either secondary coils ; the ratio between the measurement range and the length of the whole set of coils for this setting is roughly of 0.3.

These drawbacks can be remarkably reduced by the setting where the three coils are superimposed and have the same length, the primary coil being uniform, and the secondary coils having a number of spirals per unit of length that increases linearly from one end to the other, the coils being placed with alternate ends on one side; the ratio between the measurement range and the length of the measurement set is close to 0.8 for this setting.

Order of magnitude of the characteristics :

Mesurement range :

Linear displacements : ± 1 mm to ± 500 mm ,

Angular displacements :± 45° ;

Sensibility :

Linear displacements : 1 to 500 mV per V and per mm,

Angular displacements :1 to 10 mV per V and per degree ;

Linearity shift: 0.05 % to 1 % of the measurement range (MR)

Precision : mobility error : 0.002 % MR,

hysteresis error :0.002 % MR ;

Acuracy: 0.5 g to a few tens of grams of mobile mass
Input voltage: 1 to 50 $V_{eff.}$
Input frequency :50 Hz to 2500 Hz

It is important to note that the differential transformer can be used in very rough environments: high temperature (600°C) or low temperature (-250°C), high pressure (200 bars), high radioactivity, or corrosive environments.

5.4.6 Acceleration sensors

These sensors are used in some haptic devices to detect the movement of some parts or the interaction of sensitive tips of instruments (MicroTactus from McGill Haptic Laboratory) with the environment. The output signal of this sensor needs mostly very high amplification factors and represents due to this the limiting factor of the bandwidth in the control loop. This can cause instability when hard contacts are commanded. The use of this sensor to determine the dynamic state of a robotic joint has been tested at DLR on joints of the DLR LWR (light weight robot). The measured parasitic effect in the sensor signal and the needed parameter of the filter figured out to disqualify the sensor for the use in robotic joints.
A lot of chip manufacturer offer single and multi-axes acceleration sensors in quite small housings (huge variety can be seen at Analog Devices).

5.4.7 Indirect sensing. (Actuator as a sensor)

To be completed.

5.4.8 Actuators in tactile interfaces (INPG)

The actuators in tactile interfaces are not normally implemented within control loops and so there is no necessity for instrumentation. However, in the context of research device it is possible to instrument contactors in a stimulator array with miniature accelerometers or optical sensors. This allows monitoring of the tactile signals delivered to the user. In principle, error correction can be implemented by using such sensors within feedback loops, but the added cost and complexity would seem to prohibit this for a practical device.

6 A TOUR OF REPRESENTATIVE DEVICES

Introduction

The following section groups detailed technical description of more representative devices. We have separated non-commercial devices and commercial ones.
In the first category we include not only devices of the laboratories but also of the systems conceived for a specific use but not yet accessible in the trade. Our investigations were mainly focused on this last category since commercial devices are usually more known and because our prior concern was to explore original and non-common technical developments.

Some described devices are historical systems which do not exist today any more but can still be of certain technological interest.

The device descriptions comprise a general description, the context of use of the device, the corresponding technical sheet according to the methodology presented in (§4.1) and in some cases the results and comments related to our evaluation visits.

The described devices are presented in chronological order of published date, and, for the same year of publication, in alphabetical order of the university name (see also ANNEXE).

NON-COMMERCIAL DEVICES

Some devices developed in research use are presented in the following.

6.1 Argonne National Laboratory

6.1.1 Electronically Controlled Manipulator

General Description of the device

History: In the late 1940s, Goertz and his colleagues at Argonne National Laboratory (ANL), Lemon, Illinois, USA developed one of the earliest recognizable mechanical master/slave manipulators without force reflection and later with force-reflecting capabilities. Force reflection refers to the capability of reflecting the external forces experienced by the slave manipulator to the master manipulator and is typically described as bilateral control : force on the slave (master) will cause the master (slave) to move. In the early 1950s, Goertz and his colleagues developed an electric master/slave manipulator in which each slave joint servo was tied directly to the master joint servo since both the master and slave were kinematically similar. This device is described here.
Domain of application: An electronically controlled manipulator has many advantages over mechanically connected server-slave manipulators: considerable separation of slave from master, possibility of completely entombing slave arm, almost unlimited volume coverage of slave when mounted on mobile unit, and future possibility of handling loads many times operator's capacities.
Physical description: The servomechanism is a force-reflecting servo. The input motor produces torque opposing the operator to provide feel; the output motor produces torque that moves or pushes against the load. A full scale manipulator having a servo for each motion was built. Tapes and cables that produce the various motions were wound on drums fastened to the output and input gear shafts. All gear boxes were fastened to the base plate. Inertia, friction and the interaction of moving parts are low.

All motions are independent except for wrist-joint elevation and twist, produced, respectively, by similar and opposite rotation of the same two gears.

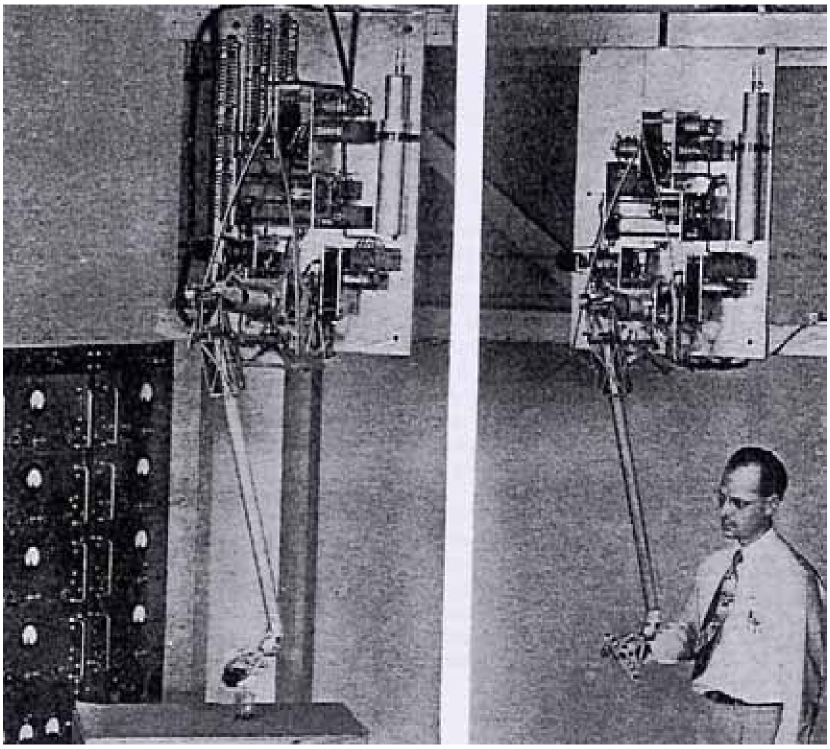


Figure 6.1 Electronically controlled servo-manipulator, Model 1

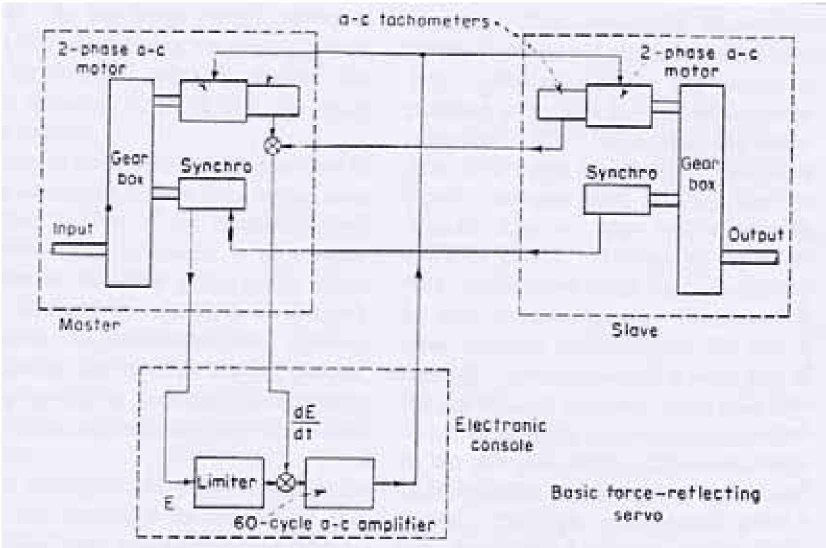


Figure 6.2 - Force-reflecting servo used for each manipulator motion.

Servo amplifier is standard type consisting of preamplifier, phase inverter, push-pull 807's (electron tubes for amplifying the curent) and output transformer. Comon d-c power suply is used for all servo amplifiers. All mechanical linkages have high efficiency and are mechanically reversible, and motor drag is small for al loads from zero to maximum. Hence motor torque is proportional to applied voltage and independent of speed whetherdelivering or absorbing power.

Level of achievement : prototype.

Technical points

Mechanism

Size of workspace	Arm movement
Spatial reference	Ground reference
Number of degrees of freedom	7
Cinematic configuration type	serial

Signal Processing

Type of the local treatments, if any.	Impedance

Actuation

Technology of Actuators

Physical principle	Asynchronous motor with carrier current Electro-magnetic

Functional Characteristics of the Actuation system

Max **continuous** force/torque exerted	17.8 N (max load : 1.8 kg)
Max speed (due to intrinsic limitation or to the driver)	0.76 m/s (max linear speed)

Sensing

Type of sensing	velocity
Physical principle of the sensors	Synchrodetector (a-c tachometers)

Other properties

Power consumption	2 kW of 208/120-v 3-phase 60-cycle power

Sources

[1] Goertz, R. and Thompson, R. "Electronically controlled manipulator," *Nucleonics*, 1954.
[2] http://www.engr.utk.edu/maes/ff/rlk/ieee/, "Teleoperation And Telerobotics", Robotics and Automation Society

6.2 ACROE

Device descritions by: INPG on 04/06/2004.

6.2.1 First device

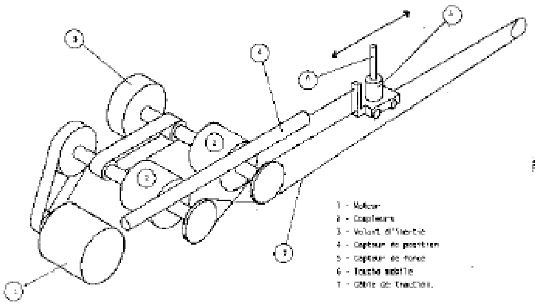


Figure 6.3. The first gestural transducer developed by J.L. Florens in 1978

6.2.2 “La touche”

This device was designed in 1981 in the field of ComputerMusic in order to obtain an instrumental interaction with a virtual instrument made by physical model simulation.(Cadoz 1984). This device was able to provide about 10N continuous force and a displacement of 5 cm. It was equipped of a precision AlNiCo magnet torque actuator and its sensors were a resistive gage force sensor and an angular synchroresolver position sensor. The sensor electronic conditioner was integrated in the bottom platform of the device. The position bandwith was about 750Hz (limited by the carrier frequency). The actuator force response time was about 500us.
This device was used with a specialized computer dedicated to intrumental mechanism real time simulation.(Berberyan 1982).and with an FPSAP120 array processor to provide visual and auditive intrumental situations (Chap 2 Florens 1986).

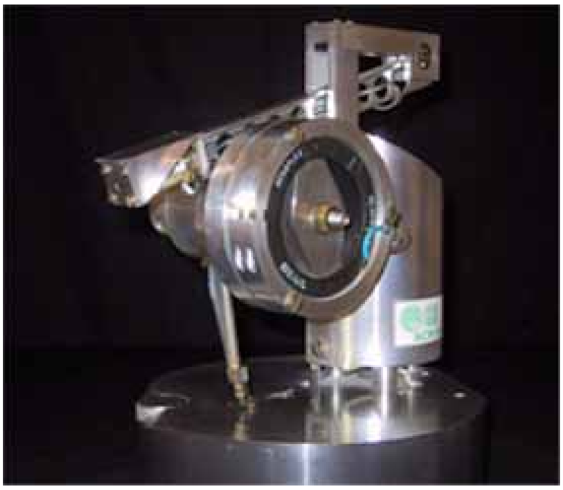


Figure 6.4 1Dof single key force feedback device.

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[Berberyan T., 1982] “Etude et realisation d’un calculateur specialsé pour la synthèse sonore en temps reel par simulation de mécanismes instrunentaux. PhD These INPG Grenoble 1982.

6.2.3 CRM (Clavier Retroactif Modulaire)

Modular Retroactive Keyboard

The Modular Retroactive Keyboard is a haptic device developed in ACROE society, Grenoble, France and patented in 1988.

General description of the device

History: In 1978, the ACROE introduced the "tactile feedback" principle in human/machine interaction by building an experimental device [Florens,78] that returned mechanical force-feedback to the user operating the device, thus creating "touch synthesis". The result was synchroneous with the sound produced and/or the visual display of the virtual instrument.
The Modular Retroactive Keyboard is based on the same principle (called TGR : Gestural Retroactive Transducer), but improves upon its predecessor by reducing bulk and increasing the number of possible Degrees of Freedom (without limit).
Domain of application: CRM research has applications in domains where human/machine interaction is important. Here are a few examples: Virtual reality, Computer animation and computer music, and Robotics.
Physical description. The device is made of two components: (1)the sensor/motor module, or actuator ("Sliced motor") and (2) the packaging (end-effectors).
Each "sliced motor", 10 cm * 18 cm * 1.375 cm in dimension can measure displacement and produce force along one degree of freedom. "Sliced motors" can be juxtaposed to in order to provide multiple degrees of freedom thanks to the packaging component.
The device's effective morphology is determined by the packaging. The packaging is achieved by plugging simple mechanical devices unto the actuators in order configure the device's Degrees of Freedom for a specific task. Examples are a virtual piano keyboard and a two-dimension joystick.
Level of achievement: prototype

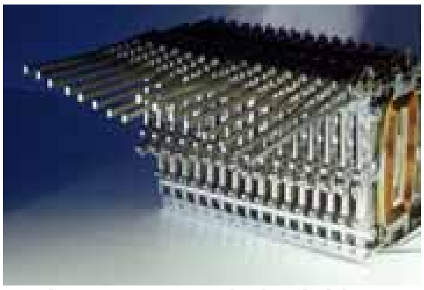

Figure 6.5 CRM device (with 16 actuator modules)

Figure 6.6 Morphological modularity: a couple of "packaging"

Technical points

<u>Mechanism</u>

Size of workspace	30 mm per axis (basic configuration)
Geometry of workspace	Configurable thanks to the end-effectors
Spatial reference	Ground-referenced
Number of degrees of freedom	Configurable thanks to the "Slice actuator" technology (3 DoF and upwards)
Cinematic configuration type	parallel
Structure of mechanism (internal cinematic configuration)	As many slice actuators as desired DoF are juxtaposed, and end-effectors are plugged upon them
Frictions: Maximum force level Non-linearities: dry friction, viscous friction	Residual friction force : 5 · 10-3 N

System statically balanced	Active weight balance.

Signal Processing

Number and structure of the signals ports.	Analog
Type of the local treatments, if any.	Impedance local loop
Technology of the local treatments	Analogical treatment

Actuation

Technology of Actuators

Physical principle	Electrodynamic
Specific technologies for the above category	Ironless multi-axis shared flux.

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	80 N
Max continuous force/torque exerted	40 N
Max speed (due to intrinsic limitation or to the driver) (peak acceleration, off-load)	1.8 m/s (660 m/s2)
Frequency response or resonance effects	0.2ms (response delay)

Sensing

Type of sensing	position
Physical principle of sensor	LVDT
Resolution	2 µm

Other properties

Weight	600 g / DoF
Whole dimensions of the system	Height : 18 cm, Depth : 10 cm, Width : 13.75 mm / DoF

Sources

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6.2.4 ERGOS

General description of the device

Haptic device developed at ACROE-ICA, INPG, Grenoble, France.
Brief history: The result of research activities realized in force-feedback interfaces and physical simulations since 1976. The principle of modularity used in the ERGOS device has been introduced in 1988.
Domain of application: Artistic applications (musical synthesis and real-time animation), instrumental simulation for training, virtual reality, teleoperation and nanomanipulators, automotive application.
Physical description: It is made of a multi-axis modular actuator on which different mechanical adapters can be plugged.

Figure 6.7 ERGOS mechanical design and multiaxis actuator

Actuator/ sensor basis : total displacement 25 mm. Maximum force : 200 N
Force settling time : (0 to 200 N) 100us, (0 to 50 N) : 50us
Moving part inertia : 300g /slice.
Residual force friction < 0,01 N
Sensor : LVDT carrier frequency :30kHz.
Displacement resolution : 1um. Position sensing bandwidth : 0- >10kHz.
Force control : analog amplifier.
Mechanical adapters.
Keyboard : displacement 40 mm
2d Joysticks : workspace : 150mm x 150mm
3d Joysticks : (W x L x H) 60 x 60 x 25 mm.
6d Ball: translations (W x L x H) 50 x 50 x 25 mm rotations : 60° on the 3 axis. All the joints are made of ball bearing and spherical ball bearing.

Technical points

Mechanism

Size of workspace	20 mm (basic configuration), 50mm (keyboards), 150mm x 150mm (2DOF joystick), 60 x 60 x 25 mm(3DOF joystick)
Geometry of workspace	Depending on the mechanical adapter : Keyboard: R=200mm (quasi-rotation)
Spatial reference	Desk-top
Number of degrees of freedom	Depending on the mechanical adapter: Keyword: n x 1-DOF quasi-rotation
Structure of mechanism (internal cinematic configuration)	Depending on the mechanical adapter:
Material of structure	Aluminum , SmCo magnet
Type, material and other characteristics of joints (if any)	Type: ball bearings, prismatic rolling joints. On the 3d and 6d adapters : spherical rolling joints.
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	Basis : < 0,01N.
System statically balanced	Active weight balance.

Signal Processing

Number and structure of the signals ports.	Analog
Type of the local treatments, if any.	Impedance local loop
Technology of the local treatments	Analogical treatment

Actuation

Technology of Actuators

Physical principle	Electrodynamic
Specific technologies for the above category	Ironless multi-axis shared flux.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	200 N
Max **continuous** force/torque exerted	80 N
Bandwidth (Dynamic range)	0,1 us (force response time from 0 to Fmax)
Max speed (due to intrinsic limitation or to the driver) (Peak acceleration)	Driver dependant

Sensing

Type of sensing	position
Resolution (Spatial resolution)	2um

Other properties

Weight (Effective mass)	300g
Whole dimensions of the system	100mm x 13mm x 100mm (W x H x L)

6.3 University of Washington

6.3.1 Excalibur system

Device description by: PERCRO on 17/11/2004

General description of the device

Excalibur is a 3DOF translating haptic device. It was designed and manufactured by Haptic Technologies, Inc. of Seattle, WA. The actuation is made by a cable system. The kinematic is a serial chain of three prismatic joints. The maximum forces (from datasheet) are very high (100N Continuous and 200 Peak).

Applications: Potential applications of Excalibur include virtual reality training, computer-aided design (CAD), telerobotic manipulation, and entertainment.

Figure 6.8 Excalibur system

Futur work: The 7DOF exoskeleton was not yet built, but the design drawing and a wood mock-up realized for ergonomical studies are possible to be seen. This device is designed for body extender, power extender and VR applications.

This device is a 7DOF arm exoskeleton for a Power Extender Teleoperation System. The first 4DOF of this haptic interface are actuated by means of cables and the motors are located at the base of the mechanism. The last 3DOFs are actuated with three motors located closer to the end effector. The main feature in this system is the fact that the forces exerted by the user are estimated measuring directly the electrical impulse of his arm muscles. This led to have an estimation of the force some cents of second before the user starts his movement.

Subjective evaluation

PERCRO

The device was tested with an application of assembling small rectangular parallelepiped (like LEGO®).This haptic device was designed with the aim of making it able to operate in Impedance Control and Admittance Control modality. It was possible to test only the device working with impedance control with the force sensors enabled.

<u>Moving in free space</u>

The friction was extremely high, without a very strong grasping of the end-effector it was really hard to move. The perceived inertia was very high. The possible cause of this behaviour could be the sliding contact of the prismatic joints. This device is can’t be used in this control modality without strongly bothering the user.

Simulation of a wall

The stiffness of a virtual wall is quite high but the high friction, again, make almost impossible to explore the surface without loosing the contact.

CEIT

The user handles the robot’s end effector and simply moves it. The present robot position is conveyed to the virtual environment and the contact forces in the virtual environment are sent back to robot’s arm.
Performed test consisted on assembly of LEGO virtual parts. The main conclusions are:
The workspace is suitable for short human arm movements.
Only translations, no rotations.
The inertia is very high. The user’s arm becomes fatigued in 2 or 3 minutes after using the device. (People from Washington University said that there was no friction compensation during the test and when the test was done, no compensation was available)
The very big forces can be exerted by the device.
The device design is very robust.
Contact tests are extremely stable and stiff.
The device is not backdrivable. This is a surprising matter since cable transmission is used.

Sources

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6.3.2 BAR haptic interface with voice coil actuators

Device description by: PERCRO on 17/11/2004

General description of the device

This device is a 2DOF planar haptic interface (very similar to the Immersion Pen Cat). The actuators are two rotating voice coil motors directly mounted on the links of the mechanism.
Applications: Haptic device for finger interaction.

Subjective evaluation

PERCRO

The device was not working so it was not possible to test it.

6.3.3 Finger Haptic Display

Device description by: INPG on 20/01/2005

General description of the device

Fingertip Haptic Display (FHD) is a 2 degree-of-freedom haptic device whose mechanical design is optimized for the workspace of the human finger. This device is being used to study human perception of curved surfaces and surface discontinuities.
Physical description: The FHD device involved an extended 5-bar kinematic linkage design that optimizes the design for maximum force output over the entire workspace, while satisfying the constraint of fitting the stochastic workspace of the human finger and any mechanical assembly constraints.

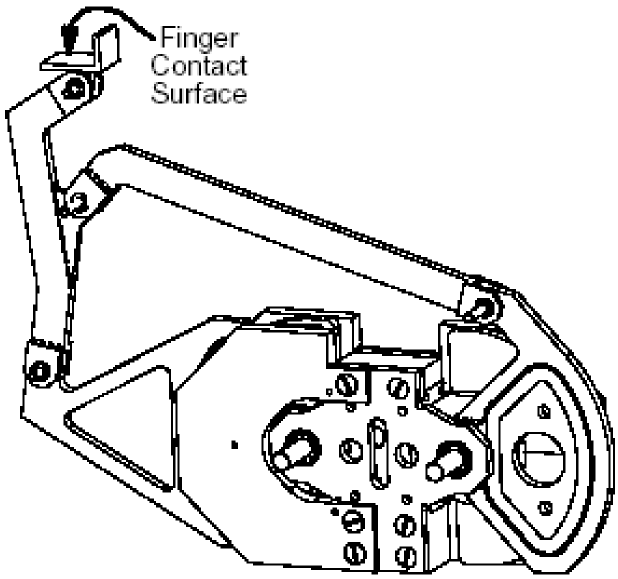

Figure 6.9 Complete FHD mechanical assembly

Sources

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6.4 Tsukuba University

6.4.1 FEELEX 2

Device description by INPG on 13/01/2005

General Description of the device

The FEELEX, a combination of an object-oriented-type force display and real-world graphics [1] is developed at VRLab, University of Tsukuba, Japan. The name FEELEX, derived from a conjunction of “feel” and “flex”, represent the project that led to the development of interface devices to provide visual and haptic sensations simultaneously.
History: A first prototype of desktop force display has been described in 1990 by Iwata [2]. This device provided force feedback for finger-hand manipulations.
As a tool-handling-type force display, the VRLab team developed in 1993 a pen-based force display [3]. A pen-shaped grip is supported by two 3DOF pantographs that enables a 6DOF force/torque feedback. Another example of this type of devices, Haptic Master, was presented by the same team at SIGGRAPH’94 [4]. The device is employs a parallel mechanism in which a top triangular platform and a base triangular platform are connected by three sets of pantograph allowing the feed-back of a 6DOF force/torque through a ball-shaped grip.
The work on rendering deformable objects through force display started in 1995 with a prototype (no publication) . The FEELEX 1 was presented in 1997 and it allowed double-handed interaction using the whole palms. To improve the resolution of the haptic surface, researches have been done, proving that the distance between the axis of the linear actuators should be smaller than the width of a finger. Thus, the second prototype, FEELEX 2 implement a piston-crank mechanism for the linear actuator reaching a 8mm resolution, which enables the user to hit at least one actuator when he/she touches any arbitrary position on the screen.
Domain of application: Medical applications (FEELEX 2 is designed as a palpation simulator), 3D-shape modeling, touch screen, interactive sculputures (to touch the image of the sculpture).
Physical description: FEELEX device is composed of a flexible screen , an array of actuators, and a projector. The flexible screen is deformed by the actuators in order to simulate the shape of virtual objects. An image of the virtual objects is projected onto the surface of the flexible screen. Deformation of the screen converts the 2D image from the projector into a solid image. The actuators are equipped with force sensors to measure the force applied by the user. The hardness of the object is determined by the relationship between the measured force and its position of the screen. If the object is soft, a large deformation is caused by a small applied force.
Level of achievement: Prototype
Future developments: Future work will include a new mechanical design for the actuators in order to solve the fabrication problems and to cancel the limitations in the type of shapes that can be displayed.

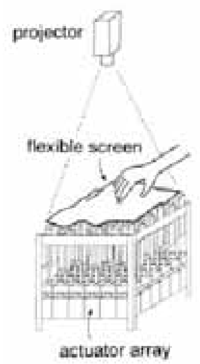
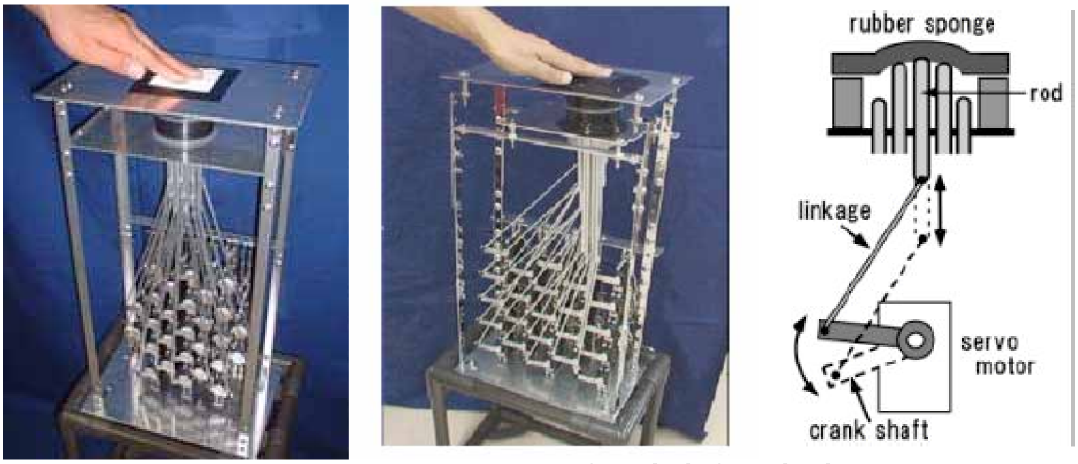


Figure 6.10 Basic concept of FEELEX

Figure 6.11 Feelex1



FEELEX 2: 23 separate sets of crank-shaft mechanism

Technical points

Mechanism

Size of workspace	50mmx50mm
Material of structure	Rubber plate and a white nylon cloth for the flexible screen

Actuation

Technology of Actuators

Physical principle	Servo-motor from a radio-controlled car
Specific technologies for the above category	The rotation of the axis of the servo-motor is converted to the linear motion of the rod by a crank-shaft and a linkage

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	Max torque : 3.2 Kg-cm which applies 1.1Kgf at the top of each rod.
Max continuous force/torque exerted	
Linearity	
Bandwidth	
Stroke / Motion range	The stroke of the rod is 18mm
Max speed (due to intrinsic limitation or to the driver)	250mm/s
Frequency response or resonance effects	Each actuator has a stroke rate of up to 7Hz (faster than the human pulse rate)

Sensing

Type of sensing	Force sensing
Physical principle of the sensors	Measuring the electric current going to each servo-motor
Resolution	40gf

Tactile Component

Number and geometry of contactors	23elements in 8mm spaced grid
Area stimulated	50mmx50mm
Stimulation method	The motors generate motion and reaction force on the screen

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6.5 Carnegie Mellon University

6.5.1 Magnetic Levitation Haptic Device

Device description by : INPG on 09/12/04.

General Description of the device

The MagLev device is developed at the Robotics Institute, Carnegie Mellon University, Pittsburgh,USA.

History: The first Lorentz force magnetic levitation device was the Magic Wrist developed at IBM T.J. Watson Research Center [1]. This device presented in the figure below was originally designed as a robot wrist for coarse-fine manipulation and later adapted for use as a haptic interface for mechanism emulation, solid contacts and texture and friction experiments. Due to the hexagonal shape of the flotor, the ranges of motion in translation and rotation are not independent. This limitation is not a problem when the wrist is carried by a 6 DOF robot arm, but as a haptic device interface it is difficult for the user to haptically recognize shape features scaled down to a motion range of under 10 mm.

Later, the UBC Wrist was developed as magnetic levitation device that has been used as a teleoperation master, as a fine motion wrist and for haptic interaction [2]. This device is smaller and has a more compact arrangement of the actuators but it has a cylindrical shape. Both IBM Magic Wrist and BC Wrist were designed, as robot wrist for high position accuracy and sensitivity, so their limited motion range and non-ergonomic shape was not a consideration.

The new device, MagLev was designed specifically for haptic interaction by reducing the mass and inertia of the previous flotors, increasing the magnetic forces and the controller sample rate.

Domain of application: for local haptic interaction using the fingertips for common tool-based tasks, Virtual Reality (3D dynamic simulated environments)

Physical description: The MagLev device has 6 DOF [3], which uses Lorentz force magnetic levitation for actuation. It is mounted in the top cover of a desk-side cabinet enclosure containing all the amplifiers, control hardware, microprocessing, and power supplies needed for operation. The levitated moving part grasped by the user contains curved oval wound coils and LEDs embedded in a hemispherical shell with a handled fixed at its center. The stationary base contains magnet assemblies facing the flotor coils and optical position sensors facing the flotor LEDs.

Level of achievement: Not a commercial device.

Future developments: A drawback of Lorentz force actuation is that the range of motion of the device, which is limited by the width of the air gap in the magnetic assemblies.

Improvement of the position resolution (to reach 3µm).

New method for controlling spatial impedance of the levitated platform.

A new version of the Magnetic Levitation device is currently in development. Prof. Hollis planned the realization of 7 new Magnetic Levitation haptic devices with bigger work space and lighter sphere (carbon fiber) and coils (made in alluminium). Several of this devices will be realized an used from different laboratories for evaluation and experiments. Prorf.Hollis forecasts the establishment of a spin-off company that will commercialize this device.

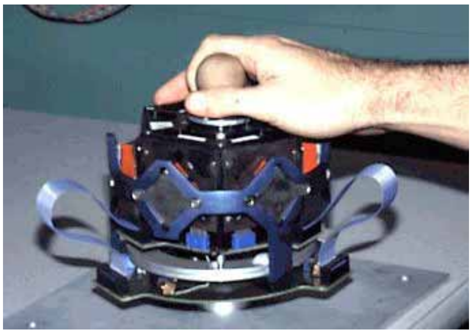

Figure 6.12 IBM Magic Wrist

Figure 6.13 UBC Wrist

a b c

Figure 6.14 Magnetic Levitation Haptic Device

Technical points

Mechanism

Number of degrees of freedom	6 DOF
Characterization of the system in a passive state	Residual stiffness (free motion): 0,005N/mm Maximum stiffness: 25N/mm in translation, 50Nm/rad in rotation
Material of structure	The structure of the flotor is a thin aluminum shell with cutouts for the actuator coils. The coils are wound from ribbon wire. 48 MGOe NdFeB permanent magnet (0,35T at the center)
Intrusion of mechanism in visual space of the user	The user'wrist and forearm rest on the stator rim and desktop while the haptic device tool handle is manipulated with the fingertips.

Signal Processing

Bandwidth or sampling rate.	Sample rate 1kHz. System response up to 75Hz remains at ±3dB.
Technology of the local treatments	The control is made through a real-time VMEbus system with a DSP communicating via Ethernet TCP/IP socket

Actuation

Technology of Actuators

Physical principle	Lorentz force (magnetic)
Specific technologies for the above category	TheLorentz force actuator consists of two opposing fixed permanent magnet assemblies and an oval wound coil suspende d between them in the magnetic circuit air gaps. The actuator magnets and coils are arranged with 3 actuators next to the hemisphere and the other 3 are positioned halfway down the hemisphere and rotated by 90°.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	Maximum forces: X: 64N Y: 55N Z: 140N Torque: X: 7,3Nm Y: 6,3Nm Z: 12,2Nm
Bandwidth	For Al coil flotor, measure taken for a 1,3kHz control rate: Vertical direction: 120Hz Horizontal direction: 100Hz Vertical rotation: 100Hz Horizontal rotation: 120Hz
Stroke / Motion range	Device motion range: ±5 mm and ±3,5° in all directions [3]. Each oval-shaped actuator coil spans a 45°x61° solid angle on the hemisphere.
Max speed (due to intrinsic limitation or to the driver)	For Al coil flotor, the acceleration is: Vertical direction: 233m/s^2 Horizontal direction: 92m/s^2 Vertical rotation: 2247 rad/s^2 Horizontal rotation: 1160 rad/s^2

Sensing

Type of sensing	Position
Physical principle of the sensors	Optical (position sensitive photodiodes-PSD)
Resolution (Spatial resolution)	10µm (due to the sensor noise)
Bandwidth, max data rate (in the case of sampled digital output)	Position control bandwidth: 75Hz
Location in the haptic system – relation / link with the geometry of the mechanism	The 3 PSDs are situated on the fixed outer stator and measure the positions of light spots from 3 LEDs mounted on the moving flotor.

Other properties

Weight (Effective mass)	850g (flotor)
Power consumption	16,5 W for Al flotor with an additional 1kg

Subjective evaluation

PERCRO

Moving in free space

The device presents, clearly, very low friction and zero backlash. The perceived inertia was quite high (the mass of the moving parts is almost 400g) but the inertia tensor is isotropic, due to its semi-spherical shape. Anyway the small size workspace (a cube of 24mm of length) don't allow to achieve to high acceleration so the inertia effect is not so relevant.

Simulated of a hard wall

- Smooth surface: The test consisted in a single point interaction with an horizontal smooth surface with the three rotational degrees of freedom blocked by control. The stiffness of the contact against the wall is very high. The contact with the virtual surfaces were very stable.
- Wavy surface: Two different wavy surfaces were tested. The first has a small scale waving and the second has larger scale waving. The first gives a quite good feeling of the bump and hole. The

second one presented some problems of coherence with video and haptic rendering (something wrong) and it was not possible to judge the quality of the force feedback effect.

- Surface with friction: Two different type of friction were simulated: stick and slip friction and columbian friction. It was not possible to feel the difference between them. Anyway a feeling of friction was well reproduced.

Assembly task (peg in a hole)

During this test the system become unstable and always hit against the stroke breakers. Probably the results of this test are non reliable for an objective evaluation.

Teleoperation System with industrial robot

In this application the Magnetic Levitation haptic interface was used as master device of a teleoperation system. The slave was an industrial robot (SCARA) with a Magic Wrist (almost identical to the master) mounted on the end effector.
The project was currently in development and it was possible o test only some of the possible control algorithm.
The first test was a speed control without force feed back: an imposed speed of the slave robot correspond to a variation of the position of the master device. This control paradigm was created to supply the lacking of workspace of the master device and was quite hard to use at the beginning.
The second test was done with the force feedback. The slave wrist was used simply as a force sensor. In this case it was not possible to feel the contact force with a soft object under the slave wrist.

UNEXE

The unique construction of this system means that it has very low friction and no backlash. It is also capable of relatively high stiffnes,as demonstrated with a point-contact against a wall demo.
Small workspace, and angular freedom (yaw) particularly poor. Prone to failure.
Some vibration was noted during some of the more complex demonstratoins. This was (believed to be) due to poor position sensing.
Techological Innovations
A new semi-commercial device should iron out some of the problems encountered with the prototype. The optical sensing has been improved, the reange of motion increased, and the mass of the sphere halved.

CEIT

Several virtual environments are tested:
1st Textures test on a flat surface.
The bandwidth is good enough to display textures.
During the free motion a low-amplitude vibration is felt.
The damping felt during free motion is negligible.
2nd Contact on a flat surface without textures.
The impact test is stable, with high bandwidth but the contact is not stiff but good enough.
There is no feeling of a flat surface. From my point of view, the problem is not the stiffness felt, but the workspace size.
3rd Peg-in-hole assembly of a prismatic polyhedron.
The contact shows almost negligible instabilities.
The peg-in-hole task can be performed easily. During the pin-in-hole insertion, the feeling was however as if there was a magnetic field that attracts the pin to the hole.
The workspace only allows to perform the assembly task with
4th Maglev device as the master of a teleoperated system (a 6DoF Puma was found as the slave robot).
The workspace is big enough to complete the task. An indexing is required many times.
The slave robot's behaviour is instable.

During all tests, I couldn't distinguish if the system has reached the end-strokes or if it has reached a virtual wall.

Notice that although the device can display torques, all tests are force feedback tests; that is to say, no torque-feedback tests.
The inertia felt in free movement negligible. The workspace is not big. It is only suitable to human wrist movements.
A bottleneck of this device is that the kinematics is solved by means of look-up table, not kinematics equations.
The last remarkable point is the control of a MagLev device is not easy and the plant without control is very instable. To improve the performance, the CMU prefers the use of non-PWM drivers (analog drivers).

DLR
The Magnetic Levitation Device (MagLev) seems to unite two fundamentally different concepts:
a) Kinesthetic feedback
b) Tactile feedback.
This is only possible due to a very high control bandwidth (required for tactile feedback) combined with a high force-torque output (for force feedback) coming along with a high position resolution.
Device Properties: Six axis parallel structure, Max stiffness: 25N/mm,Sampling rate: 1000Hz; Operating system for visualization: Linux; Real time operating system: QNX.

Advantages: High bandwidth; High position resolution; Low inertia of the device itself
Disadvantage: Limited workspace (not a big limitation if high resolution is available within the workspace (comparable to a computer mouse which is also very limited in workspace)

The Future Device (available 2005): Slightly enlarged workspace; Even higher bandwidth; Improved motion resolution; Even lower device inertia; Expected to be low cost (it is made mainly of standard components).
The device seems to be in a stage comparable to the DLR light weight robot: most weaknesses are already eliminated and the developers now focus on user friendly design, ergonomic aspects, etc.
In the near future the device will have a total of 7DoF: an additional grasping functionality will be integrated in a special handle.

Device Evaluation. Overall Impression
Performance is quite convincing, the device is nicely designed and seems to be quite robust. One could imagine this device to be one of the future human machine interfaces (comparable to DLR Spacemouse but with feedback) assuming that the hardware will be affordable and more compact.
Free motion Using All DoF And Interaction With a Textured Surface: At all velocities the device behaved very well, but there always was a small amount of remaining noise present that could be felt. People at CMU did not seem to be completely sure about where it originates from. Stiffness of virtual walls was fairly high, no instabilities were encountered when in contact. Using very high forces, the wall could be entered, but without encountering any unexpected behaviour. The high bandwidth was impressively demonstrated by following a textured surface. Even small surface details could be felt. At no time during the experiments the inertia of the device itself could be felt.
Friction on a Surface: On a virtual surface the upper half of the surface area was with viscous friction, the lower half was used to demonstrate stick-slip effects.
The background noise seemed to be more prominent in the area of viscous friction; however the overall impression was positive. Stick-slip effects did not seem to be very realistic but this probably can not be attributed to the device itself but to implementation weaknesses.
The Peg in Hole Experiment: For the Peg in Hole experiments, three holes of different sizes were implemented on a virtual surface. Reduced size of the opening as expected resulted in a more difficult insertion task. Performance of the system for the Peg in Hole test was good, however it has to be noted that the task is still considerably more difficult than in reality. Also it was interesting to observe that noise effects could not felt be felt any more by the operator as soon as he had to focus on a more difficult task.
The Cube in Cube Experiment: Moving a solid cube inside another cube allowed to verify the performance when in contact with stiffnesses in all six DoF. Performance was good for all DoF

Navigation in a Complex Environment: An environment with different objects that one could move around and lift was provided in this experiment. All six DoF were available. The overall impression in this test was good
The Magnetic Levitation Device connected to the Puma Robot Equipped with the Magic Wrist: In this experiment, the MagLev was used as the master input device. Small operator commands were transmitted to the wrist actuator only, whereas larger input device deflections were used to move the robot arm. A virtual handshake was demonstrated (one user operated the MagLev, the other user applied forces to the wrist tip). In a separate experiment the endeffector was in contact with surfaces. The experiment was not completely convincing: depending on the control mode, there were large endeffector oscillations visible and also the surface contact was only demonstrated with very soft surfaces (probably due to stability problems under more stiff.

<u>Conclusions:</u>

Although some of the demonstrations were not completely convincing, no major weaknesses of the device itself could be found. Oscillations of the Puma robot for example can be attributed to the way master and slave are coupled, but not to the input device itself. The group should focus on eliminating the remaining noise in the system which can be disturbing in certain situations. The future device should be re-evaluated when it is available next year and it also would be interesting to see if a commercialized low cost device will have similar performance.

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6.6 Tokyo Institute of Technology

6.6.1 SPIDAR-G&G (SPace Interface Device for Artificial Reality)

Device description by : INPG on 16/12/2004.

General Description of the device

The *SPIDAR-G&G* is a haptic interface for tasks requiring two-handed manipulation, developed at Tokyo Institute of Technology, Japan. The technical data come from Eurohaptics2004 for SPIDAR-G&G and from the paper [6] for SPIDAR-G.
*History: By a*ssembling two 3DOF version of SPIDAR [2, 3], two other devices were developed in the same laboratory : Both-Hand-SPIDAR [4] and SPIDER 8 [5]. These new devices improved the level of reality during virtual object manipulation, but the working area was limited, the number of degree of freedom (only 3) and strings connected to each hand interfered with each other during wide rotation.
SPIDAR-G [6] is a 7 DOF force feedback device (3 rotation forces, 3 transition forces with 1DOF in plus for the spherical grip element), which is used to track hand movement, to grasp or release a virtual object.
SPIDAR-G&G [7], uses two SPIDAR-G for bimanual tasks. The hands are independent from each other, and can cooperate to accomplish task.
Domain of application: Virtual prototyping, virtual sculpturing, free form modelling, medical simulation, molecular simulation and teleoperation.
Physical description: The SPIDAR-G&G is composed of two SPIDAR-G haptic devices linked to a PC through USB ports. Both devices are placed about 40 cm apart from each other and separated by a LCD display. The user is manipulating a grip, which has a radius of 3,25 cm inside a cubic frame of each haptic device and interact thus with the virtual objects.

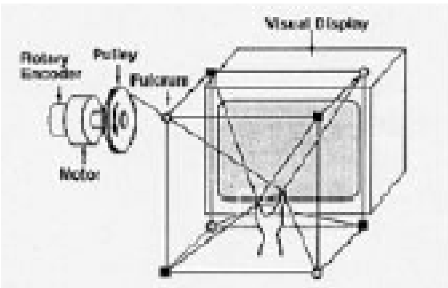

Figure 6.15 SPIDAR II

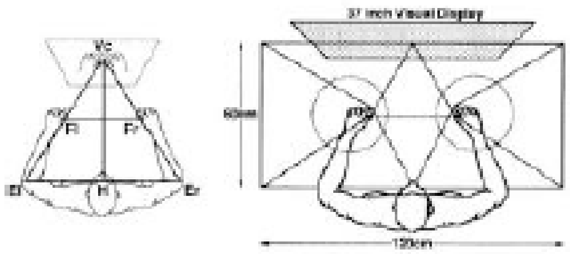

Figure 6.16 Both-Hand SPIDAR

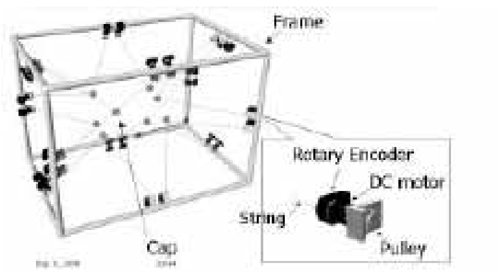

Figure 6.17 SPIDAR 8

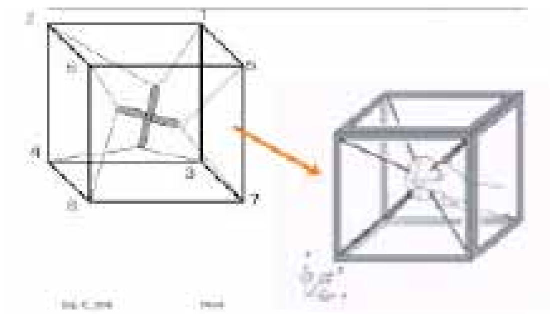

Figure 6.18 SPIDAR-G

 

Figure 6.19 SPIDAR-G&G system

Technical points

Mechanism

Size of workspace	A cubic frame with a length of 20 cm for SPIDAR-G&G. A cubic frame with a length of 48 cm for SPIDAR-G.
Number of degrees of freedom	2 haptic devices type SPIDAR-G, each has 7 DOF (3DOF for translation, 3DOF for rotation, 1DOF for grasp) assured by 8 strings.
Material of structure	Maxon DC motors

Signal Processing

Number and structure of the signals ports.	Two USB ports, one per haptic device
Type of coding and type of medium.	A freeform and implicit solid modeler are used to create the anamorphous shapes as virtual objects.
Bandwidth or sampling rate.	The complete cycle (hand movement, collision detection and force feedback creation) is at 1 kHz for SPIDAR-G&G.
Technology of the local treatments	Pentium PC 400MHz processor

Actuation

Technology of Actuators

Physical principle	Force display using string tension
Specific technologies for the above category	Controlling the tension of each spring by a DC motor.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	Are not given. In general, the maximum grip force could be obtained where maximum translation force is possible.
Max **continuous** force/torque exerted	2,9N from [7].

Stroke / Motion range	A simple shaped region cannot describe the workspace of maximum deliverable force due to the way the strings are connected. The maximum force could be reached along x and y-axis when the grip was at 10 cm of the origin. Forces go to zero when the grip was about 23 cm away of the origin in the negative direction of x-axis. Along the z-axis, maximum force was achieved at 23 cm from the origin but drop to zero at 25 cm. Maximum rotational force is achieved up to 45° rotation around any axis.

Sensing

Type of sensing	Hand position: optical encoder type HEDS-5540 made by HP
Physical principle of the sensors	Measuring the string length. A length per encoder pulse multiplied by the counter value is the length of string.
Resolution (Spatial resolution)	0,0251327 mm. An error of 0,8±0,4% was obtained for length between 10-70 cm.
Location in the haptic system – relation / link with the geometry of the mechanism	The grip is located in the middle of a cubic volume and it is linked by the strings.

Sources

[1] Web page: http://sklab-www.pi.titech.ac.jp/~hase/index.en.php
[2] M. Sato, Y. Hirata, H. Kawarada, "SPace Interface Device for Artificial Reality-SPIDAR." The Transaction of the Institute of Electronics, Information and Communication Engineers (D-II), July, 1991, J74-D-II, 7, pp. 887-894
[3]Y. Hirata, M. Sato, "3-dimensional interface device for virtual work space", Proc. 1992 IEEE/RSJ International Conference on IROS, vol. 2, pp. 889-896, 1992
[4] M. Ishii, M. Sato, "A 3D spatial Interface Device Using Tensed Strings", Presence, 3(1), pp. 81-86, 1994
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[6] S. Kim, J. Berkley, M. Sato, "A Novel Seven Degree of Freedom Haptic Device for Engineering Design", Virtual Reality, Springer-Verlag London Ltd., vol. 6, pp. 217-228, August, 2003
[7] J. Murayama, L. Bougrila, Y.L. Luo, K. Akahane, S. Hasegawa, B. Hirsbrunner, M. Sato, "SPIDAR-G&G: A Two-Handed Haptic Interface for Bimanual VR Interaction", Proceedings of Eurohaptics 2004, June5-7, Munich, Germany, pp. 138-146, 2004

6.7 ATR communication systems research Lab Kyoto

6.7.1 Palmtop Display for Dextrous Manipulation with Haptic sensation (PDDM)

Device description by: INPG on 14/01/2005

General description of the device

The PPDM system developed at ATR Communication Systems Research Laboratories, Kyoto, Japan was published in1996 [1, 2].

History: A first prototype of PDDM system, which used an Ultrasonic Motor (USM) force display was created in 1992 [3]. Then, a tactile input and reaction force generator system, a 6 DOF manipulator was created at ATR laboratory in 1993 [4].

Applications: Fine manipulating tasks in virtual space teleconferencing system.

Physical description: The PDDM consists of a palmtop display, a position and orientation sensor and a force display, and can act as a visual display and as a motion input device with haptic sensation in one unit. The PDDM system has a small LCD, a 3D mouse and a mechanical linkage (force display). The LCD display has 2 push-button on the back. The user holds both sides of the display and presses the buttons with the left fingertips. One push-button is used to shift between the observing and the handling phase. A magnetic position sensor is installed on the side of the display and provides the orientation and position of the palmtop display.

The display is connected to a 6 DOF USM force display. 3 of these are actuated with USM and generate a force in any direction at the display. The others are an unactuated 3-axis universal joint at the end of the arm. Thus, the system can't restrict rotating torque. An electrical touch sensor is installed on the back of the palmtop display. When the user is holding the display, all joints can be freely rotated. When the user releases it, the system detects it and immediately locks all joints (dynamics impedance control not implemented in 1996 PDDM model).

Figure 6.20 Palmtop Display for Dextrous Manipulation

Level of achievement: Prototype

Future developments: To construct a fully actuated 6 DOF forces display using three of ATR laboratory arms. Another planned solution is to employ a dynamic constraint method to aid the lack of DOF. As one future work for the PDDM [2], is to create an augmented reality sytem by using the CCD camera information. The system premeasures the shape of real objects. By measuring their position in any ways, i.e., a visual sensor or magnetic position sensor, the simulation process can treat real or virtual objects using the same method as used now.

Technical points

Mechanism

Size of workspace	Volume of a half sphere, 60 cm radius.
Geometry of workspace	A half a sphere

Signal Processing

Type of the local treatments, if any.	Impedance
Technology of the local treatments	PC is used to control force display and communicate with the server process (SGI) trough the ethernet.

Actuation

Technology of Actuators

Physical principle	Ultra sonic Motors (USM)
Specific technologies for the above category	An USM works with frictional force. It generates a sustaining and rotating torque .
Gear or low-level mechanisms (if any).	Not needed

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	5N reacting and sustaining force in the workable volume.
Max continuous force/torque exerted	The maximum output torque of an USM is 1.3Nm
Max speed (due to intrinsic limitation or to the driver)	60 rpm

Sensing

Type of sensing	Position sensing
Resolution	40gf

Other properties

Price	N/A
Weight	350gf (the 4-inch display)
Whole dimensions of the system	150 × 150 × 50 mm (stimulator array + drive electronics)

Sources

[1] http://www.mis.atr.jp/~noma/papers/Paper/CHI96/HN_BDY.html
[2] H. Noma, T. Miyasato, F. Kishino : "A Palmtop Display for Dextrous Manipulation with Haptic Sensation", proc of CHI'96, pp. 216-133, 1996.
[3] H. Takemura, F. Kishino, "Cooperative Work Environment Using Visual Workspace", proc. of CSCW '92, pp. 226-232, 1992
[4] Noma, Iwata :"Presentation of Multiple Dimensional Volume Data By a 6 D.O.F. force display", Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems '93, IROS '93, Vol.3 ,pp.1495-1500, 1993

6.8 State University of New Jersey, Center of Advanced Information Processing

6.8.1 Rutgers Master II New Design

Device description by : INPG on 07/12/2004.

General Description of the device

The Rutgers Master II glove is a haptic interface developed at the Center for Advanced Information Processing, The State University of New Jersey, Piscataway, USA.
History: A first model of the glove was developed in 1992 [1].
Researches at Rutgers Human-Machine Interface Lab realized in the aim of unifying the sensing and force feedback in one glove resulted inthe Rutgers Master II prototype in 1997 [2]. The redesign of the previous models lead to the Rutgers Master II-ND glove [3], which has all the sensing placed on palm support avoiding, thus routing wires to the fingertips.
Domain of application: Virtual reality: from hand rehabilitation to military command and control.
Physical description: The Rutgers Master II-ND glove is a haptic interface that provides force feedback to the thumb, index, middle and ring fingertips. The force feedback structure serves as position measuring exoskeleton. This interface position sensing consists of an “L”-shaped multilayer platform and four actuators. The shape of the platform fits behind the “middle-line” of the palm and allow the complete flexion of the metacarpal phalanx. The inside layer of the platform contains an electronic printed board and 4 flexible pneumatic tubes.
The structure linking each fingertip to the palm platform has 3 sensing joints and 5 DOF.
Level of achievement:
Future developments: A dual-glove (left and right) system, which will use a single control interface is in development. The haptic-control interface is to be redesigned to allow operation of the Rutgers Ankle haptic platform.

Figure 6.21 Rutgers Master II force feedback glove

Technical points

Mechanism

Size of workspace	45° for the second finger (proximal-inter-phalangeal)
Geometry of workspace	2m radius hemisphere
Spatial reference	
Number of degrees of freedom	5 DOF (2 spherical joints, 2DOF and 1 cylindrical joint, 1DOF)
Characterization of the system in a passive state	Static actuator friction: 0,014N
Cinematic configuration type	Serial

Material of structure	Rare earth magnetic discs, Graphite piston running inside a Pyrex glass cylinder, all being encapsulated in aluminum tubes (actuator structure).
Type, material and other characteristics of joints (if any)	Spherical and cylindrical joints
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	-

Signal Processing

Number and structure of the signals ports.	16input/8output channels of an A/D/A board (MPC550 from Micro/Sys) mounted on the PC104 bus. 12 input channel read the glove position sensors, 4 output channels control the intake microvalves, 4 output channels control the exhaust valves
Type of coding and type of medium.	WorldToolKit (Sense8 Co.) simulation containing a virtual hand driven by the RMII-ND glove
Bandwidth or sampling rate.	1kHz
Functional properties of the local loops	The embedded computer controls the solenoid valves using a PWM at 300Hz
Technology of the local treatments	Embedded Pentium PC at 233MHz with PC104 bus, Disk-on-chip memory, IDE, VGA and Ethernet interfaces. This embeded Pc communicates with the host computer by a RS232 link (38-115kb/s)

Actuation

Technology of Actuators

Physical principle	Pneumatic (direct drive)

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	
Max **continuous** force/torque exerted	16N per finger
Linearity	
Bandwidth	300Hz for valve control, 10Hz at fingertip
Stroke / Motion range	The flexion motion varies from –10° to 120° relative to the palm. The abduction/adduction motion varies from ±60°. The piston stroke varies from 28-44mm.

Sensing

Type of sensing	Position
Physical principle of the sensors	Hall effect sensors for measuring the flexion and the adduction/abduction angles. Infrared sensors for measuring the translation
Resolution (Spatial resolution)	0,1 degree (Hall sensor) 0,3 mm (IR sensor)
Bandwidth, max data rate (in the case of sampled digital output)	Sensor update rate: 435 records/sec
Location in the haptic system – relation / link with the geometry of the mechanism	They are integrated in a direct-drive configuration in the palm.

Other properties

Weight (Effective mass)	80g
Security and protection systems, if any	The direct-drive actuator placed in the palm avoid the insecure reasons generated by CyberGrasp glove.

Sources

[1] G. Burdea, N. Langrana, E. Roskos, D. Silver, J. Zhuang, “A portable dextrous master with force feedback”, in PRESENCE, Cambridge, MA:MIT Press, 1992, vol. 1, pp. 18-28
[2] D. Gomez, “A dextrous hand master with force feedback for virtual reality”, Ph.D. thesis, Rutgers University, ECE dep., New Brunswick, NJ, 1997
[3] M. Bouzit, G. Burdea, G. Popescu, R. Boian, “The Rutgers Master II – New Design Force-Feedback Glove”, IEEE/ASME Trans. on Mechatronics, vol. 7, No.2, June 2002, pp. 256-263
[4] M. Bouzit, G. Popescu, G. Burdea, R. Boian, “The Rutgers Master II-ND Force Feedback Glove”, Proceedings of IEEE VR 2002 Haptics Symposium, Orlando, FL, March 2002

6.9 University of British Columbia

6.9.1 3-DOF Twin pantograph haptic mouse

Device description by : INPG on 21/10/2004.

General Description of the device

The 3-DOF Twin Pantograph Haptic Mouse is developed at Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada.
Physical description: It uses two 2-DOF 5-bar linkages. It has a crankshaft end-effector in the plane that provide 2-DOF of translation and 1-DOF of rotation.

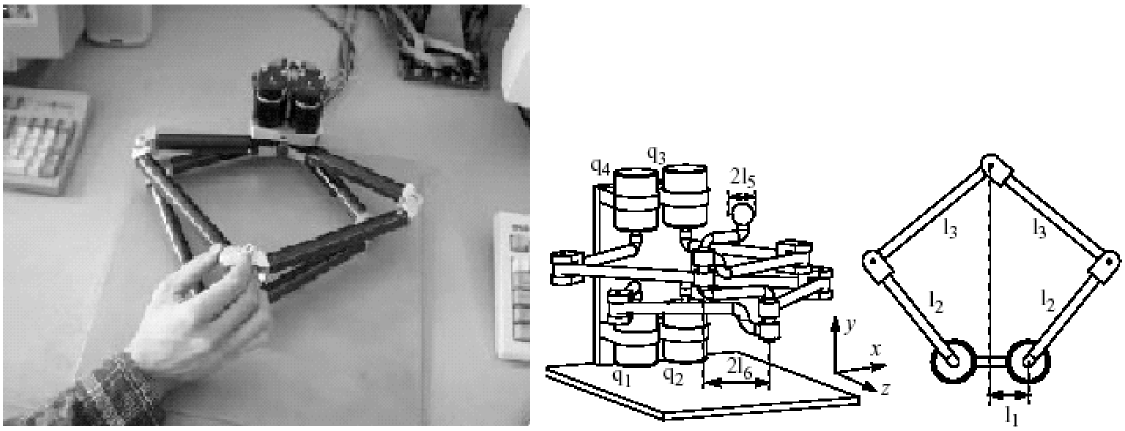


Figure 6.22 3-DOF Twin pantograph haptic mouse

Technical points

Mechanism

Size of workspace	X: ±5 cm, Z: ±5 cm, Y (rotation axis): ∞
Geometry of workspace	10cm square workspace
Spatial reference	Desktop (planar motion)
Number of degrees of freedom	2-DOF translation, 1-DOF rotation
Isotropy of workspace configuration or not, in terms of accessibility	Static force isotropy is optimized for the workspace
Characterization of the system in a passive state	Static friction: X: 0.024N, Z: 0.024N, Y (rotation axis): 0.12Ncm
Material of structure	Aluminum clevises, carbon fiber links, rare earth magnet
Type, material and other characteristics of joints (if any)	Type: rotules, driven directly by Maxon motors and roller bearing
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	Maximum stiffness: X: 25N/cm, Z: 25N/cm, Y (rotation axis): 200Ncm

Signal Processing

Type of the local treatments, if any.	Impedance local loop

Actuation

Technology of Actuators

Physical principle	Electromagnetic. Coreless Maxon motor
Specific technologies for the above category	Ironless

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	X: 23N, Z: 22N , Y (rotation axis): 115Ncm
Max **continuous** force/torque exerted	X: 2,4N, Z: 2,26N, Y (rotation axis): 12Ncm
Stroke / Motion range	Dynamic range: X: 950:1, Z: 910:1, Y (rotation axis): 950:1
Max speed (due to intrinsic limitation or to the driver)	Peak acceleration: X: 6 G, Z: 6 G, Y (rotation axis): 2405 s^{-2}

Sensing

Type of sensing	Force/Torque
Physical principle of the sensors	Optical encoder
Resolution (Spatial resolution)	X: 224 µm, Z: 224 µm, Y: 0,26°

Other properties

Weight (Effective mass)	X: 395 g, Z: 370 g, Y: 4781 gcm^2
Whole dimensions of the system	100cm x 10cm x 100cm (W x H x L)

Sources

[1] Salcudean S.E. , Stocco L., "Isotropy and Actuator Optimization in Haptic Interface Design", IEEE International Conference on robotics&Automation, San Francisco, CA, April 22-28, 2000, pp. 1-7

6.9.2 5-Dof Twin-Pantograph Haptic Pen

Device description by : INPG on 10/11/2004.

General Description of the device

The 5-DOF Twin-Pantograph Haptic Pen is a device developed at Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada.
Domain of application: Surgical training, teleoperation system.
It was tested to simulate two virtual environments. One is a virtual pencil that can write on the surface of a stiff bounding box. The other is the virtual excavator that can dig into its surrounding landscape.

Physical description: It uses two 3-DOF 5-bar linkages. It has a pen shaped end-effector and it provides 3 degrees of translation and 2 degrees of rotation. The device is designed to have force capabilities that match those of human hand as consistently as possible throughout the workspace.

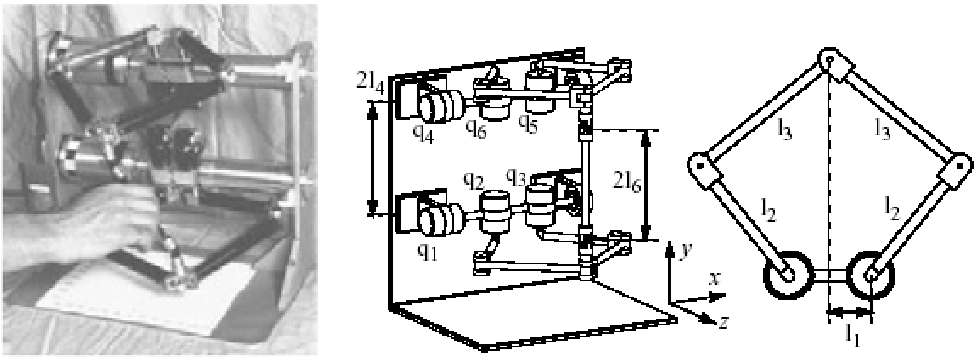


Figure 6.23 **5-DOF Twin Pantograph Haptic Pen**

Technical points

<u>Mechanism</u>

Size of workspace	Translation axis: Rotation axis: X: ±6 cm X: ±45° Y: ±3,75 cm, Z: ±45° Z: ±3,75 cm
Geometry of workspace	$1600cm^3$ (16cm(x) x 10cm(y) x 10cm(z)) Semi-dextrous workspace
Spatial reference	Desktop
Number of degrees of freedom	3-DOF translation, 2-DOF rotation
Isotropy of workspace configuration or not, in terms of accessibility	The Global Isotropy Index and a discrete optimization algorithm (culling) are computed for a high isotropy
Characterization of the system in a passive state	Static friction: X: 0.022N, X: 0,19Ncm, Y: 0.045N, Z: 0,18Ncm Z: 0.023N
Cinematic configuration type	Hybrid robot
Material of structure	Aluminum and magnesium clevises, carbon fiber links, rare-earth Maxon motors
Type, material and other characteristics of joints (if any)	Type: rotules, driven directly by a motor and roller bearing
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	Stiffness and damping coefficients are obtained using a tuned PD controller at a control rate of 1kHz with the endpoint velocity computed from low-pass filtered finite difference position readings. Stiffness: X: 16N/cm, X: 874Ncm, Y: 12N/cm, Z: 1076Ncm Z: 13N/cm
System statically balanced	Steel weights were mounted behind the shoulder motors to achieve static balance at a location just outside the workspace boundary that is nearest to the motors.

Signal Processing

Type of coding and type of medium.	SGI O2 IRIX
Type of the local treatments, if any.	Impedance local loop. The haptic pen is controlled using a PD and a braking pulse that is applied upon contact with a stiff environment and is proportional to end-point velocity. The device is controlled as two 3-DOF force sources (each pantograph, each end of the haptic pen).
Functional properties of the local loops	Not available

Actuation

Technology of Actuators

Physical principle	Electromagnetic. Coreless Maxon motors
Specific technologies for the above category	Ironless
Backlash	Backlash and friction were minimized by using direct-drive motors and roller bearings in all passive joints except for the universal joints ,which are made from Delrin.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	X: 48N, X: 324Ncm, Y: 21N, Z: 396Ncm Z: 40N
Max **continuous** force/torque exerted	X: 5N, X: 34Ncm, Y: 3,3N, Z: 41Ncm Z: 4,1N
Stroke / Motion range	Dynamic range: X: 2200:1, X: 1700:1 Y: 470:1, Z: 2200:1 Z: 1700:1
Max speed (due to intrinsic limitation or to the driver)	Peak acceleration: X: 25,8G, X: 3147 s^{-2}, Y: 9,5G, Z: 3143 s^{-2} Z: 26,1G

Sensing

Type of sensing	Force/torque sensing
Physical principle of the sensors	4000 cpt optical encoder
Resolution (Spatial resolution)	X: 142 µm, X: 0,122°, Y: 314 µm, Z: 0,O99° Z: 175 µm

Other properties

Weight	70 – 130 g
Whole dimensions of the system	(W x H x L)

Sources

[1] S.E. Salcudean, L. Stocco, “Isotropy and Actuator Optimization in Haptic Interface Design”, IEEE Int. Conf. On Robotics & Automation, April 22-28, 2000.

[2] L. Stocco, S.E. Salcudean, F. Sassani, “Optimal Kinematic Design of a Haptic Pen”, IEEE/ASME Trans. on Mechatronics, in press, 2001

6.9.3 PowerMouse Electro-mechanical Design

Device description by : INPG on 10/11/2004.

General Description of the device

Power Mouse is a haptic device developed at Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada in 1997.

Domain of application: The device is envisaged to be used as (1) intelligent haptic interface emulating simple mechanisms such as limit stops, gimbals, sliders, (2) a “dumb” haptic interface or teleoperation master, with the microcontroller board acting as an input-output board and most calculations being performed by the host or another external computer.

Physical description: The device has 6-DOF and is composed by a mouse-like handle attached to a mobile “flotor” structure with six flat coils embedded in its faces. The flotor can move within the confines of a stator that is attached by three mounting posts to a plastic base. A printed circuit board (PCB) fits between the stator and the plastic base and carries the device sensing and power electronics and a microcontroller.

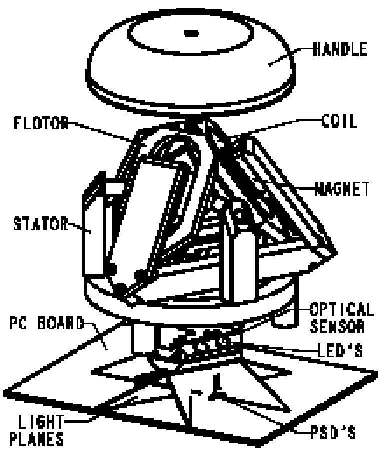


Figure 6.24 PowerMouse mechanical design

Technical points

Mechanism

Size of workspace	Translation motion range: ±3 mm, Rotation range: ±5°
Geometry of workspace	Semi-dextrous workspace
Spatial reference	Desk-top
Number of degrees of freedom	6-DOF
Isotropy of workspace configuration or not, in terms of accessibility	The force/torque vector is isotropic by design
Material of structure	Magnet, voice-coils, optical sensor
Type, material and other characteristics of joints (if any)	Wide magnetic gaps

Signal Processing

Number and structure of the signals ports.	Two serial and one parallel communication ports. One serial port allows real-time control by a remote host, while the second one is provided for the use of debugging tools.
Type of the local treatments, if any.	Impedance local loop

Functional properties of the local loops	50MHz Intel 80C196NU microcontroler with associated EPROM and RAM for generating the time-multiplexed light planes needed for optical sensing and PWM signals.
Technology of the local treatments	Pulse-Width-Modulation (PWM) driven H-bridges for the coils

<u>Actuation</u>

Technology of Actuators

Physical principle	Electromagnetic, (flat coils-Lorentz actuators)
Specific technologies for the above category	Inside the flotor shell, stator magnets matching the coils are arranged on a cubic soft iron core. Outside the flotor shell, magnets matching the coils are mounted on soft-iron return plates arranged in a cubic structure.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	34N
Max **continuous** force/torque exerted	16N
Max speed (due to intrinsic limitation or to the driver) (Peak acceleration)	>10G

<u>Sensing</u>

Type of sensing	Positions and orientation offsets of the flotor with respect to the stator.
Physical principle of the sensors	Novel optical sensor composed of three linear position sensing diodes (PSD). Three light planes are generated by wide-angle infrared light emitting diodes (LEDs) and projecting infrared light through narrow slits towards the vertex.
Resolution (Spatial resolution)	10 µm, 0,05°
Location in the haptic system – relation / link with the geometry of the mechanism	The PSDs are placed on a horizontal plane under the flotor, while the three LEDs are attached to the flotor.

<u>Other properties</u>

Weight	260 g (moving mass)
Whole dimensions of the system	(W x H x L)
Power consumption	1,6W (power needed to actively levitate the cubic flotor and a handle attached to it).

Sources

[1] S.E. Salcudean, L. Stocco, "Isotropy and Actuator Optimization in Haptic Interface Design", IEEE Int. Conf. On Robotics & Automation, April 22-28, 2000.

[2] S.E. Salcudean, N.R. Parker, "6-DOF Desk-top Voice-Coil Joystick", 6th Annual Symposium on Haptic Interfaces for Virtual Environments and Teleoperation Systems, Intl. Mech. Eng. Congr. Exp., ASME, Winter Annual Meeting (Dallas, Texas), DSC-Vol. 61, pp. 131-138, Nov. 16-21, 1997

6.10 Mc Gill, Haptic Laboratories

6.10.1 STReSS (UNEXE)

Device description by : UNEXE on 21/12/2004.

General Description of the device

This sheet describes a tactile display system, which was designed to produce “tactile movies”, i.e. rapid sequences of tactile images refreshed at a rate of up to 700 Hz. The display uses an array of one hundred laterally moving skin contactors designed to create a time-varying programmable strain field at the skin surface. The density of the array is of one contactor per millimeter square, resulting in a device with high spatial and temporal resolution.
The motivation behind the construction of this device came from Vincent Hayward's idea that lateral skin stretch is sufficient to give the impression of skin indentation.
The device is constructed from ten piezoelectric combs, each cut to form ten tooth-like actuators, which are packed one next to another to form a matrix with one mm pitch in both directions. In the figure below four actuators are shown with an exaggerated displacement. The upper side is in contact with the skin.

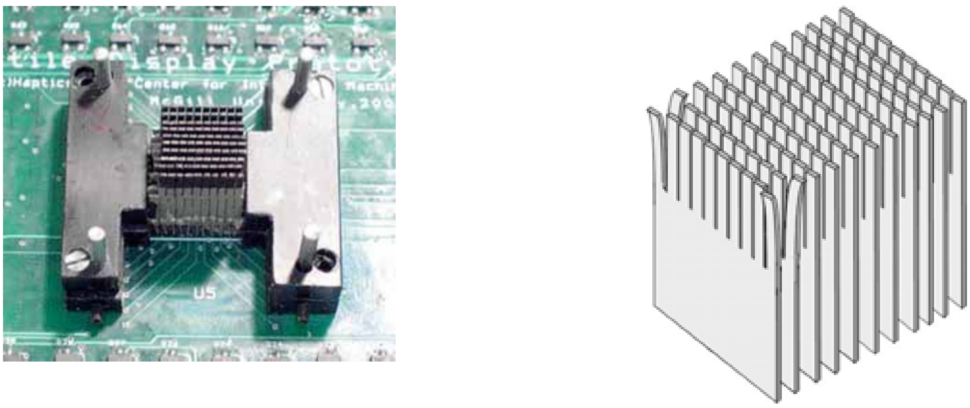


Figure 6.25 Stress device

This device is a research prototype which is too early in development for commercial applications.
Technological Innovations
One of the major headaches encountered when implementing high density tactile displays is the large number of parallel signals. The actual computational load tends to be low, but a lot of information needs to be moved around in a timely fashion. The McGill group have overcome part of this bottleneck by using an external FPGA chip to buffer the display frames.
The large number of parallel channels in a tactile display has usually led to very large and complex drive electronics. Use of MEMs driverchips has made the STReSS devices very compact and power efficient.
The next generation of the device will feature a curved surface. This is an attempt to mimnimise signal to noise ratio caused by the uneven contact pressure of the fingertip on a flat display.

Technical points

Mechanism

Size of workspace	Fingertip display
Geometry of workspace	10mm _ 10mm square
Spatial reference	Fingertip
Number of degrees of freedom	100 independent actuators
Isotropy of workspace configuration or not, in terms of accessibility	N/A

Characterization of the system in a passive state	N/A
Special effects coming from the morphology (such as non isotropic inertia).	N/A
Type, material and other characteristics of joints (if any)	N/A
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	N/A

Actuation

Technology of Actuators

Physical principle	Piezo electric
Specific technologies for the above category	Bimorph bending elements
Type of Commutation system (if any)	N/A
Gear or low-level mechanisms (if any).	N/A

Power driver system

Technology of the power modulator	audio-type amplifiers (80Vpp)
Low level control loop	

Functional Characteristics of the Actuation system

Bandwidth	**700 Hz**
Stroke / Motion range	25 µm max

Tactile Component

Number and geometry of contactors	100 elements (0.8×0.4mm) in 1mm spaced square grid
Area stimulated	$1cm^2$
Stimulation method	Lateral stretching of skin surface
Parameters under hardware/software control	

Other properties

Price	N/A
Whole dimensions of the system	150 × 150 × 50 mm (stimulator array + drive electronics)

Subjective evaluation for STReSS

PERCRO

Applications

This device is able to simulate small shapes and textures on one direction. Its most suitable application is the realization of a Braille display. There is an extension project in which a bi-directional actuator will be realized. In that case the applications will be more general: such as a common tactile display.

Test

Unfortunately this device was not more used so it was not tested. The principle of working is valid but this device is unable to exert enough amount of force to give the correct skin stimulation.

UNEXE

The STReSS device is an interesting technological proof-of-principle, but it has insufficient output to be a useful display.

CEIT

The user touches softly the array by one side and when the test starts, the user can feel different patterns: saw tooth, sine waves, etc.

My opinion is that it is hard to distinguish among the different patterns. That is to say, I didn't manage to feel, by touching, if the sensed pattern was a sine wave, or a random pattern, or anything else. But I would rather consider the opinion from visual impaired people, because their touch sense is more developed.

After testing the device during several minutes, the user feels a little degradation of touch sense in the finger used to test the device.

When the system is being tested, the shape/pattern perception depends on the relative position of the fingerprints. The optimum is got when the trails of the finger tip are perpendicular to the actuators' movement.

DLR

The very positive feature of this work is that the device delivers a good test bed for the basic studies related to the physiology of the skin stimulation done in this laboratory.

http://www.cim.mcgill.ca/~jay/index_files/research.htm

The representation is very accurate and the displayed sharp edges could be very good distinguished. But the subjective impression about the Braille display was in my case very neutral, because of the lack of experience with this kind of representation.

Sources

[1]Pasquero, J., Levesque, V., Hayward V., Legault, M. 2004. Display of Virtual Braille Dots by Lateral Skin Deformation: A Pilot Study. Proc. Eurohaptics 2004. Munich, Germany, June 5-7. pp.96-103.

[2]Levesque, V., Hayward, V. 2003. Experimental Evidence of Lateral Skin Strain During Tactile Exploration. Proc. Eurohaptics 2003. pp. 261-275.

[3]C. Pasquero, J., Hayward, V. 2003. STReSS: A Practical Tactile Display System with One Millimeter Spatial Resolution and 700 Hz Refresh Rate. Proc. Eurohaptics 2003. pp. 94-110.

[4]Hayward, V. 2004. Display of Haptic Shape at Different Scales. (Keynote Paper) Proc. Eurohaptics 2004. Munich, Germany, June 5-7. pp. 20-27.

[5] V. Hayward, "Survey of Haptic Interface Research at McGill University", Proceedings of Workshop on Advances in Interactive Multimodal Telepresence Systems, march 2001, Munich, Germany, Hieronymus Buchse productions GmbH

6.10.2 VBD (Virtual Braille Display)

Device description by : UNEXE on 21/12/2004.

General Description of the device

When a progressive wave of localized deformations occurs tangentially on the fingerpad skin, one typically experiences the illusion of a small object sliding on it. This effect was investigated because of its potential application to the display of Braille. The device described here was constructed tin order to produce such deformation patterns along a line.

The device comprised a tactile display mounted on a frictionless slider moving laterally. The display had 12 piezoelectric benders, 0.38mm thick, sandwiched at their base between 0.5mm thick neoprene spacers. The corners of the blades were beveled to create a linear array of skin contactors with spatial period of 0.88mm, each providing a contact area of about 0.2 mm^2.

When activated, the benders caused longitudinal deformations to the fingertip skin. When unloaded the actuator tips deflected by approximately ±0.5 mm. The position of the slider was measured by optical encoder with a resolution of 17 μm. Interfacing electronics was constructed to permit the refresh of the 12 actuators at 500 Hz according to patterns programmed on a personal computer.

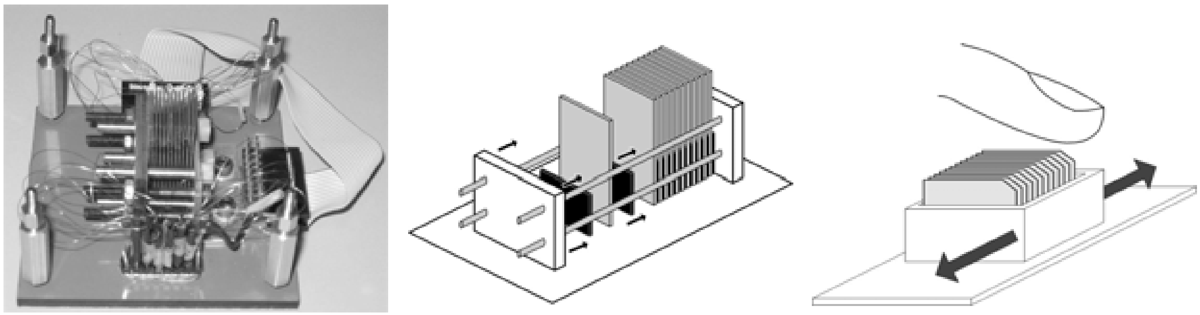


Figure 6.26 Virtual Braille Display

This device was a spin-off to the developement of the STReSS, carried out in conjuction with Visuaide Inc. a Montreal-based company specializing in products for the visually impaired.
Initial results suggest that reading Braille with devices based on the principle of the VBD is possible with a high legibility rate.

Technical points

Mechanism

Size of workspace	100mm in 1D
Geometry of workspace	1D slider
Spatial reference	Fingertip
Number of degrees of freedom	independent actuators

Signal Processing

Type of local treatments, if any.	No feedback mechanism

Actuation

Technology of Actuators

Physical principle	Piezo electric
Specific technologies for the above category	Bimorph bending elements
Type of Commutation system (if any)	N/A
Gear or low-level mechanisms (if any).	N/A

Power driver system

Technology of the power modulator	audio-type amplifiers (80Vpp)

Functional Characteristics of the Actuation system

Bandwidth	500Hz
Stroke / Motion range	0.5 mm

Tactile Component

Number and geometry of contactors	12 blades, bevelledinto a 1D line display
Area stimulated	Fingertip, or line across fingertip
Stimulation method	Lateral stretch of skin surface
Parameters under hardware/software control	Independent position control of each element

Subjective evaluation

PERCRO
This device was used for testing the effectiveness of the lateral skin deformation stimulation for the realization of a Braille display.

Feeling a small bump

The device simulates a fixed small bump that could be explored moving the slider. The feeling wasn't very realistic if the pushing force of the finger was light, but became more realistic as the force magnitude raised. The feeling became even more realistic if the finger was not in contact with all the surface of the display, but only with lateral edge.

Feeling a series of bump

The device simulates a series of bumps located at different distance from each other. The bump feeling was the same of the first test, but it was possible to evaluate the distance form one bump to another. This last feature is important to validate the possibility to use this device as a Braille display.

INPG

Simulation: a 1D signal (bumps, sinusoidal, squares) excites the blades laterally to grip or stress apart the skin of the finger. We move a lateral slider (sensor) in order to move the virtual topology.

Experience report -a

Property to target	Evaluation of the render of the bumps
Strategy planned	I will put my finger on the frame and move the slider
Result	Since I'm not supposed to move, I just can undergo the frame vibrating on my skin. The feeling is quite uncomfortable and itchy, like an insect running on the skin, but not hurting. It gives the impression that something is moving right to left under my finger, while I move the slider. It's difficult to say whether it looks like a bump, a hole or a crack. The skin becomes progressively insensitive after 30 seconds or 1 minute of use, which may not happen for blind people who use to use their tactile feeling.
Modification of the strategy	I try to modify the pressure on the frame to feel if the effect changes.
Result	The effect is more clear while pressing harder on the blades frame, but still present at light pressure.
Modification of the strategy	As recommended, I put my finger on the edge of the blades square
Result	The feeling is more clear than on the surface of the frame, probably because the phenomenon interacts more locally with the skin, and is not dissipated through all the surface of the finger tip.
Experience report	The feeling is uncomfortable but regular and reproduceable. The feeling is the same than crossing a crack with the finger, at a high velocity and with a low pressure. At a low speed, the feeling is difficult to understand.

Experience report -b

Property to target	Evaluation of the effect of frequency on the bumps serie. The bumps are very close to eachother.
Strategy planned	I will put my finger on the frame and move the slider, trying to feel the difference with the previous experiment.
Result	As the frequency is higher than before, I perceive some slight differences. It's something like strokes or noise, that makes me impossible to feel the bumps clearly.
Modification of the strategy	I try to move the slider at a different speed
Result	Now it makes quite no difference between moving the slider at low or high speed.
Experience report	Raising up the frequency makes the things difficult to feel, just like a friction on a thorn-bush surface.

Experience report -c

Property to target	Identify the changes using a square-shaped bumps row (instead of round bumps)
Strategy planned	I will put my finger on the frame and move the slider, trying to feel the difference with the first experiment.
Result	The result is a bit similar to the raise of the frequency, except that the noise repartition is not uniform. I feel alternatively strokes and smooth very short area.
Modification of the strategy	I will change the speed of the slider.
Result	It does not make much different. The feeling is more confuse.
Experience report	I feel the rendering is different than in the case of sinusoidal bumps, but I can not really match this feeling with any real impression. I do not use my sense of touch so often in everyday life. After a few seconds, my finger tip turns insensitive.

Experimenter report on the system.

Global strategy followed.: I tried to feel the little difference when changing the exciting signal and to match it with an experienced feeling:

-Evaluation of the render of the bumps:

The feeling is uncomfortable but regular and reproduceable. The feeling is the same than crossing a crack with the finger, at a high velocity and with a low pressure. At a low speed, the feeling is difficult to understand.

- Evaluation of the effect of frequency on the bumps serie.

The bumps are very close to eachother

Raising up the frequency makes the things difficult to feel, just like a friction on a thorn-bush surface.

- Identify the changes using a square-shaped bumps row (instead of round bumps)

I feel the rendering is different than in the case of sinusoidal bumps, but I can not really match this feeling with any real impression. I do not use my sense of touch so often in everyday life. After a few seconds, my finger tip turns insensitive.

General opinion on the system

As said for the Microtactus evaluation, the use of this device for a general purpose does not appear obvious. It is quite clear for me now that I never use my sense of touch so frequently and repeatly than in these tactile experiments. These experiments are interesting and should be compared with an active device such as the roughness rendering with the Pantograph. However the device has a good efficiency for its purpose, and it could be improved by designing small blades, higher force and smaller displacement of each blade, in order to get a very accurate feedback.

UNEXE

The VBD produces very believable bumps, particularly when just the edge of the display is touched. The realism is further improved with the addition of a pink-noise at edges of the “dot”. An interesting side effect of the lateral-stretch approach is the introduction of directional ansitropy into the perception of the shape, i.e. The dot feels different when the finger is placed on the display along the direction of motion or at 90° to the motion. This system demonstrates that lateral stretching of the skin can create an effective illusion of an indentation.

Sources

[1] http://www.cim.mcgill.ca/~haptic/devices.html

[2] http://www.cim.mcgill.ca/~haptic/pub/JP-VL-VH-ML-EH-04.pdf

[3] J. Pasquero, V. Levesque, V. Hayward, M. Legault, « Display of Virtual Braille Dots by Lateral Skin Deformation : A Pilot Study », Proceedings of Eurohaptics2004, pp. 96-103, Munich, Germany, June 5-7, 2004

6.10.3 Pantograph

General description of the device

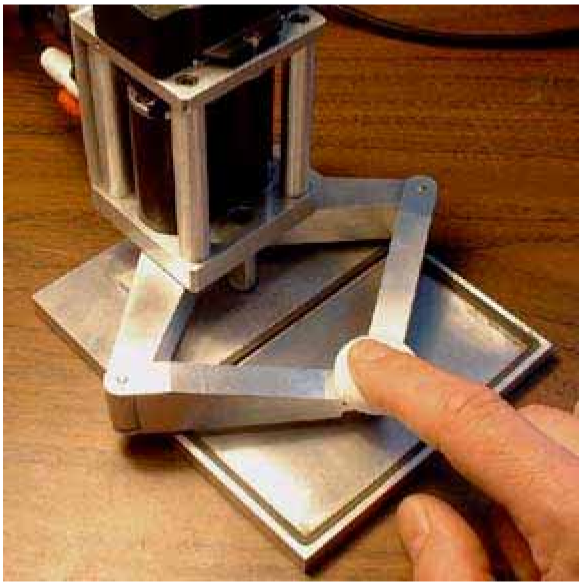


Figure 6.27 McGill Pantograph

This device is a planar 2DOF haptic interface for one finger. It is a simple 5 bar mechanism actuated at the base with two DC motors. The most relevant features are the very low friction and inertia obtained due to light weight aluminum structures. The bandwidth of the force response is very large (up to 400hz).

Subjective evaluation

PERCRO

Applications

This device is used for simulating small bump using the haptic illusion of lateral force. Its application could be as aid of visually handicapped persons. The particular feature of this haptic device was that the control is unstable until the finger is in contact with the plate.

Test

Moving in free space

The device was testes while the motors were switched off. The friction and inertia forces were almost not perceivable when the finger was far from the motor axis, but the inertia force raise as the finger get closer them. Anyway, with low acceleration the feeling was almost as moving on an oiled surface. The design of this device was very well optimized.

Feeling bump series

This test is done to show how the high frequency capabilities of this device can simulate a series of bump very close to each others (almost 1mm). The feeling of the bumps in fact was very clear also if the finger was moving quite fast.

Comparison with Phantom

The same bump series was tested with a Phantom® haptic device. In this case the bumps were perceivable only if the speed of the finger was very low, because of its smaller bandwidth.

INPG

Experience report a

The exploration occurs on the wall on the left area of the surface.

Property to target	Evaluation of the render of the roughness.
Strategy planned	I will find the wall contact and evaluate its stiffness by a normal direction into it.
Result	The contact is precise and rather sharp. The stiffness is rather high for a one-finger movement. However it is still possible to penetrate in the wall if I apply a high force.
Modification of the strategy	I will now try to explore the stability of the contact while pressing on this wall.
Result	Whatever the force applied, the contact remains stable and I cannot feel any significant noise. As I am sliding aside, I get the feeling of the roughness.
Modification of the strategy	I will slide along the wall and focus now on this roughness, in a slow motion.
Result	The roughness is very clear, even if the space between the bumps appears to be very small. I don't feel any oscillation besides the bumps, the rendering is very sharp.
Modification of the strategy	I will increase the speed of my finger along the wall to check if I can perceive some differences.
Result	The rendering of the bumps remains very clear, the trajectory is straight and the feeling is itchy, similarly than with the VBD.
Experience report	My first impression is that the precision of this haptic device is quite remarkable. The area of exploration is well corresponding to a finger if we don't move the forearm. The force feedback is much sufficient for a finger movement. The rendering is very comfortable and fair. As I moved in the free space, I felt the device is very low inertia and the feeling is very clean, such as a iced surface. The contact with the wall is very sharp and the bumps can be felt very well, even at high speed.

Experience report b

The exploration occurs on the wall on the right area of the surface, which is at the limit of the stability.

Property to target	Evaluation of the render of the roughness.
Strategy planned	I will find the wall contact and evaluate its stiffness by a normal direction into it.
Result	The contact is very unstable. I cannot evaluate the stiffness since a stronger pressure on the wall induces larger instable oscillations.
Modification of the strategy	I try to test if the instabilities appear uniformly along the wall.
Result	As I move, I feel the apparition of instabilities occur along a straight line and they seem to be uniform.
Modification of the strategy	I will stay on a fixed point and try to analyse the vibrations of the contact.
Result	The instability seems to be divergent with high amplitude since it is difficult to keep the finger on the same point without being rejected and bounced out. Besides this instability is low frequency. Pressing more on the wall, it appears higher frequency instabilities, as the low frequency instability is damped.
Experience report	The model is here set up in order to get instabilities. I notice we can find high or lower frequencies according the intensity of the pressure on the wall. The behaviour is reproducible along the wall.

Experience report c

The exploration occurs on the lower 2D wall in the 3D space.

Property to target	Evaluation of the render of the roughness.
Strategy planned	I will find the wall contact and evaluate its stiffness by a normal direction into it.
Result	Since the movement occurs in a 3D space and the tool is not a fingerplate but a handled pencil, we cannot fully compare the rendering with the Pantograph.

	However there is some similarities. I can follow and side along the 2D surface wall (instead of a 1D wall). The bound of the contact is well defined but the stiffness of the wall is lower than using the Pantograph, moreover if we consider that it is an end-effector adapted to the hand, instead of the finger.
Modification of the strategy	I will move along the surface and perpendicular to the rails to feel the bumps and the quality of the roughness.
Result	I feel the bumps like some rails in a corrugated roof surface. At a low speed, the rendering is rather good and it is stable. My feeling is that the wavelength is larger than the one of the Pantograph model.
Modification of the strategy	I will increase the speed of my finger along the wall to check if I can perceive some differences.
Result	The feeling of the bumps disappears as I am increasing the speed of my movement along the wall. At higher speed, the surface becomes flat and slippery.
Experience report	The rendering is not so accurate than using the Pantograph. This may be due to the model or to the Phantom it self. Using the Phantom, we cannot perceive any instabilities as in the second model of the Pantograph.

Experimenter report

Global strategy followed.

I tried to feel the differences in the roughness accuracy and in the origins of instabilities:

- Evaluation of the render of the roughness on a 1st model, using Pantograph

My first impression is that the precision of this haptic device is quite remarkable. The area of exploration is well corresponding to a finger if we don't move the forearm. The force feedback is much sufficient for a finger movement. The rendering is very comfortable and fair. As I moved in the free space, I felt the device is very low inertia and the feeling is very clean, such as a iced surface. The contact with the wall is very sharp and the bumps can be felt very well, even at high speed.

- Evaluation of the render of the roughness on a 2nd model, using Pantograph

The model is here set up in order to get instabilities. I notice we can find high or lower frequencies according the intensity of the pressure on the wall. The behaviour is reproducible along the wall.

- Evaluation of the render of the roughness of these 2 models using Phantom

The rendering is not so accurate than using the Pantograph. This may be due to the model or to the Phantom itself. Using the Phantom, we cannot perceive any instabilities as in the second model of the Pantograph.

The first model was a wall with a very accurate roughness (maybe less than 1 mm). The feeling of this roughness is very clear using the Pantograph. However the Phantom didn't render this roughness very well, particularly at high speed, the bumps faded out. The second model was a wall with an average roughness (2 to 10 mm) and whose parameters were set in order to give instabilities at high frequency. In this case, the Pantograph transmitted these instabilities and turned out of control. However the Phantom remained very stable with this model, which shows its inability to follow such high frequencies. In this case, the Phantom acted like a low-pass filter and cut out the instabilities. If we want to transmit a signal in the same bandwidth than this phenomenon or any accurate behaviour, we will not be able to do it using a Phantom, and the Pantograph will give a better rendering of such phenomena.

General opinion on the system

Even without relating to the IIc (Phantom) experiment, my general feeling is that the Pantograph is a very good device, with high accuracy and bandwidth, compared with a large range of haptic devices. One of its limitations is the number of degrees of freedom: movements on 2D surface using one fingertip. The comparison with the Phantom is limited by the difference in morphology (2D instead of 3D) but still interesting to perform. I saw some so-called "realistic" complex phenomena in a useless 3D scene, which would gain to be simplified into a 2D scene (for a comfortable interaction) and perform with a Pantograph.

CEIT

The user touches softly the pantograph endpoint. The first impression is its workspace only allows short hand movements (just a few centimeters). It could be suitable for index-finger movements but not for arm movements.

The 1st evaluation test is the free-movement test: The inertia and the frictions were almost negligible. The virtual wall contact was stiff but sometimes unstable (the device requires a finest tuning). The texture feeling was really good (high bandwidth).

No corner test was completed.

An accelerometer is used to force measurement so the system is noise-sensitive.

The control loop is executed at 10 kHz under RT-Linux.

DLR

The impression without actuated motors is of a very good free movement without friction or backlash and no inertia can be felled. The represented textures are very good but in the classic impedance control scheme the device gets very quick unstable. When the proportional term of the control loop is adapted by using a pressure sensor, the performance improves significantly.

Sources

[1] C. Ramstein, V. Hayward, “The PANTOGRAPH: a Large Workspace Haptic Device for a Multi-Modal Human-Computer Interaction”, Conference Companion, CHI’94, Boston, Massachussetts, April 24-28, 1994, pp. 57-58

6.10.4 Morpheotron

General description of the device

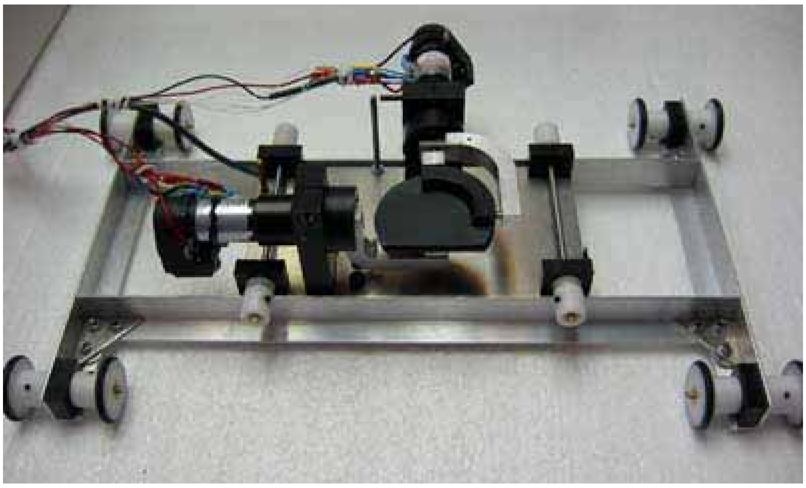


Figure 6.28 Morphetron (Haptic laboratories,McGill)

The Morpheotron is a 2-DOF spherical mechanism. It works by rolling a plate around a center of rotation that is located inside of the operators fingerpad, generating local deformation caused by the movement of the contact area respect to the finger. This has been shown to result in a strong sensation of experiencing shape with large curvature. The Morpheotron is mounted on top of a lightweight gantry allowing it to be rolled on a table under the control of the operator along the x and y directions thereby providing an additional two translating degrees of freedom.

Subjective evaluation

PERCRO

Simulation of concave surface

A concave surface of curvature radius of dozen of centimeters was simulated. The virtual object was fixed and the user can explore by moving the 2DOF sliders. The feeling of the surface is very realistic. The 2DOF slider could be more reliable in fact there are some problem of position evaluation caused by error buildup and sliding of wheels.

INPG

Description of the experimental configuration

Principle: The finger is fixed on the device plate. When moving the gantry, the 2D position is captured by a mouse light sensor and sent to the computer. The model sends back the 2D orientation slope of the plate, actuated by 2 servo-motors. - OS: Linux ? - No visualisation - Sampling rate = 1kHz - Resolution of the servo-motors: 100 counts - Some limitations: Motors backlash, friction caused by gantry (to be replaced by a elevator fingerpad in the future), friction caused by the wires (may be replaced with wireless system but problem of battery weight)

Description of the test(s) proposed for the evaluation:

Simulation of the interaction with a topologic surface which represents a bump (convex) or a hole (concave). Set of parameters for this mock-up not given.

Experience report - a

Property to target	Free space motion behaviour.
Strategy planned	I put my finger (lower side, opposite to the nail) on the plate, I close my eyes not to be influenced by the device appearance, I will move in the free space along straight movements in 2D.
Result	I feel the reaction area over the virtual bump, so I try to stay in the free plane area on the side. I feel the inertia of the rolling gantry but it's quite light. The feeling is the same than touching a ice-cube surface wearing a glove: the viscosity is very light, I have no tactile feedback. There is no friction forces. Sometimes I feel some unstable strokes, apparently due to a shortcut or poor contact in the connection cables, I disregard it and focus on the surface. The surface is isotropic in X and Y.
Modification of the strategy	I will try to modify the pressure of my finger on the plate to check the vertical resistance and to try to perceive any lateral friction.
Result	The surface touches hard and stable (as far as I dare to press). However, the more I press, the more I feel some lateral reaction. This reaction is not friction (white noise) and not instabilities (strokes). It's like very small bumps on the surface, something about 2 or 4 mm of diameter, maybe less. The more I press, the more they appear clearly. The speed and acceleration does not change anything on the feeling. If I go very slow, I don't feel the small bumps anymore.
Experience report	The free space motion in 2D seems not to be limited as long as the table which supports the device is large. The inertia and the viscosity are light, the render is very isotropic in the 2 directions. If we press hard and with a certain speed, we can detect a kind of small bumps.

Experience report -b

Property to target	Exploring an object: contact with the virtual bump
Strategy planned	I will move forward and backward, then left and right to feel the reaction of the plate and try to identify the bump.
Result	When I move from side to side, I cross an area which gives me the impression of a wave or a bump. At first try, I really can't say whether it is a concave or convex topology. Besides, my lateral movement is not deviated by the shape and get

	straight, which is not the natural geodesic path for a bump. Slowing my movement I feel a positive slope (from the place the plate touches my finger, not from any force) and then a negative slope, which let me think about a bump topology. The feeling is isotropic in X and Y, showing a central symmetry shape.
Modification of the strategy	From this exploration, I will try to follow some guidance on the surface. I still keep my finger vertical, touching the plate.
Result	Moving around, I feel no force guidance, I have to rely on the feeling of the orientation of the plate (whether the plate touches the right side of my finger or the left side of my finger). I'm able to follow the circular contour of the bump shape (about 6 or 10 centimeters of diameter), rolling around it, according to the feeling of slope orientation. It's not so easy, since as soon as I press a little laterally, the slope will change. However, I can press very hardly on the vertical direction, the slope barely changes. On the real world, when I press on a ice-cube surface, if there is a bump on the surface, I will slide aside of it, which is not the case with this bump. I can easily stay upon it. Moving laterally, the bump do not stop or deviate my movement, I simply go over it. Since I feel no elasticity, no lateral or vertical force variations, it's not simple to perform a natural gesture with this shape.
Modification of the strategy	I will now change the position of my finger and try to keep it stuck on the plate, parallel to the plate whatever the slope.
Result	The impression is very vague, I still can feel the reaction of the model but less intense.
Experience report	I can't determine if it is a bump or not. I just can say that the plate reacts on my finger and its slope changes. I can say there is a central symmetry in this model. I feel difficult to interact with this object, since I have no force feedback. I can't slide up, I can't slide down, I just slide uniformally on the lateral directions. I guess I could say if the bump is high or not, from the slope rate, but I wouldn't have more effort to give to cross a high or a low bump.

Experience report –c

Property to target	Exploring an object: contact with the virtual hole
Strategy planned	I will move forward and backward, then left and right to feel the reaction of the plate and try to identify the hole.
Result	At the first try, I have not a different feeling from the bump before. It's still a cntral symmetry shape. Moving at average speed, I can detect the hole, from the deflection of the slope during the movement. Actually, I would say I can best differentiate the bump from the hole at average speed: if too fast, I can't say because I don't have time to assess the slope variations, and if too slow, I can't get the feeling of a global shape.
Modification of the strategy	From this exploration, I will try to follow some guidance on the surface. I still keep my finger vertical, touching the plate.
Result	Here again, the remarks than for the bump. On the real world, when I press on a ice-cube surface, if there is a hole on the surface, I will slide inside, I will oscillate up and down inside the hole and I will find a stable position at the bottom. Trying this experiment with the virtual hole, I can't reproduce it. I stay on the X,Y position as long as I don't decide to move laterally, no force pushes me aside.
Modification of the strategy	I will now change the position of my finger and try to keep it stuck on the plate, parallel to the plate whatever the slope.
Result	Same remarks than for the bump.
Experience report	This hole is not a better hole than the bump was a good bump. I feel a reshaping of my finger while moving, but no force feedback, so I can't feel, for instance, the lateral resistance of a topology. I have a reaction to the displacement, a tactile impression, but I couldn't link this feedback with any dynamic metaphor.

Experience report -d

Property to target	Trying the so-called "semi-active mode"
Strategy planned	Moving the mouse left-right and then forward-backward with the left hand, while holding a right-hand finger fixed on the plate.
Result	I have the same feeling than before, the plate is rolling around my finger. I have the same partial illusion of a hole. I notice that the little bumps on the surface are much more difficult to feel than before.
Modification of the strategy	I try to follow the circular path around the hole, to see if I can do it as easily as on the first experiment.
Result	As far as I'm dexterous with my left hand, I feel no special difficult to control the movement and follow a circular guidance of the hole.
Experience report	This experiment is very interesting because it shows that in this case, the action and the feeling can be completely separated with a few trouble. Since there is no exchange of energy between the finger and the virtual scene during the manipulation, it is not a problem to separate action and perception.

Experimenter report on the system.

Global strategy followed.

I mostly try to figure out the feeling of presence of the bump or hole during the exploration of the surface, as well as the free motion:

- Free space motion behaviour

The motion in 2D space can be done at a very large scale. The system is very light and easy to manipulate. The rendering is isotropic in X and Y. There is a kind of small bumps on the surface when pressing hard.

- Exploring an object: contact with the bump and the hole

I can't say it behaves like a real bump. I just can say that the plate reacts on my finger and its slope changes, so it looks like a bump. I feel difficult to interact with this object, since I have no force feedback. I can't slide up, I can't slide down, I just slide uniformally on the lateral directions. From the slope rate, I could say if the bump is high or not, but I wouldn't have more effort to give to cross a high or a low bump. Same remarks for the hole, I feel a reshaping of my finger while moving, but I can't feel, for instance, the lateral resistance of a topology. I have a reaction to the displacement, a tactile impression. Basically, I don't feel in direct contact with the surface, I don't even feel the same as if I followed the contour of a real topology with a very light pressure, keeping my finger vertically and looking at the hole shape to predict my future pressure to apply. We are not directly in contact with the virtual object, but we have a kind of plate in between, which follow our finger and roll on the surface.

- Separating action/perception: feel of the surface moved by the other hand

This experiment is very interesting because it shows that in this case, the action and the feeling can be completely separated with a few trouble. Since there is no exchange of energy between the finger and the virtual scene during the manipulation, it is not a problem to separate action and perception.

General opinion on the system

My opinion is that this kind of device is closer to a tactile device than a kinesthetic device. We can model mostly smooth shapes (sphere, concave/convex shape) but because of the plate, it would be difficult to simulate a corner or cubic surface. Since there is no force interaction between the finger and the virtual surface, we can't modelize any stiffness of the surface but only the geometrical topology. We can't interact with the model. This is a particularity of tactile display and passive interfaces, the illusion conveyed by the model doesn't bring much information than visual. This kind of device can be great for specific applications which requires topology to be felt by the touch (eg. blind people), or to analyse behavioural differences on the same model using an interactive haptic interface.

UNEXE

Appraisal

The demonstration was intended to represent a large concave feature in a flat plane. The device was found to be good at suggesting gross curvature, giving a very believable sensation of shape. The crude platform and tracking did lead to errors, but the idea seems to be sound.

Techological Innovations

This is a simple but very effective demonstration of the imporatnce of perceived curavture, and an innovative solution to the problem. Could it be combined with other technologies?

DLR

Moving without X-Y axes test results

In this configuration the rotational DOF (spherical mechanism) allow the representation of physical surface shapes (plane areas, convex, concave structures). The representation mode is very intuitive and sensitive. There where disturbances perceptible caused by the cabling (is moved in every configuration, but could be avoided with a good cord grip) which had some contact problems and also by the low sensitivity of the position sensors (encoders with 512 lines per revolution). This sensor deteriorates the good performance which could be achieved with the implemented motor solution (maxon brushed DC motors).

Sources

[1] H. Dostmohamed, V. Hayward, "Contact Location Trajectory on the Fingertip as a Sufficient Requisite for Illusory Perception of Haptic Shape and Effect of Multiple Contacts", Preprint Workshop on Multi-point Interaction in Robotics and Virtual Reality, F. Barbagli, F. Prattichizzo, D. Salisbury, J.K., IEEE Int. Conf. Robotics and Automation, New Orleans, USA

6.10.5 MicroTactus

General description of the device

The aim of this device is to improve the sense of touch of a surgeon holding an instrument during tissue examination. The objective is to amplify the mechanical signal generated during the exploration by the end tip of the instrument (a probe) and the surface of tissue. The design is very simple there is an accelerometer that measure the acceleration of the tip and a voice coil actuator that generates a vibrating signal on the user hand. There are two other version of this instrument: one where the actuator is located away, on another pen like device (it is hold in the other user hand); in the third version the actuator is replaced with a speaker that generates audio signals.

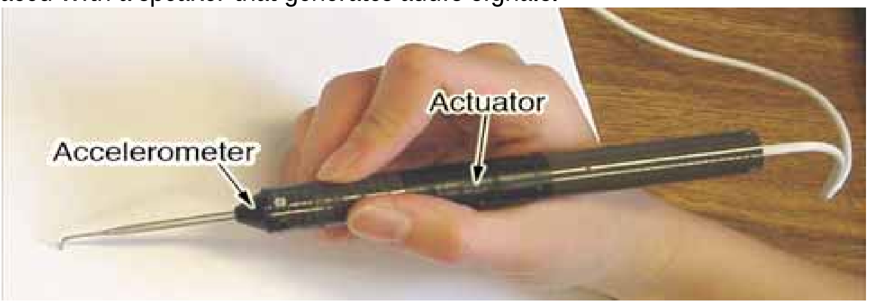


Figure 6.29 MicroTactus

Subjective evaluation

PERCRO
Minimally invasive Surgery

<u>Test</u>

The three configuration were tested.

No feedback

At the beginning the instrument was tested when the actuator was switched off. It was possible to verify that the tactile sensation of rugosity and stiffness of the surfaces were very hardly noticeable.
The first test was done on an hard and smooth surface (table): it was possible only to feel a very small vibration .
The second test was done on a spunge: it was possible to feel a sort of sticking and sliping of the instrument.
A relevant test was to try to feel a small cut made in a nubby material: that was almost impossible to detect.

First version (voice coil on the probe)

The same tests were made for the actuated probe.
The exploration of hard surfaces generates a sort of instability in the system and led it into a continuous mono frequency oscillation. Probably the acceleration sensor is too close to the actuator and it close a positive feedback loop.
On the soft tissue (spunge and rubber) it worked fine. The vibration generated during the interaction with these tissues has a lower frequency content and the damping of contact is higher, so the instrument was stable. The feeling was really improved, in particular the user is able to detect small cut applied on the spugne surface.

Second version (voice coil in the other user hand)

In this case the instability don't appear (in fact there is no mechanical coupling between the actuator and the acceleration sensor). Exploring hard surfaces the feeling was a high frequency vibration. If the tip hit the surface, it was possible to feel a very sparkly the cue (the voice coil has a very large bandwidth so it able to reproduce signals with high frequency content like an impulse).
The results obtained in the two following tests were very similar to the first version

Third version (sound feedback)

In this version the tactile feedback was substituted by the audio feedback. The signal acquired by the acceleration sensor was amplified and sent to a common loudspeaker. The user can identify the quality of the surface (rigid, wrinkle, discontinuity and cut) by the generated sounds. High stiffness materials crate high frequency sounds, nubby materials create low frequency sounds and sparkling noise. In this configuration it was not so easy to detect the cut in the spunge.

INPG

Description of the experimental configuration

- OS: No computer, just a DSP control (portable instrument). - No visualisation - Sonofication from the friction signal (highspeaker output) - DSP: Conversion 16/32 bits, Audio codec 48kHz - Signal amplification: audio amplifier - Some limitations: Resonance instabilities in the feedback, difficulty to insert a sensor built-in the small tool at the end of the probe.

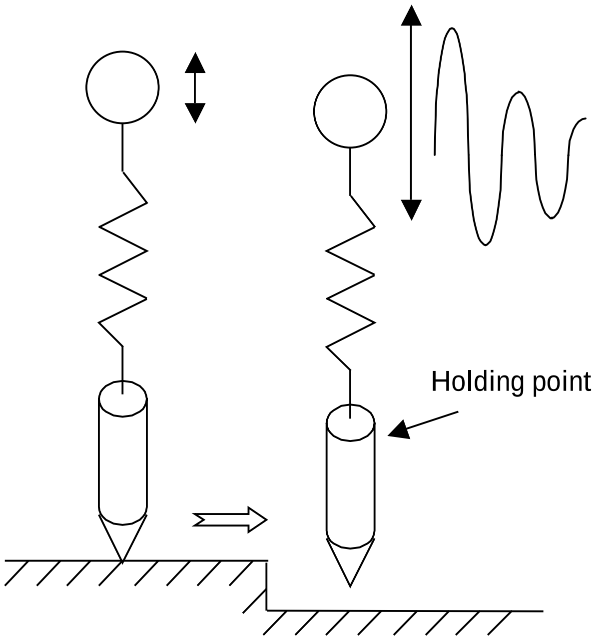
Description of the test(s) proposed for the evaluation:
No simulation.
Vibro-tactile feedback amplification for assistance to real friction gesture.

Experience report –a

Property to target	Behaviour on a isotropic matter (piece of plastic foam).
Strategy planned	I will make some uniform scratch movement with the probe on the foam at a constant speed.
Result	I feel some smooth vibrations in the handle. The vibrations are rather high frequencies and very light. I'm not sure whether I handle the tool in the correct way, because I can't intuitively feel that this vibration would correspond to the matter I'm scratching. Or maybe I just feel some noise and not the effective signal.
Modification of the strategy	I will change the speed of my movement.
Result	At some certain speeds, a resonance phenomenon occurs and masks the normal vibration by high amplitude oscillations (demolition hammer effect). It seems to depend on the speed and on the pressure applied on the surface. I still can understand the feedback.
Experience report	I'm not sure to have felt what it has to be felt. I couldn't correlate the vibration feeling with what I expected, maybe because this manipulation (scratching probe and palm vibration feedback) is not very natural for me. I don't know where the resonance comes from. It may be a coupling between elements of the probe or due to the active feedback element.

Experience report -b

Property to target	Behaviour on a non-isotropic matter (piece of plastic foam with a crack).
Strategy planned	I will make some uniform scratch movement with the probe on the foam at a constant speed, going over the crack.
Result	When I go over the crack, the end of the probe suddenly jump from a side to another. I feel a high amplitude oscillation which get damped in about 1 second.
Modification of the strategy	I will get across the crack with a different speed and a different pressure.

Result	The oscillation doesn't change that much when changing the speed. However, the more I press on the surface, the more the amplitude of the oscillation increases.
Experience report	The global feeling is that I hold a pen with an oscillator attached to it. When I am scratching the uniform surface, the oscillator is excited but damped. At a certain speed, the excitation frequency reaches a threshold and there is a resonance of the oscillator. When I go over the crack, I feel just like a response of an oscillator to a step. The oscillation is high, then damped. It doesn't bring the feeling that I'm touching a crack, but the feeling that I go over an asperity of the surface. I can't deduce the geometrical shape of the crack. However, I can detect the presence of an asperity, which was quite impossible to find without the vibrotactile feedback. 

Experience report -c

Property to target	Using sound to vibrotactile feedback of the probe
Strategy planned	I will make some uniform scratch movement with the probe on the foam at a constant speed.
Result	I have the same vibrotactile feeling than before. Besides, I can hear the sound of the surface when I move. This sound is very real, just like if there were a microphone plugged on the surface. I feel I get much more information from this signal than from the vibrotactile feedback.
Modification of the strategy	I will go over the bump to check if I have oscillations in the sound feedback.
Result	While in contact, the sound is a scratch noise. Suddenly leaving the edge, there is a short dry sound, instantaneously damped, so with no oscillation. There is no sound until the probe touches the surface again. We can detect a very light white noise in the background, much less than in the vibrotactile feedback.
Modification of the strategy	I will test the probe on a hard and less rough surface (the desk table).
Result	Some differences in the vibrations but which don't make me feel the type of surface (maybe I'm not sensitive to vibrotactile signals ?). However the sound is pretty different from the foam sound and make me feel the different roughness of this surface.

Experience report	The audio feedback sounds very real and more convincing than the vibrotactile feedback. I guess the resonance and instabilities may come from the amplifier elements or the actuator itself.

Experimenter report on the system.

Experimental configuration(s): (ref to sheets)
Vibrotactile enhanced feedback from the end part in the handle of a probe tool. Sound feedback of the friction signal of the probe on the surface.

Synthesis on the experiences made
Global strategy followed.
I mostly try to feel a friction behaviour while I was scratching the real surface (piece of foam):
- *Behaviour on a isotropic matter (piece of plastic foam)*
I'm not sure to have felt what it has to be felt. I couldn't correlate the vibration feeling with what I expected, maybe because this manipulation (scratching probe and palm vibration feedback) is not very natural for me. I don't know where the resonance comes from. It may be a coupling between elements of the probe or due to the active feedback element.
- *Behaviour on a non-isotropic matter (piece of plastic foam with a crack)*
The global feeling is that I hold a pen with an oscillator attached to it. When I am scratching the uniform surface, the oscillator is excited but damped. At a certain speed, the excitation frequency reaches a threshold and there is a resonance of the oscillator. When I go over the crack, I feel just like a response of an oscillator to a step. The oscillation is high, then damped. It doesn't bring the feeling that I'm touching a crack, but the feeling that I go over an asperity of the surface. I can't deduce the geometrical shape of the crack.
- *Using sound to vibrotactile feedback of the probe*
The audio feedback sounds very real and more convincing than the vibrotactile feedback. I guess the resonance and instabilities may come from the amplifier elements or the actuator itself.

General opinion on the system
This device doesn't involved virtual reality. It would be interesting to add some augmented reality to enhance, compare, add virtual and real friction signals. The device enhances the feeling of scratching by vibrations and sound. These vibrations are not natural to me, but I guess this feedback can be improved and reach a good rendering. By the fact it's a vibrotactile device and it's a specific shape (probe tool), I can't compare or classify it easily among other haptic devices.

DLR
Due to the narrow bandwidth caused by the high amplifying of the acceleration sensor output, the device gets very quick stability problems, when used in hard contacts. In a pure haptic display mode the differences between textures are not very clear distinguishable. Scratches or edges in a texture can be distinguished but the amplitude of the devices movement doesn't match the sizes of the scratch forms (deepness and extension).
When the acoustic mode is combined with the haptic display the impression is much better and by this way more impressive and representative.

Sources

http://www.cim.mcgill.ca/~haptic/pub/HY-VH-RE-MICCAI-04.pdf
http://www.cim.mcgill.ca/~hyyao/utactus.pdf
http://www.cim.mcgill.ca/~hyyao/research.html

6.10.6 PENCAT

General description of the device

This device is a planar 2DOF haptic interface. It is hold by the user through a pen like End Effector. This was introduced on the market in 1998 (now no more available). The planar mechanism is a 5bar kinematics actuated trough two voice coil motors.

Figure 6.30 Pencat (Haptic laboratories, McGill)

Note (INPG): PenCat/Pro™ device was commercialized by Haptic Technologies, compagny bought later by Immersion Inc. This device received in 1998 the product of month NASA award [Hayward,01]. Price was 679US$ [2].
The "PenCat" devices have the following technical characteristics[2]:
Workspace: 125x75 mm;
Peak force: 10 N;
Position resolution: 1500 dpi;
AD/DA Conversion: 16 bit AD / 12 bit DA;
Embedded 25 MHz Intel 386 microprocessor;
Internal loop frequency: 800 Hz;
Connection to the PC: RS 232 - data transfer freq. 100 Hz;
Force calculation: Visco-elastic model.

Subjective evaluation

PERCRO

Applications

Virtual Reality, Interaction with windows like operative system, phsycophysics experiments etc...

Test

The device was tested only offline. The inertia and the friction was very low.

Sources

[Hayward,01] Hayward, V. 2001. Survey Of Haptic Interface Research At McGill University. Proc. Workshop on "Advances in Interactive Multimodal Telepresence Systems", March 2001, Munich, Germany (Invited Keynote). Hieronymus Buchreproduktions GmbH.
[2]http://recherche.ircam.fr/equipes/analyse-synthese/wanderle/Gestes/Externe/Ramstein.html

6.11 M.I.T. Touch Laboratory

6.11.1 Linear and Planar Graspers

Device description by: INPG on 14/01/2005

General description of the device

History: The Laboratory for Human and Machine Haptics, less formally known as the Touch Lab, at the Massachusetts Institute of Technology. The Touch Lab was founded by Dr. Mandayam A. Srinivasan in 1990.

Over the past few years, the laboratory activities concerned device hardware, interaction software and psychophysical experiments pertaining to haptic interactions with virtual environments. Two major devices for performing psychophysical experiments, the Linear and Planar Graspers, have been fitted with additional sensors for improved performance.

The Linear Grasper is now capable of simulating fundamental mechanical properties of objects such as compliance, viscosity and mass during haptic interactions.

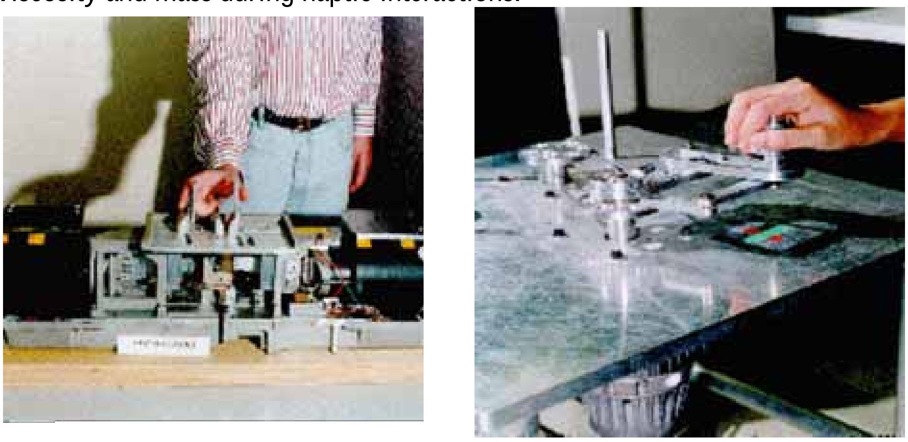


Figure 6.31 Linear and planar graspers

Virtual wall and corner software algorithms were developed for the Planar Grasper, in addition to the simulation of two springs within its workspace.

Sources

[1] http://touchlab.mit.edu/oldresearch/areas/hapticdevicedev/

[2] Srinivasan, M. A. (1994). Virtual Haptic Environments: Facts Behind the Fiction. Eighth Yale Workshop on Adaptive and Learning Systems, Center for Systems Science, Yale University, New Haven.

[3] Srinivasan, M. A. (1995). Haptic interfaces: hardware, software, and human performance. Proceedings of the workshop on human-computer interaction and virtual environments, Hampton, VA.

[4] LaMotte, R. H., M. A. Srinivasan, C. Lu, P. S. Khalsa and R. M. Friedman (1998). "Raised object on a planar surface stroked across the fingerpad: Responses of cutaneous mechanoreceptors to shape and orientation." J. Neurophysiology 80: 2446-2466.

6.12 Scoula Superiore Santa Anna, PERCRO

6.12.1 Haptic Pen

Device description by : PERCRO, on 19/09/04.

General Description of the device

The HAPTIC PEN is a Kinestetic Haptic interface developed by PERCRO laboratory.
History: HAPTIC PEN was designed and builted with for the learning of Japanese alphabet.
Domain of application: One point kinestetic force feedback for interaction with virtual and remote environments. Typical application are learning writing, drawing etc...
Physical description The haptic PEN is an intuitive haptic display for hand-based interaction. The system is a 2+1 DOF Haptic Interface having its end-effector shaped in the form of a pen. The Force Display has been designed in order to exhibit the higher kinematic isotropy over the worskpace. The system has been designed in order to allow users working in the same space defined by a letter size. It can measure and control the motion on the paper plane, while measuring the pression of the pen exerted by the user along the pen axis.
The device is composed of two rotary actuators, driving a closed 5-bar linkage by two pairs of opposed tendons realized through steel cables. The actuators are located apart from the linkages of the mechanism. Each motor has two tendon transmissions in order to realize a pre-tensioned bi-directional tendon drive.
Level of achievement: Prototype
Future developments: NA

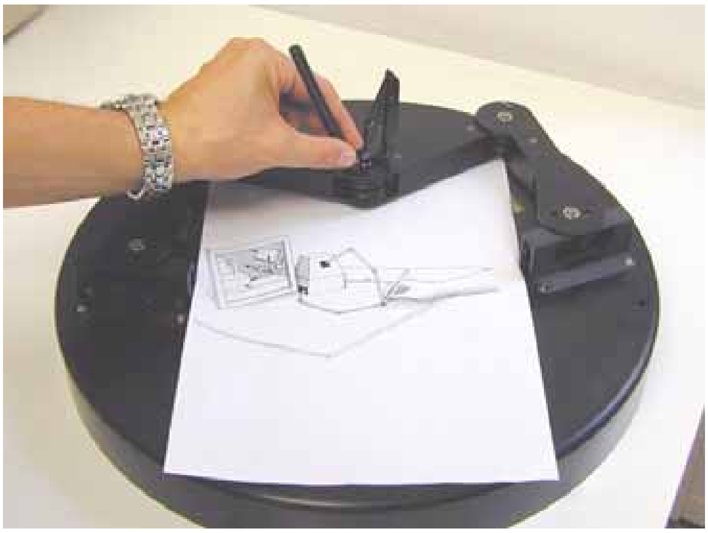


Figure 6.32 HAPTIC PEN Design

Technical points

Mechanism

Size of workspace	140 mm x 120 mm (Planar)
Geometry of workspace	Rectangular
Spatial reference	Desktop
Number of degrees of freedom	3DOF (actuated and sensorized)+2Passive+ 1DOF Sensorized in force
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high istropy

Characterization of the system in a passive state	Inertia: kg (worst case) (typical), Friction: <mN
Cinematic configuration type	Parallel
Structure of mechanism (internal cinematic configuration)	Cable Transmission inside the link of the mechanism.
Material of structure	Alluminium and steel
Type, material and other characteristics of joints (if any)	rotational joints with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	NA
Intrusion of mechanism in visual space of the user	No visual intrusion because the interaction non collocate
System statically balanced	Planar mechanism : always balanced in horizontal position;

<u>Signal Processing</u>

Number and structure of the signals ports.	2 Digital Encoders 2 Analog signals to drivers
Type of coding and type of medium.	P.P. IEEE 1284.3
Bandwidth or sampling rate.	5 kHz
Type of the local treatments, if any.	Impedance control with open loop force control (see scheme)
Functional properties of the local loops	5khz control, 20khz PWM driver
Technology of the local treatments	Analog

<u>Actuation</u>

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Moving coil rotor
Type of Commutation system (if any)	Graphite Brush
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash

Power driver system

Technology of the power modulator	PWM
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 7 N (worst case), 20 N(typical) Motors: 115 mNm
Max **continuous** force/torque exerted	EE: 3 N (worst case), 9 N(typical) Motors: 40 mNm
Bandwidth	At EE: 0-70 hz
Stroke / Motion range	Continous Rotation
Max speed (due to intrinsic limitation or to the driver)	4500 rpm
Efficiency	0.91

Sensing

Type of sensing	Angular Position
Physical principle of the sensors	Optical encoder
Resolution	1/2000 rad
Bandwidth, max data rate (in the case of sampled digital output)	Not relevant
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	4 kg
Whole dimensions of the system	Included in a cilinder D=500mm H=140mm
Power consumption	~ 200 W
Security and protection systems, if any	Industrial Emergency Button

Sources

[1] "HI 2 : a Two Degrees-of-Freedom Planar, Highly Isotropic Haptic Interface for the Desktop" Antonio Frisoli, Giuseppe Maria Prisco, Fabio Salsedo, Massimo Bergamasco; , Proc. of Photonics East SPIE99, The International Society for Optical Engineering - Boston (MA-USA);
[2] "Design of Haptic Interfaces" Avizzano, C.A.; Raspolli, M.; Fontana, M; Frisoli, A.; Bergamasco
[3] "Experimental Identification and Evaluation of Performance of a 2DOF Haptic Display" Frisoli, A.; Bergamasco, M.

6.12.2 Haptic Desktop

Device description by : PERCRO on 29/09/04

General Description of the device

Haptic Desktop is an integrated system, which merges haptic functionalities and VDT systems into one, developed by PERCRO laboratory.

History: Haptic Desktop System was designed and built within the internal RIS2002 project. It is a new haptic system that improves the human-computer interaction from the following points of view: esthetical, ergonomic and functional.

Domain of application: A haptic system, which presents collocation between its end-effector and the graphical cursor of a common PC. It allows reducing considerably the mental load from users during interaction operations with the PC.

Physical description: The HDS layout present the device as a multifunctional desk: the transparent haptic interface, designed using a plastic material with low refraction index, can be grasped directly with the finger or manipulated by means of a sensorized pen.

Level of achievement: The HDS is not a commercial product but thanks to its low price it could be commercialized.

Future developments: One version with haptic device under the desk plane is currently in development.

Figure 6.33 Haptic Desktop design

Technical points

Mechanism

Size of workspace	It can contain a 350X300 (mm) rectangle
Geometry of workspace	Sum of circular sectors
Spatial reference	Desktop
Number of degrees of freedom	2 DOF (actuated and sensorized)
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high isotropy
Characterization of the system in a passive state	Friction: < 150mN
Cinematic configuration type	Hybrid
Material of structure	Aluminum, and steel
Type, material and other characteristics of joints (if any)	Rotational joints all designed with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	<350 mN dry friction (active compensated)
Intrusion of mechanism in visual space of the user	Visual space in different position with respect to device workspace
System statically balanced	Passive: all WS Active: all WS

Signal Processing

Number and structure of the signals ports.	Integrated system. Ethernet port only for external communication
Type of coding and type of medium.	
Bandwidth or sampling rate.	2 kHz
Type of the local treatments, if any.	Library for Scale conversion and sum check
Functional properties of the local loops	Position, Force Control
Technology of the local treatments	SBC Pentium III 1.4 GHz

Actuation

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Moving coil rotor
Type of Commutation system (if any)	Graphite Brush
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash
Backdrive forces	See compensated friction forces

Power driver system

Technology of the power modulator	Linear
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 10N (worst case) Motors: 510 mNm
Max **continuous** force/torque exerted	EE: 4N (worst case), Motors: 80 mNm

Stroke / Motion range	Continous Rotation
Max speed (due to intrinsic limitation or to the driver)	5300 rpm
Efficiency	0.83

Sensing

Type of sensing	Angular Position
Physical principle of the sensors	Magnetic encoder
Resolution	1.5/1000 rad
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	30 kg
Maximum achievable stiffness	4N/mm
Whole dimensions of the system	1200X800X800 (mm)
Power consumption	max 100 W

Sources

[1] Solis J., Marcheschi S., Portillo O., Raspolli M., Avizzano C.A., Bergamasco M., "The Haptic Desktop: a novel 2D multimodal device", RO-MAN 2004, 13th IEEE International Workshop on Robot and Human Interactive Communication, September 20-22, 2004 Kurashiki, Okayama Japan.

6.12.3 3DOF Joystick

Device description by :PERCRO on 29/09/04.

General Description of the device

3Dofjoy is a Kinestetic Haptic interface developed by PERCRO laboratory.
History: 3Dofjoy HI was designed and built within the IT METAFORE project. The main aim of this project was to design an Haptic “Master” structure controlling a “slave” structure to be used in the medical field as a support in surgical operations of vertebrae drilling.
Domain of application: Haptic pen for exerting forces in arbitrary direction for the interaction with virtual and/or remote environments or with a remote slave device.
Physical description: The 3Dofjoy is a 3 DOF desktop HI connected to the user’s hand by a stylus. It has parallel kinematics with 3 actuated legs. Its innovative parallel kinematics provides a purely translating upper platform.
Level of achievement: 3Dofjoy is not a commercial product; anyway 2 prototypes have been built within some projects.
Future developments: Recently 3Dofjoy has been completely re-designed introducing significant improvements of performances in terms of exertable forces, gravity auto-compensation capability, backlash and constructive simplification.

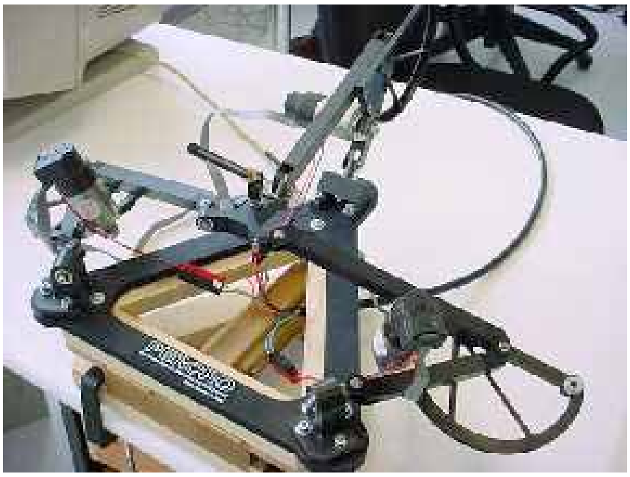


Figure 6.34 3Dofjoy design

Technical points

Mechanism

Size of workspace	R=100 H=200
Geometry of workspace	Cylindrical
Spatial reference	Desktop
Number of degrees of freedom	3 DOF (actuated and sensorized)+2Passive
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high istropy
Characterization of the system in a passive state	Inertia: 0.4kg (worst case) 0.2 (typical), Friction: <200mN
Cinematic configuration type	Parallel
Structure of mechanism (internal cinematic configuration)	Not redundant
Material of structure	Aluminum and steel
Type, material and other characteristics of joints (if any)	Rotational joints all designed with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	<20mN viscous friction (active compensated)
Intrusion of mechanism in visual space of the user	Visual space in different position with respect to device workspace
System statically balanced	Passive: never Active: all WS

Signal Processing

Number and structure of the signals ports.	1 Ethernet Port
Type of coding and type of medium.	16Bit PP
Bandwidth or sampling rate.	1 kHz
Type of the local treatments, if any.	Library for Scale conversion and sum check
Functional properties of the local loops	Position, Force Control
Technology of the local treatments	SBC Pentium III 800 MHz

Actuation

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Moving coil rotor
Type of Commutation system (if any)	Graphite Brush
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash
Backdrive forces	See compensated friction forces

Power driver system

Technology of the power modulator	PWM
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 9N (worst case), 18N(typical) Motors: 510 mNm
Max **continuous** force/torque exerted	EE: 18N (typical) Motors: 80 mNm
Stroke / Motion range	Continous Rotation
Max speed (due to intrinsic limitation or to the driver)	5300 rpm
Frequency response or resonance effects	52 Hz
Efficiency	0.83

Sensing

Type of sensing	Angular Position
Physical principle of the sensors	Optical encoder
Resolution	3.14/1000 rad
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	2 kg
Maximum achievable stiffness	8 N/mm
Whole dimensions of the system	600X300X300 (mm)
Power consumption	max 300 W
Security and protection systems, if any	Industrial Emergency Button

Sources

[1] Checcacci, D.; Frisoli, A.; Bergamasco, M. L'Interfaccia aptica master del sistema METAFORE. Proceedings of AIAS National Congress. September 12-25 2001, Alghero (CA), Italy.
[2] Frisoli, A.; Checcacci, D.; Salsedo, F.; Bergamasco, M. Translating in-parallel actuated mechanisms for haptic feedback. HAPTIC INTERFACES for Virtual Environment and Teleoperator Systems 2000 ASME International Mechanical Engineering Congress and Exposition, November 5-10, Orlando, Florida.
[3] Frisoli A.; Sotgiu E.; Avizzano C.A.; Checcacci D.; Bergamasco M. Sensor Force-based impedance control of a haptic master system for teleoperation. 6 February 2004, vol. 24, iss. 1, pp. 42-50(9) MCB University Press.

[4] D. Checcacci, E. Sotgiu, A. Frisoli, C.A. Avizzano, M. Bergamasco, "Gravity Compensation Algorithms for Parallel Haptic Interface" 2002 IEEE Int. Workshop on Robot and Human InteractiveCommunication ROMAN 2002.
[5] D. Checcacci, A. Frisoli, M. Bergamasco "Screw geometry approach to a novel 5DOFs haptic interface design" Proceedings of Roman2001, International Workshop on Robot-Human Communication. September 18-21 2001, Bordeaux-Paris, France.
[6] A.Frisoli, D. Checcaci, F.Salsedo, M.Bergamasco,"Synthesis by screw algebra of translating in-parallel actuated mechanisms" in "Advances in Robot Kinematics", ed. by J. Lenarcic and M.M. Stanisic, 2000 Kluwer Academics Publ.

6.12.4 GRAB

Device description by :PERCRO on 11/06/04.

General Description of the device

GRAB is a Kinestetic Haptic interface developed by PERCRO laboratory.
History: GRAB HI was designed and builted within the EU GRAB project. The thee main aim of this project was to allow to blind people to interact with virtual environment thruogh the sense of touch.
Domain of application: One point kinestetic force feedback for interaction with virtual and remote environments.
Physical description: The GRAB is a 3 DOF desktop HI connected to the user's finger by the mean of a passive gimbale. It has three actuated DOF. The designed kinematic and transmission allow to place two of the three motors at the base of the mechanism achieving low inertia without using any compensation.
Level of achievement: GRAB is not a commercial product, anyway several prototypes have been builted within some projects.
Future developments: One bigger version with larger workspace and higher maximum forces is currently in developement.

Figure 6.35 Grab design

Technical points

<u>Mechanism</u>

Size of workspace	400x400x600mm BOX
Geometry of workspace	Hollow Sphere Sector
Spatial reference	Desktop
Number of degrees of freedom	3 DOF (actuated and sensorized)+3Passive
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high istropy

Characterization of the system in a passive state	Inertia: 0.4kg (worst case) 0.2 (typical), Friction: <0.2mN
Cinematic configuration type	Serial
Material of structure	Alluminium and steel
Type, material and other characteristics of joints (if any)	rotational joints + 1 prismatic all designed with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	<0.02 mN dry friction (active compensated)
Intrusion of mechanism in visual space of the user	
System statically balanced	Passive: At the WS center Active: all WS

<u>Signal Processing</u>

Number and structure of the signals ports.	1 ECP Parallel Port IEEE 1284 Specs
Type of coding and type of medium.	16Bit PP
Bandwidth or sampling rate.	2 kHz
Type of the local treatments, if any.	Library for Scale conversion and sum check
Functional properties of the local loops	Position, Force Control
Technology of the local treatments	SBC Pentium III 800 MHz

<u>Actuation</u>

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Moving coil rotor
Type of Commutation system (if any)	Graphite Brush
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash
Backdrive forces	See compensated friction forces

Power driver system

Technology of the power modulator	PWM
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 4N (worst case), 6-7N(typical) Motors: 2500 mNm
Max **continuous** force/torque exerted	EE: 4N (worst case), 6-7N(typical) Motors: 201 mNm
Stroke / Motion range	Continous Rotation
Max speed (due to intrinsic limitation or to the driver)	7580 rpm
Efficiency	0.91

<u>Sensing</u>

Type of sensing	Angular Position
Physical principle of the sensors	Optical encoder
Resolution	1/2000 rad
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	9.5 kg
Power consumption	~ 300 W
Security and protection systems, if any	Industrial Emergency Button

Sources

[1] http://www.grab-eu.com/id17.htm

6.12.5 EXOS

Device description by : PERCRO on 11/06/04.

General Description of the device

ARM EXOSKELETON is a Kinestetic Haptic interface developed by PERCRO laboratory.
History: ARM EXOSKELETON HI was designed and built within the EU PURE FORME project. The main aim of this project was to allow to blind people to interact with virtual environment thruogh the sense of touch.
Domain of application: L-Exos (light EXOSkeleton) is an innovative haptic interface wearable on the arm. Its functionalities allow to record the arm position in the 3D space and to provide forces at the level of the hand's palm for the interaction with virtual or remote environment.
Physical description: L-Exos is a serial robotic structure, with 4 primary sensorized and actuated dofs to which may be added respectively 1 sensorized dof in one configuration, or 6 sensorized and actuated dofs and 6 idle dofs in the coupled configuration (with Hand-Exos). All the primary DOFs are rotational joints connecting in series 4 movable links to a fixed one, which can be rigidly connected to a fixed or movable support. The designed kinematics and transmission allow placing the four motors at the base of the mechanism achieving low inertia without using any compensation.
Level of achievement: ARM EXOSKELETON is not a commercial product; anyway this prototype has been used in several European museums during last months.
Future developments: During this last years three arm exos have been designed at PERCRO so, being the result of a very long time research, presents many innovative technical solutions

Figure 6.36 ARM EXOSKELETON design

Technical points

Mechanism

Size of workspace	
Geometry of workspace	Hollow Sphere Sector
Number of degrees of freedom	4 DOF (actuated and sensorized) + 1 sensorized in a one configuration; 4 DOF (actuated and sensorized) + 6DOF (actuated and sensorized) and 6 passive (in the configuration with Hand-Exos)
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high istropy
Characterization of the system in a passive state	Friction: < 700mN
Cinematic configuration type	Serial
Material of structure	Alluminium and steel
Type, material and other characteristics of joints (if any)	Rotational joints all designed with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	< 350 mN dry friction (active compensated)
System statically balanced	Passive: At the link1 end of course Active: all WS

Signal Processing

Number and structure of the signals ports.	UDP - TCP/IP
Type of coding and type of medium.	6 double
Bandwidth or sampling rate.	2 kHz
Type of the local treatments, if any.	Library for Scale conversion and sum check
Functional properties of the local loops	Position, Force Control
Technology of the local treatments	SBC Pentium IV 2.4 GHz

Actuation

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Moving coil rotor
Type of Commutation system (if any)	Graphite Brush
Properties of the Commutation System	
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash
Backdrive forces	See compensated friction forces

Power driver system

Technology of the power modulator	PWM
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 100N Motors: 3.7 Nm
Max **continuous** force/torque exerted	EE: 50N Motors: 2 Nm
Stroke / Motion range	Continous Rotation

Sensing

Type of sensing	Angular Position
Physical principle of the sensors	Optical encoder
Resolution	0.77/1000 rad
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	11 kg
Maximum achievable stiffness	3N/mm
Whole dimensions of the system	See previous picture
Power consumption	max 700 W
Security and protection systems, if any	Industrial Emergency Button

Sources

[1] http://www.pureform.org/pubblicationEvents.htm
[2] M. Bergamasco, B. Allotta, L. Bosio, L. Ferretti, G. Parrini, G. Prisco, F. Salsedo and Sartini, « An Arm Exoskeleton System for Teleoperation and Virtual Environments Applications », Proceedings of the IEEE Interbational Conference on Robotics and Automation, San Diego, CA, pp. 1449-1454, May, 1994

6.12.6 Hand-Exos

Device description by : PERCRO on 29/09/04.

General Description of the device

Hand Exoskeleton is a Kinestetic Haptic interface developed by PERCRO laboratory.
History: HAND EXOSCHELETON HI was designed and built within the EU PURE FORME project. It is a new haptic device developed for specific manipulative tasks.
Domain of application: Two-point kinesthetic force feedback corresponding to user's index and thumb fingertips for interaction with virtual and remote environments.
Physical description: HAND EXOSKELETON is a wearable device composed of two serial limbs; each one has three actuated degrees of freedom. The last actuated links of the two limbs are connected to the respective end-effector (a thimble) by means of a gimbal, which allows the mechanism to reach the user's fingertip with any orientation.
Level of achievement: HAND EXOSKELETON is not a commercial product; anyway this prototype has been used in several European museums during last months.
Future developments: One version with larger workspace and anthropomorphic structure for more than 2 fingers is currently in development.

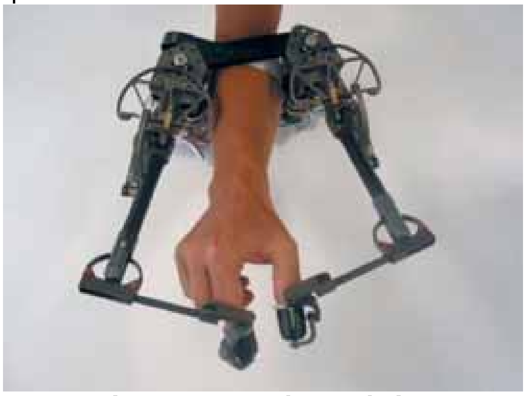


Figure 6.37 Hand Exos design

Technical points

Mechanism

Size of workspace	All the possible movements of the fingertips during a 45° flexion and 45° extension of the wrist
Geometry of workspace	2 Hollow Sphere Sectors
Spatial reference	Desktop
Number of degrees of freedom	3 DOF (actuated and sensorized) + 3Passive for each limb
Isotropy of workspace configuration or not, in terms of accessibility	Designed for high istropy
Characterization of the system in a passive state	Inertia: 0.1N (worst case), <0.1N (typical), Friction: <100mN
Cinematic configuration type	Serial
Material of structure	Aluminum, carbon fibers and steel
Type, material and other characteristics of joints (if any)	Rotational joints all designed with ball bearings
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	<10 mN dry friction (active compensated)
Intrusion of mechanism in visual space of the user	Visual space in different position with respect to device workspace
System statically balanced	Passive: never Active: all WS

Signal Processing

Number and structure of the signals ports.	UDP-TCP/IP
Type of coding and type of medium.	6 double
Bandwidth or sampling rate.	2 kHz
Type of the local treatments, if any.	Library for Scale conversion and sum check
Functional properties of the local loops	Position, Force Control
Technology of the local treatments	SBC Pentium IV 2.4 GHz

Actuation

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	Ironless
Type of Commutation system (if any)	Brushless system
Properties of the Commutation System	
Gear or low-level mechanisms (if any).	Cable transmissions
Backlash	No-Backlash
Backdrive forces	See compensated friction forces

Power driver system

Technology of the power modulator	Linear
Low level control loop	Current Control

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	EE: 15N (worst case) Motors: 280 mNm
Max **continuous** force/torque exerted	EE: 4N (worst case), Motors: 29.7 mNm

Stroke / Motion range	Continous Rotation
Max speed (due to intrinsic limitation or to the driver)	11000 rpm
Efficiency	0.87

Sensing

Type of sensing	Angular Position
Physical principle of the sensors	Magnetic encoder
Resolution	1.5/1000 rad
Range of measurements	Unlimited
Location in the haptic system – relation / link with the geometry of the mechanism	At the motor

Other properties

Price	NA
Weight	2.5 kg
Maximum achievable stiffness	8N/mm
Whole dimensions of the system	300X300X200 (mm)
Power consumption	max 120 W
Security and protection systems, if any	Industrial Emergency Button

Sources

[1] Frisoli A, Simoncini F, Bergamasco M., " Mechanical Design of a Haptic Interface for the Hand", 2002 ASME International DETC- 27th Biennial Mechanisms and Robotics Conference , Montreal-Canada, September 29 - October 2, 2002.
[2] http://www.percro.org/researchmore.html#ancHaptic

6.13 Standford University, CCRMA

Device descriptions by: INPG on 17/01/2005

6.13.1 Moose

General Description of the device

Domain of application: The primary aim of the Moose was to provide access for blind computer users to graphical user interfaces, and in particular those found in digital sound studios. It was also intended to supplement visual presentation with haptic presentation for all users.
Physical description: The figure bellow shows the hardware components of the planar haptic interface. the Moose. The puck or manipulandum under the user's hand is coupled to two linear voice coil motors through two perpendicularly oriented flexures. The workspace is 3 cm square while the device footprint is 33 cm square and height is 5 cm. The effective mass in each direction is 172 grams while the maximum force output is about 6 Newtons. The workspace of the current Moose is limited by the linear motors.
The unique feature of the hardware design is the double flexure. It is executed in two pairs of 7-cm strips of spring steel. The double flexure conveniently decouples the 2-axis motion of the puck into two single-axis motions at the linear motors. Moments and vertical forces are resisted, yet translations in the horizontal plane are transmitted directly to the motors by the manipulandurn. The kinematics of this device are simple and very nearly linear, making forward and inverse kinematic calculations unnecessary. Furthermore, the work-space is flat, square like a mousepad. and free of singularities.

Figure 6.38 - the Moose, with user hand on the puck

Level of achievement: prototype
Future developments: Improving haptic palette.
Extending software to haptic browsing of the web.
Addition of a Braille device to the Moose.
Use of rotary motors and capstan drives to increase workspace.

Technical points

<u>Mechanism</u>

Size of workspace	3 * 3 cm square
Spatial reference	desk reference
Number of degrees of freedom	2
Cinematic configuration type	parallel

Structure of mechanism (internal cinematic configuration)	a double flexure decouples the 2-axis motion of the puck into two single-axis

Actuation

Technology of Actuators

Physical principle	linear motors
Functional Characteristics of the Actuation system	
Max force/torque exerted at peak	6 N
Linearity	nearly linear

Sensing

Type of sensing	linear position encoder
Resolution	59 lines per cm

Other properties

Whole dimensions of the system	33 * 33 * 5 cm

Sources

[1] M. Sile O'Modhrain and R. Brent Gillespie, "The Moose: A Haptic User Interface for Blind Persons", 1995

6.13.2 vBOW

Device description by : INPG on 10/01/2005.

General description of the device

The vBOW, a haptic musical-controller human computer interface was realized at CCRMA (Center for Computer Research in Music and Acoustics), Standford University, USA.

Domain of application : The vBow is the product of research intent on developing an electronic musical instrument that expressively translates physical gesture into synthesis parameters, while providing useful haptic feedback to the performer by simulating vibration, friction, detents, elasticity, and barriers with servomotor and cable systems. What is unique to the vBow is its ability to simultaneously simulate four independent haptic cues, mapped to four diverse yet interdependent bowing motions, with a four degree of freedom human-computer interface, built specifically to meet the performance needs of a violinist.

Brief history : A first version of the vBow (version 1) was developped in 2000. It was designed around a single servomotor with digital encoder and cable system, which sensed one degree of freedom of the bowing gesture of a violinist, and provided the haptic feedback of a randomly varied vibration.

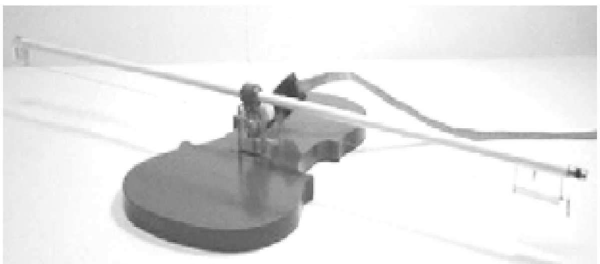


Figure 6.39- vBow version 1

The second version of the vBow (2001) incorporated the design of the first version into an interface that could sense three more degrees of freedom, and provide the haptic feedback associated with these additional kinds of bowing motion. The latest version is version 2.2 (2003)

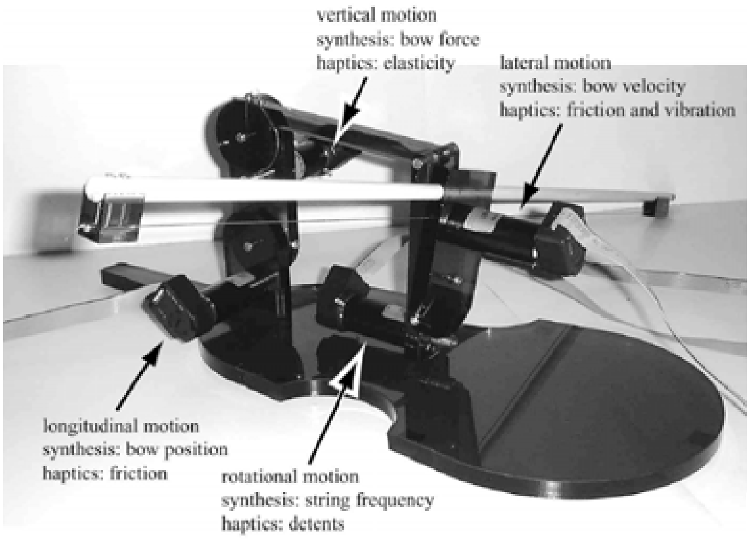


Figure 6.40- vBow version 2.1, with servomotor and encoder mapping

Physical description

The instrument is assembled from eight acrylic pieces, and one fiberglass stick. At the base of the vBow is a violin-shaped body, with holes drilled through its height, through which screws secure the rest of the instrument to the body. Attached to the body is a base, which houses the servomotor with encoder that senses longitudinal motion, and provides the haptic feedback of friction, as the bow travels along the length of the virtual string.

The vBow, a virtual violin bow musical controller is composed of four cable and servomotor systems allow for 4DOF including the lateral motion of a bow stroke across a string, the rotational motion of a bow crossing strings, the vertical motion of a bow approaching and pushing into a string, and the longitudinal motion of a bow traveling along the length of a string. This version incorporates the single servomotor from the first version, that sensed and provided haptic feedback for the lateral motion of the bowing gesture of a violinist.

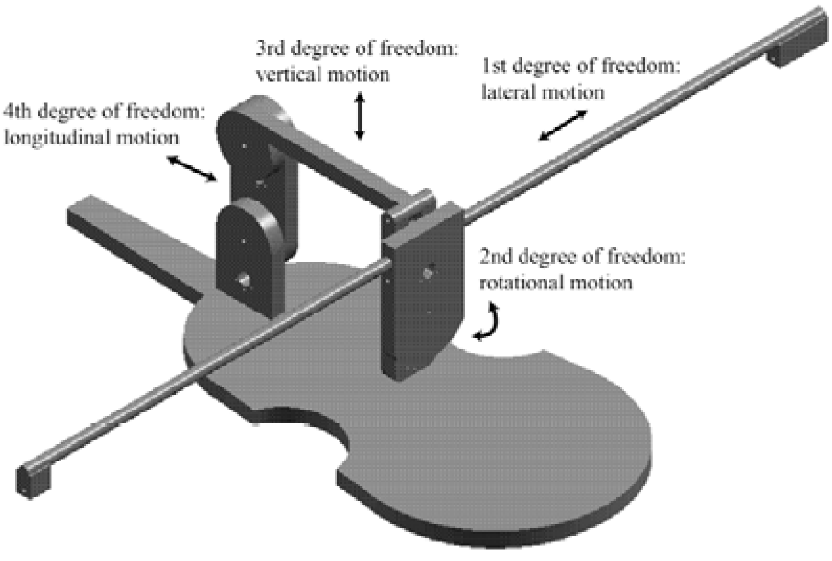


Figure 6.41 - Degrees of freedom of the vBow

Level of achievement: prototype

Future developments: Further development of the vBow hardware and software will endeavor to integrate the mapping of bowing gesture to sound synthesis and haptic feedback, into an expressive interactive computer music composition and performance system.

In addition to playing the bowed-string physical model, the instrument will be used to test the playability of other physical models. Examples are a bowed-string physical model that accounts for torsional waves, the “exciter-resonator” models of a glass harmonica and bowed
saw, and a Tibetan singing bowl. Along with the inclusion of other physical models in the vBow software, future developments include the implementation of polyphony, so that more than one string can be bowed at a time.

Technical points

Mechanism

Spatial reference	Base of violin
Number of degrees of freedom	4
Material of structure	acrylic and fiberglass pieces, aluminum capstans, aluminum capstans, nylon-coated stainless steel cable, and various fasteners.

Signal Processing

Number and structure of the signals ports.	Control of the data sensed by encoder and haptic feedback is assured by servomotor control, data acquisition card using the ServoToGo control.
Technology of the local treatments	Pentium III, 600MHz PC

Actuation

Technology of Actuators

Physical principle	Four Advanced Motion Control servo amplifiers with filter cards

Sensing

Type of sensing	Force/torque
Physical principle of the sensors	Servomotors are used with encoder to sense the vertical motion above and into the virtual string and provides the haptic cue of bow pressure and string elasticity
Resolution	Digital encoder provides 500 slots per turn in two channels, allowing 2000 counts per revolution

Sources

[1] C. Nichols “The vBow : a Haptic Musical Controller Human-Computer Interface”, Center for Computer Research in Music and Acoustics, Stanford University, 2000
[2] C. Nichols “he vBow: A Virtual Violin Bow Controller for Mapping Gesture to Synthesis with Haptic Feedback”, Stanford University, 2002
[3] C. Nichols PHD “the vBow : an Expressive Musical Controller – haptic Human-Computer winterface”, Stanford University, 2003

6.14 University of Colorado

6.14.1 5DOF haptic interface

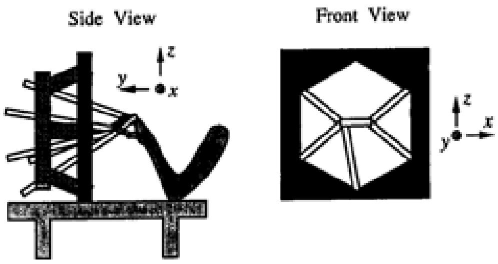
Device description by : INPG on 02/11/2004.

General Description of the device

Domain of application: Initial use of this interface was scientific visualization applications. This device could find application in every haptic device where a linear motion is required.
Date of publication: 1996.
Physical description: Parallel mechanism designed to the motions that can be produced by a pencil-type grip on a stylus with the elbow resting on a table top.
The force sensor is placed as close to the user's finger as possible so that the bandwidth describes what the user actually feels.
5 force sensors are installed, each of them in the end of each actuator rod, proximal to the gimbal attachment on the stylus. The distal-end gimbal is composed of miniature clevis with a ball bearing at the pin. Forces are transmitted to the fingers by a member loaded only in axial tension or compression using the prismatic joints. A bandwidth of approximately 175Hz for the individual force control loops which is less than the vibration sensitivity of the fingers up to about 300Hz.
Level of achievement: Prototype

Figure 6.42 5 DOF Colorado haptic interface

On-going and future work:
(1)To assess more carefully the coupling between the rods and designing a controller for the interface from a direct multivariable control framework.
(2)To develop models of the nonlinearities (such as friction) for use in the controller design.



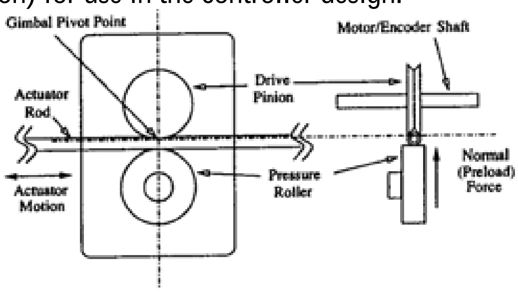


Figure 6.43 Kinematic arrangement of the parallel haptic interface

Figure 6.44 Schematic of the friction drive actuator

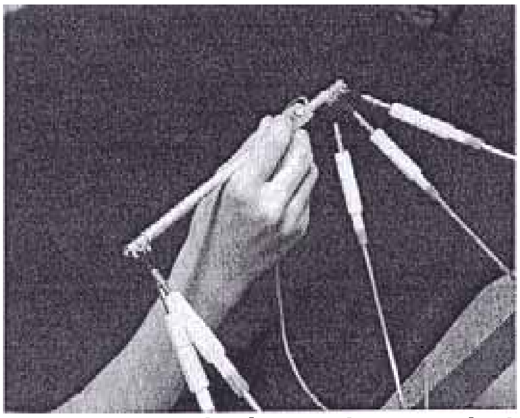


Figure 6.45 Force sensors implementation to a stylus handgrip

Technical points

Mechanism

Size of workspace	40 cm translation (3DOF), ±60° angular motion (2DOF)
Number of degrees of freedom	3-DOF translation, 2-DOF angular motion
Cinematic configuration type	Parallel haptic interface
Structure of mechanism (internal cinematic configuration)	5 thin rods extend from actuator units mounted to a stiff ring. Forces are transmitted to the fingers by a member loaded only in axial tension or compression.
Material of structure	Air-hardening steel (AISI A2) for drive pinion, hard drawn 304 stainless steel tube for driven rod, ABEC-7 ball bearing , molded nylon for shaft hanger
Type, material and other characteristics of joints (if any)	Prismatic joints
Frictions: Maximum force level Non-linearities: dry friction, viscous friction	Natural Coulombic friction forces < 0,4N With active compensation: 0,01N

Signal Processing

Number and structure of the signals ports.	
Type of coding and type of medium.	
Bandwidth or sampling rate.	Control loop rate 2207Hz. Total control loop period: 453microsec.
Type of the local treatments, if any.	Impedance local loop
Functional properties of the local loops	Transfer function between the commanded rod force (in volts) and the measured force at the tip of the rod (in volts) . Rate of magnitude: 40db/decade at low frequencies (bellow 10Hz). Loop gain at 10Hz: 20dB.
Technology of the local treatments	The control structure consists of 5 single-input single-output (SISO) rod force control loops, integrated into an overall multivariable system.

Actuation

Technology of Actuators

Physical principle	Mechanical. 1Volt correspond to 4,45N. Tractive shear forces are provided by a dry friction (drive pinion and an opposing pressure roller are in contact with the rod).
Specific technologies for the above category	Actuator units provide axial rod force via friction drive. They are mounted to the base with a 2DOF gimbal, with actuator rod passing through the gimbal axis intersection.
Backdrive forces	0,01N (with active compensation)

Power driver system

Technology of the power modulator	
Low level control loop	Force control loop

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	Maximum (slipping) force to running friction: 12N axial forces.
Max continuous force exerted (24h)	
Bandwidth	175Hz. For stability, a phase margin of 50° and a gain margin of 10dB are desired.

Sensing

Type of sensing	5 axis force sensors
Physical principle of the sensors	Steel core sensors, 5mm in diameter, shaped to desensitize 4 bonded semiconductor strain gauges . Position sensors: optical encoder
Resolution (Spatial resolution)	Force resolution: 0,03N Spatial resolution: 7 micrometers
Range of measurements	Full scale axial force: 50N; noise floor 0,012N RMS
Location in the haptic system – relation / link with the geometry of the mechanism	A force sensor is installed in the end of each actuator rod.

Subjective evaluation

This part of the Technical Sheet is reserved to the description of the manipulation of the evaluated device.

COLORADO TEAM [1, 2]

To test the perceive motion resistance that includes acceleration, viscous and other frictional effects, the stylus is moved back and forth about 12 cm at a rate of 0,8Hz. The RMS force obtained from this test is 0,032N. With the controller turned off, the level of friction for similar motion has an RMS value of 1,47N.

PERCRO

This is a 5DOF haptic device with a pan-like end effector (the missing DOF is the rotation around the pen axis). The pen is attached to the ground trough two different parallel kinematic mechanism. The firs attached to the pen tip trough a universal joint is a three leg RRPRR, the second is a two leg still RRPRR. Every leg has a force sensor on the tip of the rod. Every prismatic joint is actuated by a friction driver. It's important to notice that the legs of this mechanism are very thin. This is possible because they are not loaded with any torque.

Applications: Visualization of 3D graph in fluido-dynamic and physics.
Test: The device was tested partially. In fact the pen was connected only to the three leg mechanism and only in free space moving without simulation of virtual contact.

Moving in free space

Without friction compensation: The friction was quite high in fact the prismatic joints were realized with sliding contact bearings. At low speed there was a very high stick-slip effect.
With friction compensation: With friction compensation algorithm the feeling was really better but the system became instable very easily by changing the grasping of the end effector. At low speed a big amount of friction is still perceivable. Moreover this last effect is not uniform in the workspace probably because of the kinematic properties are position dependant or because the friction model is independent by the position of the actuators (in prismatic actuators could be necessary).

6.14.2 Linear actuator with step-motors

Technical Description by PERCRO on 17/11/2004

In this laboratory there was the purpose of using a Step-Motor for the actuation of a linear joint of a haptic interface. The research focuses on the compensation of torque-ripple. The main motivation of this study is to find a low cost and effective actuator for the 5DOF haptic device that was built in the laboratory. In order to achieve a smooth torque, the current and the switching was regulated according to the motor position. The rotational motion was converted into linear motion using a cable (a steel tape in this case) bound on a pulley and a preloaded spring system (a long bended beam), that make it able to generate the bi-directional force.
The actuator was driven by a special designed large bandwidth driver with a switching frequency of 10khz and a custom optical resolver (with resolution of 1/50000 of 360°).
It was present a force sensor on the tip of the actuator.
Applications: This device could find application in every haptic device where a linear motion is required.

Subjective evaluation

PERCRO
The mechanism was tested holding a Pen-like end effector attached to the tip of the actuator (attached on the force sensor). The linear actuator was free to rotate around the motor axis.
The motor was tested with and without ripple compensation.

Moving in free space

Without ripple compensation: the friction was very low but the ripple gives a very bad stepping movement. At high speed the effect was less perceivable. The elastic force of the spring was well compensated and the system was stable in every position of its stroke.
With ripple compensation: The friction was still low and the ripple was really decreased. A little of stepping movement is still perceivable. The elastic force is still perfectly compensated.

Simulation of a wall

The virtual wall (1DOF) was very stiff if compared with the thin and light structure of the transmission structure. The force of contact was very sparkling and gives a very realistic feeling.

CEIT
The user handles the robot's end effector and simply moves it. The present robot position is conveyed to the virtual environment and the contact forces in the virtual environment are sent back to robot's arm.
Only one test was performed on the 5 DoF (infact, the test was done using only 3 DoF): free test movement with and without friction compensation. However, a flat virtual wall was tested on a newer 1 DoF prototype.

The main conclusions are:
The actuator is almost 100% backdrivable.
High and stable stiffness on impact test. However, during the soft contact test, it is not clear if the sensed stiffness is a virtual stiffness or if it becomes from the stiffness of a tendon that is used to preload the cable transmission.
Without ripple torque compensation, the device is not valid to be used as a haptic device. After the ripple torque compensation, the improvement is good enough. However a ripple of almost negligible amplitude is still felt.
The actuators's friction is so high that friction compensation is required. The stick-slip motion is present.
The multi-DoF device's behaviour is high-dependant on the position of its end-effector, even it becomes unstable near singular configurations or if the operator changes the apparent stiffness of his arm.
The free movement test reveals a low inertia but the operator's arm becomes fatigue due to the ripple torque.
The workspace is suitable for short human arm movements.

UNEXE
Appraisal
The 5DOF Pen had some noticable friction, and the workspace was unusual. It wasn't possible to test the device fully.
The new actuator was very impressive. One of the major goals of the research has been to compensate for the torque-ripple. The motor was tested with and without ripple compensation, and it seems to be successful. The motion was very smooth, with very little inertia, and the hard walls felt very real.
Techological Innovations
The new actuator is bulky in its current incarnation, but it should be cheap, and it provides probably the smoothest motion and the best hard-stop I have experienced.

INPG
Experiment report a
There is no model in this case (free space).

Property to target	Evaluation of the free space rendering with and without the ripple torque compensation.
Strategy planned	The compensation is not active. I will explore the space, first with a vertical movement at constant speed from top to bottom and bottom to top.
Result	As I'm going down, the tape is rolling down and the bow relaxes. First, I can feel bumps very clearly. They are due to the steps of the motor (ripple). Then if I stop to apply a force, the pen immediately stops. The behaviour is identical to a solid friction: I feel a light friction when I'm moving (i.e. applying a force) but I need to apply a non-negligible force at the beginning to move the pen against the solid friction and finally get into the compensated mode.
Modification of the strategy	I will try to make the same movement faster.
Result	I still feel the ripple bumps (kind of stick and slip effect) but the friction is lighter. Whatever the speed the top-to-bottom and bottom-to-top movements are quite similar in their rendering.
Modification of the strategy	I will try to change slightly the orientation of my gesture (left or right)
Result	When I'm not properly in the axis of the pulley, I feel more resistance (stick and slip) and the rendering is not so good. I guess the tape will have to be guided strictly straight in the direction of the pulley, for the final version of this haptic device.
Modification of	Now we have set up the ripple torque compensation. I will explore again the space,

the strategy	first with a vertical movement at constant speed from top to bottom and bottom to top.
Result	The oscillation is much lighter than before, but still perceivable. The friction during the movement is still light, like in the previous test. I feel also the same stick and slip effect from a solid friction. The minimal force to apply for moving the pen is not negligible and there is a sudden stop of the pen when I stop to apply a force.
Experience report	In spite of the complexity of this system (preloaded bow on a steel tape), the rendering of the free space in 1D is isotropic and the same in both directions. With the ripple torque compensation, the steps are much less perceivable than without. However I can still feel the stick and slip effect when we apply the very little force. Particularly, I think it is difficult to correct the stepping effect at the starting of the movement (a minimal force is required to move the pen) and at the end (the pen stops suddenly with a solid friction effect). It would be interesting to trying the device with a virtual inertia added into the model, to see if the behaviour changes.

Experiment b

The implemented model is a wall (no force, then a repulsive force in 1D).

Property to target	Evaluation of the wall rendering.
Strategy planned	I will make a top-to-bottom movement as before and find the position of the wall.
Result	The position of the wall is very accurate. I can feel a very small sticking effect (attraction) at the moment I touch the wall (due to stepping motor?). The contact is very sharp, but the inner stiffness of the wall is not very high.
Modification of the strategy	I will analyse the contact of the wall by applying a force of it.
Result	The contact is perfectly stable; there are no oscillation instabilities while pushing on the wall. It would be interesting to evaluate the maximum stiffness we can get with this device, since here the inner stiffness of the wall is quite low. I feel very impressed by the sharpness of the contact, once of the most sharp I ever feel with a haptic device. I have an impression of damped oscillation at the moment of the contact, probably due to the steel tape. The haptic feeling can be felt as if we abruptly stretched apart a hard-stiffness tape (whatever tissue, paper, steel...).
Modification of the strategy	I will focus now on the pen withdraw from the wall, by applying a bottom-to-top movement from the contact of the wall.
Result	Here again it is necessary to apply a minimal force in order to make the pen starts to move (sticking effect or solid friction effect). However this is similarly to the force required to move from any other positions in free space.
Experience report	The sharpness of the contact for the wall rendering is very impressive. However, the free space-to-wall direction was the same as the rolling-out direction for the steel tape, so that the contact sharpness may be due to the high stiffness of the steel tape combined with the precise positioning of the stepping motor. I doubt that we could get such a sharp rendering if the wall were in the upper position (and free space lower), since the steel tape would then roll up and the contact would be then mostly guaranteed by the stiffness of the squashed bow (which is lower than the steel tape stiffness).

Synthesis on the experiences made

Global strategy followed.

I tried to feel the effect of the stepping motor and the ripple torque compensation in the free space movement, and then to evaluate my feeling in the interaction with the virtual wall:

- Evaluation of the free space rendering with and without the ripple torque compensation

In spite of the complexity of this system (preloaded bow on a steel tape), the rendering of the free space in 1D is isotropic and the same in both directions. With the ripple torque compensation, the steps are much less perceivable than without. However I can still feel the stick and slip effect when we apply the very little force. Particularly, I think it is difficult to correct the stepping effect at the starting of the movement (a minimal force is required to move the pen) and at the end (the pen stops suddenly with a solid friction effect). It would be interesting to trying the device with a virtual inertia added into the model, to see if the behaviour changes.

- Evaluation of the wall rendering

The sharpness of the contact for the wall rendering is very impressive. However, the free space-to-wall direction was the same as the rolling-out direction for the steel tape, so that the contact sharpness may be due to the high stiffness of the steel tape combined with the precise positioning of the stepping motor. I doubt that we could get such a sharp rendering if the wall were in the upper position (and free space lower), since the steel tape would then roll up and the contact would be then mostly guaranteed by the stiffness of the squashed bow (which is lower than the steel tape stiffness).

General opinion on the system

The main goal for using the stepping motor technology is the fact that nowadays, such components are easy and cheap to buy, as they are manufactured for many electronics and computer device. The use of a stepping motor combined with a steel tape is interesting to get a high sharpness in the contact with a virtual wall. However this technology is not very well adapted for haptic device, as shown in the free space movements experiment. It is difficult to compensate the ripple of such motors, and in spite of the impressive result, there is still a feeling of light stick and slip friction. The maximum rendered force may also be limited by the stiffness of the preloaded bow that we use. For similar reasons, the force interaction may be dependent on the direction of the movement. To conclude, I have been very interested in this device, which gives a very realistic, sharp and stable contact for the virtual wall model, and whose design concept is utterly different from other haptic devices.

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6.15 Southern Methodist University, Mechanical Engineering Departement

6.15.1 MasterArm Pneumatic Haptic Interface

Device description by: INPG on 17/01/2005

General Description of the device

Domain of application Presence in virtual environments, a topic pursued by many investigators, offers a new venue in robotics research. Teleoperation systems based on this concept lead to exciting applications in surgery planning, personnel training, and physical rehabilitation.

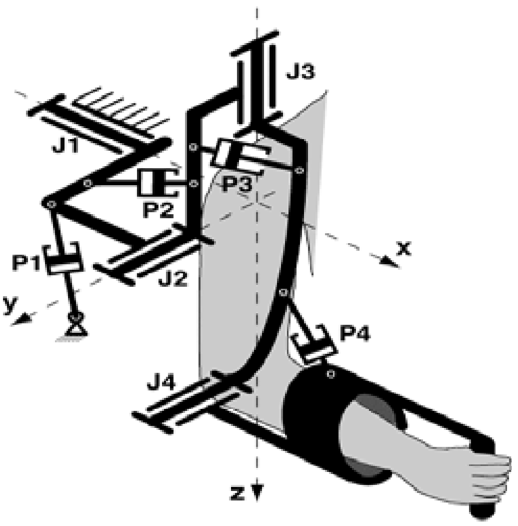
Physical description: The master is a unilateral aluminum manipulator with four revolute joints. It tracks the shoulder-elbow motions of the right arm of the human operator. The manipulator is fixed at one end to the chair that the PHI (Pneumatic Haptic Interface) is mounted on. The other end of the manipulator is a handle that is grasped by the operator. The master is strapped to the right arm of the human operator by using a set of inflatable cushions and various length adjustments to accommodate different operators. The spherical joint of the shoulder is implemented by three cylindrical joints J1, J2, and J3 , with orthogonal axes intersecting at the center of the shoulder. The elbow joint is implemented by the cylindrical joint J4 .

The joint displacements are acquired by using linear position transducers mounted parallel to each cylinder.

The force feedback is relized by actuating the joints of the master manipulator by the pneumatic cylinders (P1, P2, P3, and P4). The stroke of the pistons and the connection points on the structure are chosen to provide the operator with a convenient range of motion. Each double-acting cylinder is connected to a pneumatic proportional valve. We have used electrically actuated 4-way valves with voice coils (Numatics PositionX Valve). Pressure transducers are used as sensors in the control loop that is responsible for applying the desired forces at the actuators. The pressure signals are amplified and communicated to the A/D converters on the Mac that houses the force actuation controller.

Two control systems are developed and implemented on-line to perform the force actuation and gravity compensation that are needed by the master manipulator. The pneumatic force actuation controller is a modified PD (Proportional plus derivative) algorithm that includes specialized schemes to compensate for the aerodynamic effects in the pneumatic circuitry and the cylinders. The gravity compensation controller is a neural network based algorithm that can be trained on-line to compensate for the gravity vector of the master manipulator and provide transparent interface.

Level of achievement: prototype



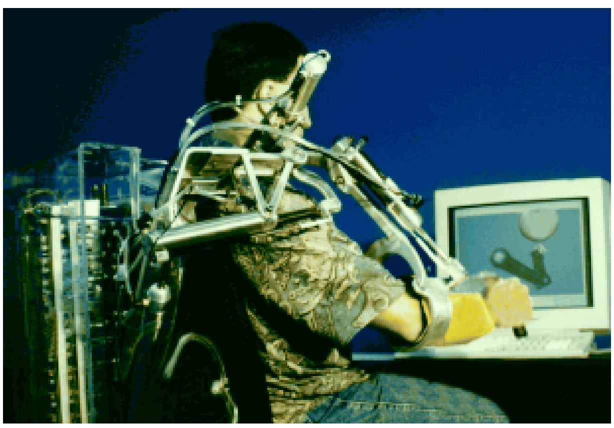


Figure 6.46 - Schematic of the mechanical interface

Figure 6.47 - MasterArm device and operator

Technical points

Mechanism

Spatial reference	chair reference
Number of degrees of freedom	4 DoF
Cinematic configuration type	serial
Structure of mechanism (internal cinematic configuration)	3 cylindrical joints for the shoulder, and one cylindrical joint for the elbow
Type, material and other characteristics of joints (if any)	cylindrical joints

Signal Processing

Bandwidth or sampling rate.	actuator force control and data acquisition: 500 Hz communication with virtual slave : 140 Hz

Actuation

Technology of Actuators

Physical principle	pneumatic cylinders (by Numatics® Inc.)
Specific technologies for the above category	Electrically actuated 4-way valves with voice coils (PositionX Valve by Numatics® Inc.)

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	854 N (corresponds to 25-58 Nm torque at each joint, depending on arm configuration) with pressure of 100 psi

Sensing

Type of sensing	Analog MLT linear position transducers by Data Instruments mounted parallel to each cylinder pressure transducers (by SenSym, Inc.) used for control loop
Bandwidth, max data rate (in the case of sampled digital output)	11 Hz, 12 Hz, and 12.5 Hz for 200 N, 100 N and 500 N force levels (experimentally estimated)

Subjective evaluation

In [2] are described a series of experiment to evaluate the impact of the Pneumatic Haptic Interface in task performance. Using Weber fractions, the outcome of the force sensation experiments was contrasted against results reported by psychophysical researchers.

The results indicated that the perception of weight (or force magnitude) through the haptic interface was signifi-cantly affected for relatively low reference force levels (4.44 N, Weber fraction = 0.5). The effect progressively diminished as the force level was increased, and almost matched the natural human capabilities for a reference force level of 18 N (Weber fraction = 0.06). The haptic shape identification experiments showed that the subjects were able to identify various shapes using the PHI system (1 = 0.3 m reference length, with Weber fraction = 0.38). This identification, however, was adversely affected by the lack of tactile sensation in the haptic device. The outcome of the force-feedback experiments demonstrated mixed results, an observation that was consistent with experimental studies of other researchers. While force feedback did not affect the time needed to complete the task, the subjects' performance was significantly improved when the experiments involved controlling the thickness of a curve drawn on a pressure-sensitive tablet.

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6.16 Université des Sciences et Technologies de Lille, Laboratoire d'Informatique Fondamentale de Lille (LIFL)

6.16.1 DigiHaptic

Device description by: INPG on 17/01/2005

General Description of the device

Domain of application: The originality of this device lies in having three end effectors which can be handled at the same time with force feedback. A large set of applications such as CAD software or gaming can be imagined.
Physical description: The DigiHaptic device comprises three levers associated with the thumb, forefinger and ring finger disposed ergonomically on a hand rest. Each lever is associated with a DC motor to provide force-feedback.
The DigiHaptic can be used in isotonic and elastic mode with force feedback and in isometric mode.

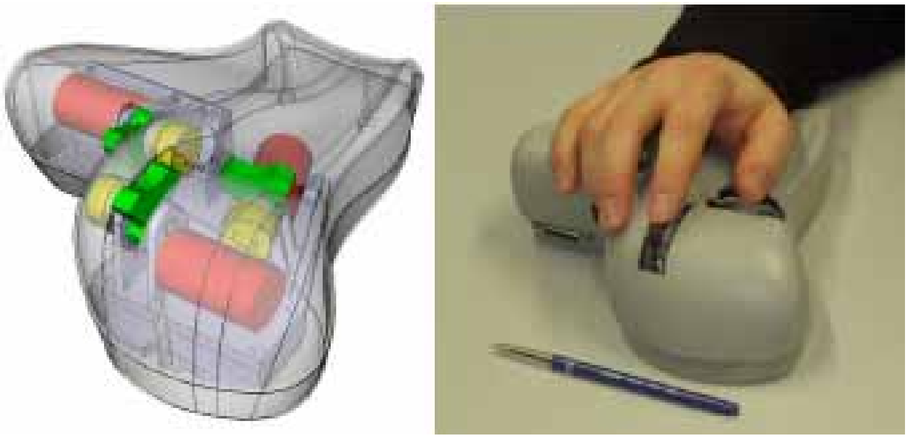

Figure 6.48 - the DigiHaptic with its three levers actuated by motors and the way the user puts his hand on it

Level of achievement: prototype
Future developments, if any: Tests must be carried out in various applications in order to find the qualitative and quantitative limits in each of the three modes (isotonic, isometric and elastic).

Technical points

Mechanism

Size of workspace	Each lever has 120° freedom and 2 cm redius, but hand morphological constraints mean the user can only use up to 60° of each lever's freedom. (equivalent to a 10 * 10 * 10 cm workspace)
Spatial reference	desk reference
Number of degrees of freedom	3
Characterization of the system in a passive state	Configurable (isotonic/isometric)
Cinematic configuration type	Paralel (DOF are independent)
Structure of mechanism (internal cinematic configuration)	Each of the three levers is actuated by a DC motor
Morphology of the system.	

Signal Processing

Bandwidth or sampling rate.	1000 Hz

Actuation

Technology of Actuators

Physical principle	Linear DC motors
Type of Commutation system (if any)	Stainless steel cable Iron brush bearings

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	2 N
Max continuous force/torque exerted	2 N

Sensing

Physical principle of the sensors	potentiometer
Resolution	0.02° theoretical 0.06° practical
Bandwidth, max data rate (in the case of sampled digital output)	1000 Hz

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6.17 DLR

6.17.1 Light-Weight-Robot (LWR)

Device description by : DLR on 22/12/2004.

General Description of the device

The Institute of Robotics and Mechatronics plays a major role in the field of applied robotics. Three generations of light-weight robots have been developed so far. The latest version has, like its predecessors, an outstanding load to weight ratio. The robot weighs just 14 kg and is able to handle loads up to 14 kg.

The extreme light-weight construction was feasible by optimizing all crucial parts. FEM and concurrent engineering methods were consequently used. The robot is composed of optimized Harmonic Drive gearboxes, the DLR-RoboDrive motor, weight-reduced safety brakes, and a lot of electronics and sensors. The light-weight robot of the third generation is a modular system. The individual joints are connected via carbon-fiber structures. The innovative hand-axis design enables the configuration as pitch-pitch as well as pitch-roll unit. Similar to the human arm the robot has seven degrees of freedom. This leads to a higher flexibility and less restricted areas compared to industrial robots.

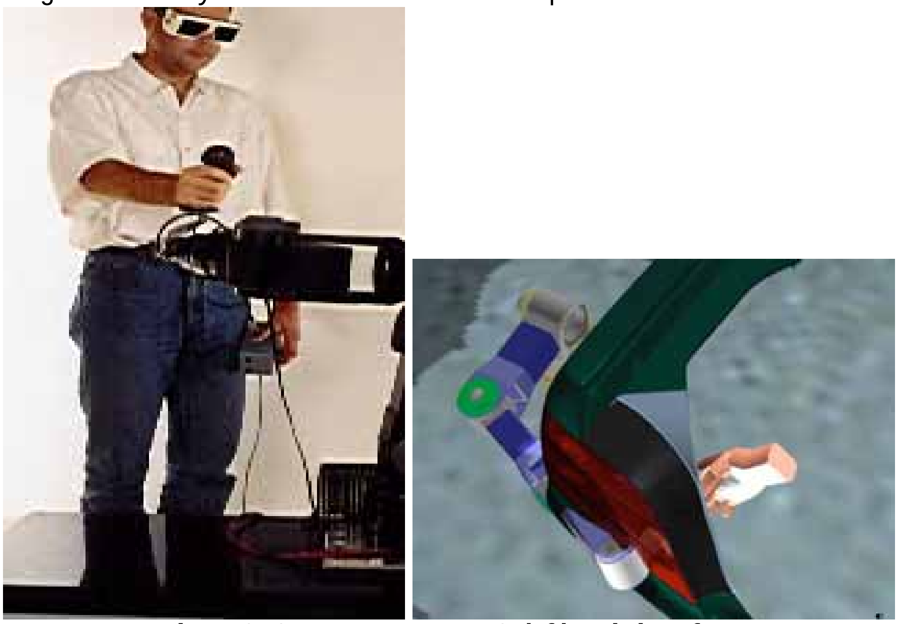


Figure 6.49 DLR –LWR II as 6-dof haptic interface

The complete electronics, including the power converters, is integrated in the arm. A bulky external rack, as known from standard robots, is not needed. A novelty in robot technology is the integrated sensors. Each joint is equipped with a motor position sensor, a joint position sensor and a joint torque sensor. The advanced control algorithms enable vibration-free and high-dynamic movements. Besides position and velocity mode the robot can be used in a torque-controlled manner. Especially the torque-controlled mode opens new fields of application. The individual joints are galvanically isolated. They communicate via a fiber optical bus system. All the cables are leaded internally.

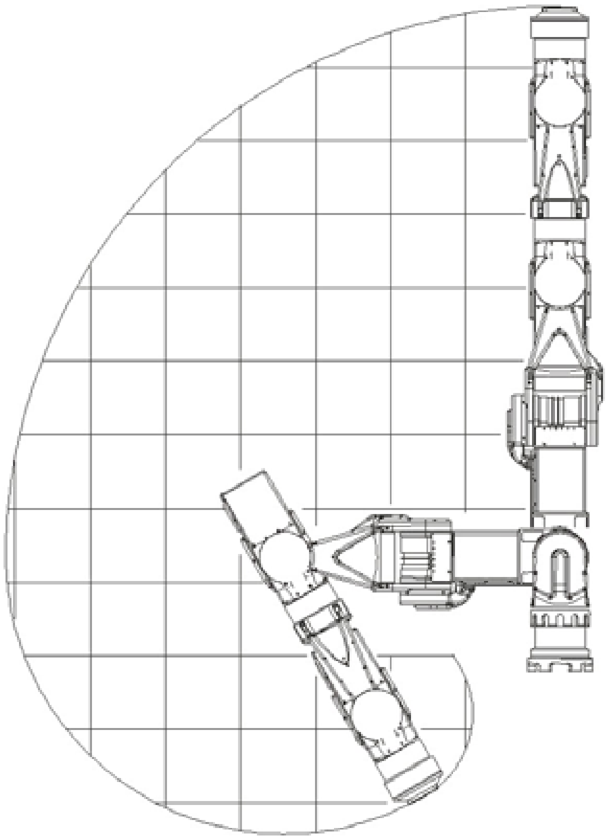
Besides space applications there are a lot of terrestrial possibilities to use the light-weight robots and their technology.

Level of achievement: Prototype.

Future developments: Commercialization with industrial partner

Technical points

Mechanism

Size of workspace	 Spherical diameter: 1000mm
Geometry of workspace	Spherical.
Spatial reference	Floor grounded
Number of degrees of freedom	7 actuated joints
Isotropy of workspace configuration or not, in terms of accessibility	Ergonomically accessible thanks to the redundant kinematics.
Characterization of the system in a passive state	Low inertia through high-bandwidth torque control. Active gravity compensation. No backlash: Harmonic Drive gearboxes are used
Special effects coming from the morphology (such as non isotropic inertia).	Freely programmable behavior (Cartesian stiffness and damping)
Cinematic configuration type	Serial cinematic 3 or 4 roll joints 4 or 3 pitch joints
Structure of mechanism (internal cinematic configuration)	Serial kinematic chain/
Morphology of the system.	/
Material of structure	Carbon fiber links
Type, material and other characteristics of joints (if any)	Light weight structure with aluminum and carbon fiber parts

Frictions: Maximum force level Non-linearity: dry friction, viscous friction	<1Nm (>1% Torque peak) < 1% (accuracy of the torque sensor)
Intrusion of mechanism in visual space of the user	Yes.
System statically balanced	Active gravity compensation

Signal Processing

Number and structure of the signals ports.	Each joint is equipped with a motor position sensor joint position sensor joint torque sensor Optional: 6-DOF-force-torque-sensor at the endeffector.
Type of coding and type of medium.	/
Bandwidth or sampling rate.	Current control: 40 kHz Torque control: 3 kHz Cartesian control: 1 kHz
Type of the local treatments, if any.	Impedance control.
Technology of the local treatments	Digital.

Actuation

Technology of Actuators

Physical principle	Electromagnetic rotary motors.
Specific technologies for the above category	/.
Type of Commutation system (if any)	Brushless DC motors.
Properties of the Commutation System	Analog Hall sensors, which will be replaced by a magneto-resistive (MR) system.
Gear or low-level mechanisms (if any).	Rotational gearboxes. (1:160, 1:100)
Backlash	Zero
Backdrive forces	Axes dependent value

Power driver system

Technology of the power modulator	PWM
Low level control loop	Sinusoidal current control (40 kHz)

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	200N
Max continuos force/torque exerted	140N
Bandwidth	15 Hz
Stroke / Motion range	See Datasheet
Endurance	Prototype; not yet determined

Sensing

Type of sensing	Torque and position (redundant) in every joint
Physical principle of the sensors	Torque: Strain gages. Position: Magnetic (motor position) and resistive (joint position).
Resolution	0.01°
Range of measurements	Force: 200Nm (joint1), 30Nm (joint 7)

	Position: +- 170°.
Location in the haptic system – relation / link with the geometry of the mechanism	Located in every joint

Other properties

Weight	14kg
Power consumption	50W for the electronics. 100W at low speed
Thermal dissipation	
Security and protection systems, if any	Redundant sensors, Model-based safety checks. Compliant movement.

Sources

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6.17.2 DLR Force-Feedback Joystick

Device description by : DLR on 22/12/2004.

General Description of the device

Numerous simple command tasks in telerobotics and telepresence can be accomplished with human machine interfaces with a maximum of two or three degrees of freedom (DOF). For this kind of applications the joystick represents a very intuitive way to command a teleoperator or an object within a virtual environment in two DOF. This type of human machine interface became more popular after being used as a command input in PC games. In the last years the functionality of joystick systems has been expanded by adding electric actuators to the joystick axes, enabling in this way force feedback commands to the operators hand and thus a more precise and intuitive command issue.
The goal of our development works concerning force feedback joysticks was to obtain a high fidelity haptic display with two DOF which allows a very realistic force display.
The mechatronic solution adopted for the force exertion was to add a drive combination of ironless DC brushed motors and cable gears to the cardanic joint of the joystick axes. This approach allows changeability of different force levels by adapting the motor-gear combination.
To obtain high accuracy the position in both joystick axes is measured by high resolution encoders and the motors have ironless and sloped windings. The power electronics assure a very precise current control in both axes with very high chopping rates.

Figure 6.50 USB Force Feedback Joystick

Figure 6.51 Steer-by-Wire Joystick

For the use in different applications at DLR have been developed three versions: the dSpace Force-Feedback Joystick, Steer-by-Wire Joystick and the USB Force-Feedback joystick

Technical points

Mechanism

Size of workspace	spherical sector 2 x +/- 20°
Geometry of workspace	Spherical sector
Spatial reference	Desktop application
Number of degrees of freedom	2 actuated joints
Isotropy of workspace configuration or not, in terms of accessibility	Isotropic beahavior
Characterization of the system in a passive state	Low inertia due to mechanic design No backlash, very low friction
Special effects coming from the morphology (such as non isotropic inertia).	/.
Cinematic configuration type	Cardanic joint (2 DoF rotational)
Structure of mechanism (internal cinematic configuration)	Serial kinematic chain/
Morphology of the system.	/
Material of structure	Aluminum and rapid prototyping plastics
Type, material and other characteristics of joints (if any)	/.
Frictions: Maximum force level Non-linearity: dry friction, viscous friction	<20N (>1% Torque peak) < 0,2%
Intrusion of mechanism in visual space of the user	Yes.
System statically balanced	No

Signal Processing

Number and structure of the signals ports.	Each axe is equipped with a motor position sensor joint position sensor Communication: parallel port-dSpace or fast USB
Type of coding and type of medium.	/
Bandwidth or sampling rate.	Current control: 40 kHz Impedance Control: 4 kHz
Type of the local treatments, if any.	Impedance control.
Technology of the local treatments	Digital. (Freescale DSP)

Actuation

Technology of Actuators

Physical principle	Electromagnetic rotary motors.
Specific technologies for the above category	/.
Type of Commutation system (if any)	Brushed DC motors.
Properties of the Commutation System	Mechanic collector
Gear or low-level mechanisms (if any).	Rotational gearboxes. (1:14)
Backlash	Zero
Backdrive forces	negligeable

Power driver system

Technology of the power modulator	PWM
Low level control loop	Current control (40 kHz or 80kHz)

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	20N
Max continuos force/torque exerted	18N
Linearity	0,1%
Bandwidth	100 Hz
Stroke / Motion range	2 x +/- 20°
Max speed (due to intrinsic limitation or to the driver)	/
Endurance	First Prototype works since 1996

<u>Sensing</u>

Type of sensing	Position (redundant) in every joint
Physical principle of the sensors	Current: resistors Position: Optical Encoder (motor position) and potentiometer (joint position).
Resolution	0.0127°
Range of measurements	Current: up to 4 A Position: +/- 20°.
Location in the haptic system – relation / link with the geometry of the mechanism	Located in every joint

<u>Other properties</u>

Weight	2 kg
Whole dimensions of the system	270 x 180 x 260 mm (L x W x H)
Power consumption	Max. 50 W (4W when motors disabled)
Thermal dissipation	
Security and protection systems, if any	Redundant sensors, ‘Dead man’ switch.

Sources

dSpace Force-Feedback Joystick and Steer-by-Wire Joystick reports are only DLR internal available.

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[2] Y.Yokokohji and T.Yoshikawa, "Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling -Formulation and Experiment-," IEEE Transaction on Robotics and Automation, Vol.10, No.5, pp.605 - 620, 1994.

[3] T.Imaida, Y.Yokokohji, T.Doi, M.Oda, T.Yoshikawa: "Ground-Space Bilateral Teleoperation of ETS-VII Robot Arm by Direct Bilateral Coupling under 7-sec Time Delay Condition," IEEE Transaction on Robotics and Automation, Vol.20, No.3, pp.499-511, 2004.
[4] SL811S/ USB Sual Speed Slave Controller; Data Sheet; Cypress, October 2001

6.17.3 DLR SENSO-Wheel SD-17C from SENSODRIVE

Device description by : DLR on 22/12/2004.

General Description of the device

The innovative SENSO-Wheel SD-17C is primarily used for force-feedback simulators and steer-by-wire systems. The SENSO-Wheel incorporates SENSODRIVE® technology. The SENSO-Wheel is a compact system which can be quickly and easily installed. High resolution torque generation results in a very realistic driving sensation. User-definable damping and friction enables an optimized system feedback. The SENSO-Wheel has been developed by SENSODRIVE (www.sensodrive.de), which is a spin-off company from DLR.

Figure 6.52 SENSO-Wheel SD-17C

Level of achievement: Commercially available standard product.
Future developments: /

Technical points

Mechanism

Size of workspace	Rotational +/- 4 turns
Geometry of workspace	Rotational. (1 DoF)
Number of degrees of freedom	1
Isotropy of workspace configuration or not, in terms of accessibility	Compact design
Characterization of the system in a passive state	Low inertia through high-bandwidth torque control; No backlash: Harmonic Drive gearboxes are used..

Special effects coming from the morphology (such as non isotropic inertia).	Friction of gear with periodical effects (due to Harmonic Drive gearbox)
Type, material and other characteristics of joints (if any)	Standard materials /
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	Maximum torque 26Nm Remaining friction 0,03Nm Bandwidth of the torque controller 30Hz < 1% (accuracy of the torque sensor)
Intrusion of mechanism in visual space of the user	Yes.
System statically balanced	Active gravity compensation

<u>Signal Processing</u>

Number and structure of the signals ports.	Absolute multi-turn position sensor Torque senor
Type of coding and type of medium.	Hiperface/ Ethernet UDP or CAN
Bandwidth or sampling rate.	Current control: 16 kHz Torque control: 3 kHz
Type of the local treatments, if any.	Impedance control.
Technology of the local treatments	Digital.

<u>Actuation</u>

Technology of Actuators

Physical principle	Electromagnetic rotary motors.
Type of Commutation system (if any)	Brushless DC motors
Properties of the Commutation System	Multi-turn Hiperface-Encoder
Gear or low-level mechanisms (if any).	Rotational gearboxes. (1:50)
Backlash	Zero
Backdrive forces	Active state: 0.03Nm Deactivate state: 4Nm

Power driver system

Technology of the power modulator	PWM.
Low level control loop	Current control (16 kHz)

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	26Nm
Max **continuous** force/torque exerted	26Nm
Linearity	1 %
Bandwidth	30 Hz (torque control loop)
Stroke / Motion range	+/- 4 x 360° mech. rotation
Max speed (due to intrinsic limitation or to the driver)	115 rpm
Endurance	1 year warranty

<u>Sensing</u>

Type of sensing	Torque and position.
Physical principle of the sensors	Strain gages. Optical position sensor.

Resolution	0.01°
Range of measurements	Force: 200Nm (jonint1), 30Nm (joint 7) Position: +- 170°.
Location in the haptic system – relation / link with the geometry of the mechanism	

Other properties

Weight	3kg
Power consumption	150W
Security and protection systems, if any	Model-based safety checks.

Sources

[1] Hirzinger, G., Sporer, N., Schedl, M., Butterfaß, J., Grebenstein, M.: Torque-Controlled Lightweight Arms and Articulated Hands: Do We Reach Technological Limits Now.

[2] International Journal of Robotics Research, 23, 4-5, (2004), S. 331-340, Datasheets and further descriptions can be found at www.sensodrive.de

6.18 CEIT

6.18.1 LHIfAM

Device description by : CEIT on 30/06/2004.

General Description of the device

Brief history: The whole haptic system has been created from scratch by CEIT Applied Mechanical Department. It is a multidisciplinary development that includes, amongst others, the following disciplines: mechanical design, control theory, computer graphics, computational geometry and human-machine interaction.
Domain of application: Maintainability simulation in Aeronautics. The system is designed and built to realistically simulate assembly-disassembly operations as well as accessibility, interference and maintainability analysis by using virtual reality techniques instead of physical mock-ups.
Physical description: The system is floor-grounded due to the large workspace needed for the maintainability application. The basic workspace of the haptic interface occupies a cylindrical sector, which corresponds to a wide work area of a virtual 3D aircraft engine full-scale mock-up.
Level of achievement: Prototype.
Future developments: Implementation of torque feedback.

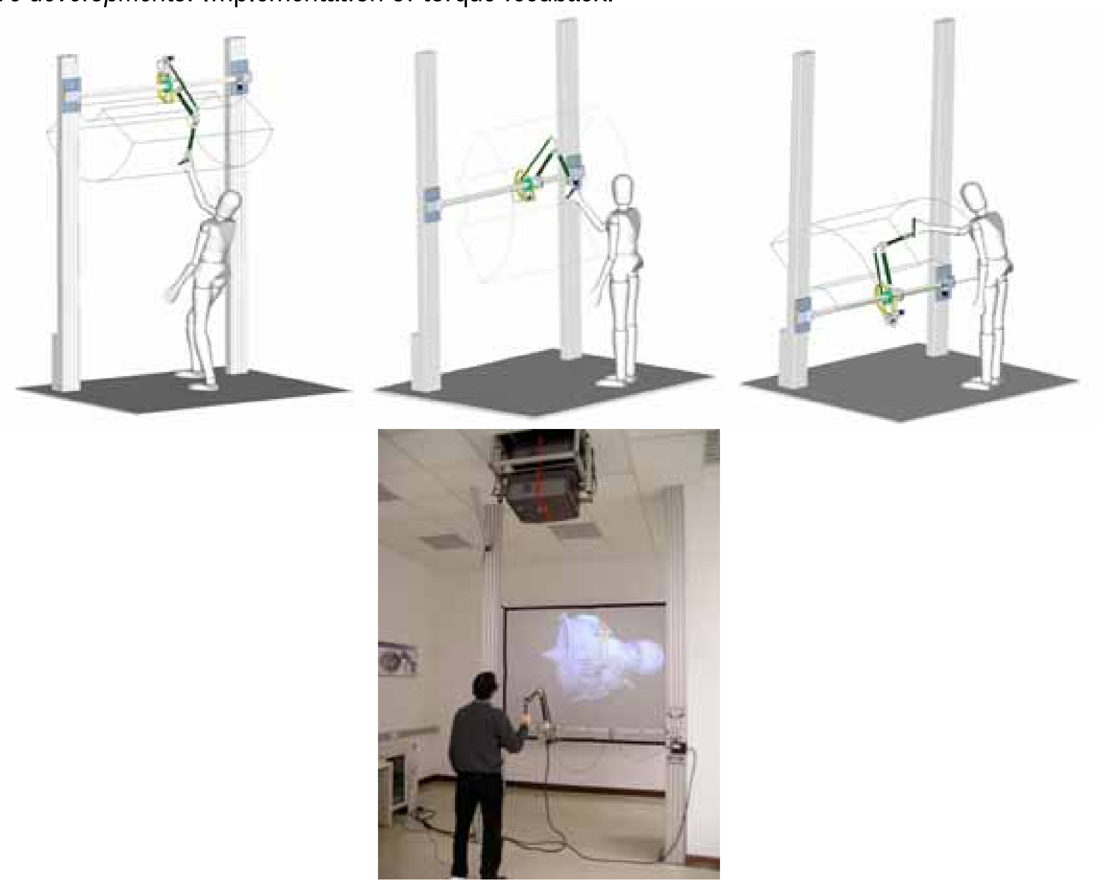


Figure 6.53 LHIfAM device manipulation

Technical points

Mechanism

Size of workspace	Cylindrical sector: Rmax=790mm, Rmin=235mm, length=1500mm, angle=120º

Geometry of workspace	Cylindrical sector. Possibility of reorientation around its axis and relocation in height
Spatial reference	Floor grounded
Number of degrees of freedom	6: 3 translational measured & actuated, 3 rotational measured
Isotropy of workspace configuration or not, in terms of accessibility	Ergonomically accessible thanks to the possibility of the aforesaid workspace reorientation and relocation.
Characterization of the system in a passive state	Low inertia in the directions normal to the cylindrical workspace axis. Passive gravity compensation without the addition of dead weight. Minimum backlash through pretensioned cable transmissions.
Special effects coming from the morphology (such as non isotropic inertia).	Bigger inertia in the cylindrical workspace axis direction is compensated by the control loop.
Cinematic configuration type	3 translational dof: Hybrid mechanism. 3 rotational dof: Serial wrist.
Structure of mechanism (internal cinematic configuration)	3 translational dof: PRR (Prismatic-Revolute-Revolute) The prismatic joint corresponds to the cylindrical workspace axis direction 3 rotational dof: RPR (Roll-Pitch-Roll). Rotations decoupled from translations.
Morphology of the system.	A parallelogram mounted on a linear guide with a wrist attached to its endpoint.
Material of structure	Carbon fiber links, aluminum for the rest of the pieces.
Type, material and other characteristics of joints (if any)	Ball bearings for revolute joints, linear motion-rolling guide for the prismatic joint.
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	 <1N (1.4%Fpeak) <3.5Ns/m
Intrusion of mechanism in visual space of the user	Yes.
System statically balanced	Yes.

<u>Signal Processing</u>

Number and structure of the signals ports.	6 encoder inputs, 3 analog force outputs.
Type of coding and type of medium.	
Bandwidth or sampling rate.	Control PC: 0.5kHz.
Type of the local treatments, if any.	Impedance control with force feedforward for inertia compensation.
Technology of the local treatments	Digital.

<u>Actuation</u>

Technology of Actuators

Physical principle	Electromagnetic rotary motors.
Specific technologies for the above category	Ironless rotor.
Type of Commutation system (if any)	DC graphite brushed motors.
Gear or low-level mechanisms (if any).	Linear & rotary cable transmission
Backlash	Near zero

Power driver system

Technology of the power modulator	PWM.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	70N
Max **continuous** force/torque exerted	18N

Sensing

Type of sensing	Force and position.
Physical principle of the sensors	Force: Strain gages. Position: Optical incremental rotational encoders.
Resolution	Position: 0.02mm
Range of measurements	Force: 40N Position: Unlimited.

Subjective evaluation

PERCRO

Moving in free space

Actuators off

The device was tested enabling the motors. As expected the inertia was quite low if moving in the vertical longitudinal plane but very high if moving along the prismatic joint. The friction is anyway very low.

Actuators on

When the actuators are switched on the inertia along the horizontal direction was drastically reduced. The lack of gravity compensation is probably the main cause of parasitic forces during the free space movement. The isotropy of the perceived inertia is well optimized at workspace center but in other position the gravity forces makes impossible to judge the inertia properties.

One point contact with a CUBE

Simulation of a rigid wall

The stiffness is very high (50N/mm) and the static contact is stable. The stability is not influenced by the changing of the way to handle the end effector.

Surface exploration with light forces

During this test the surfaces of the cube were explored exerting very light forces. Tin this case there was a directional dependent quality of contact. The contact was smooth while exploring the horizontal surface and the lateral surfaces of the cube but a small ripple was perceivable while “touching” the frontal surface.
This phenomena was not dependant from the way of gripping the end effector.

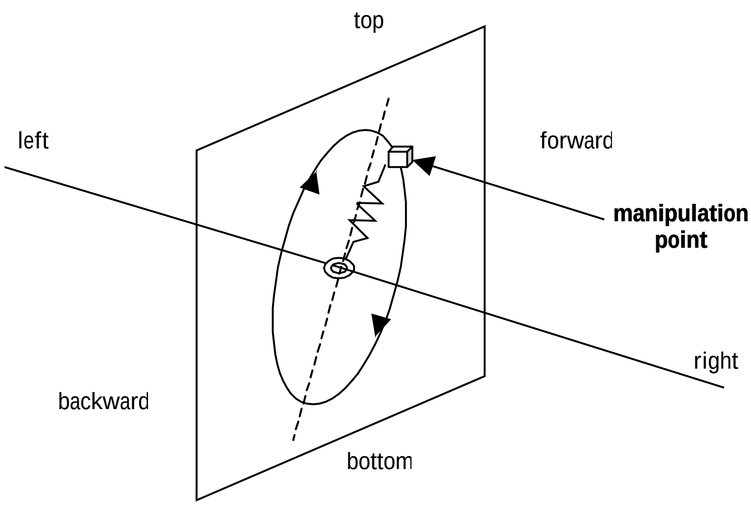
Simulation of impact

This test consist in moving in quite fast way the haptic interface “against the virtual object” in order to verify the stability of elastic response. Also in this case there was a directional behavior of the device. When “hitting” the horizontal and lateral surface the contact was stable, while hitting the frontal surface the elastic response was bigger than expected.
This phenomena was not dependant from the way of gripping the end effector.

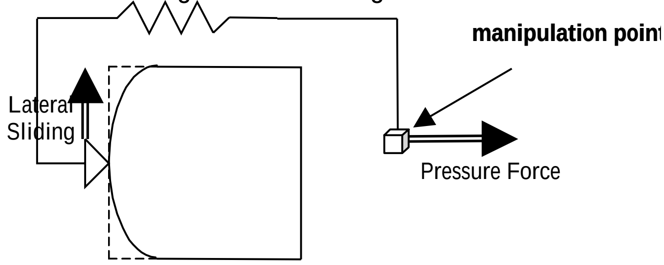
INPG

Experience report IIa

Property to target	Free space motion behaviour.
Strategy planned	I hold the stick as a pen, I close my eyes not to be influenced by the visualisation, I will move in the free space along straight movements.
Result	Moving left and right in free space, I feel an obvious inertia, which needs some effort to initiate the movement and some effort to stop abruptly the haptic device. Moving at constant speed, this inertia is not damped, the environment viscosity is very low. I feel a small lateral friction (left-right), which is difficult to assess because I'm influenced by the noise of the haptic device (rail). There is no apparent big instabilities during these movements. I feel a difference while moving left-right, top-bottom or forward-backward.
Modification of the strategy	From this difference, still closing the eyes, I will try to make some circular movements to check the isotropy of the forces.
Result	I try to perform circular movements in the vertical front plan. My circle looks like a square, I have to move very slowly to be able to follow a circular path.
Modification of the strategy	I will perform circular movements in the 2 other plans, as comparison.
Result	I still feel the forces in the 3 plans are not isotropic. It's particularly different in the forward-backward/top-bottom plan, and along the forward-backward direction.
Modification of the strategy	I try to push and pull to fill the forward-backward direction.
Result	I feel the force is not zero, some force tries to bring me back in the middle position. Actually, there is a kind of spring, which always bring me back in a fixed middle position in the plan (forward-backward/top-bottom), but not along the left-right lateral axis (see scheme below).
Modification of the strategy	I will take the haptic stick as a hammer to see if I have the same feelings of the forces.
Result	There is no much difference, but I have a better control of my movements (the impedance of my hand is higher).
Experience report	The motion in 3D space can be done in a very large scale (several dozens of centimetres). The system is difficult to move left-right at high frequency (inertia). There is also some viscosity on this axis (the system stops by itself on a short distance). The force field is not isotropic in the forward-backward/top-bottom plan. There is a kind of elliptic guidance in this plan for a given force.

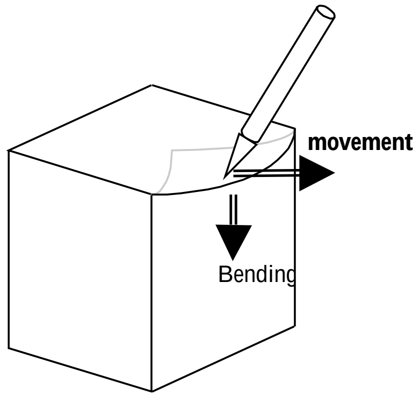


Experience report IIb

Property to target	Exploring an object: contact with the cube surface.
Strategy planned	I open the eyes, I will explore the top surface of the cube by approach-retract and I will modulate the velocity to try to feel the edge of the contact.
Result	It needs a few seconds of learning to get use to quickly find the position of cube related to the position of the manipulation point in the 3D space. The contact is sharp and hard. I can easily exert a pressure of 10 or 20N of force, it's stable. I feel a bounce when I reach the surface with high velocity. With a low velocity I can't determine accurately the moment when I arrive on the surface.
Modification of the strategy	I will try to exert a stronger pressure on the surface to test the stability of the contact.
Result	What I feel and what I see are not correlated, in the way that I feel an elasticity whereas I can't see any visual deformation of the cube. Since I see the deformation of the haptic arm, this elasticity seems to be due to the haptic arm. While I'm applying a strong pressure, I can't control and stay on a fixed point of the surface, but I'm sliding apart and I lose the contact with the cube. The feeling is like if my contact point were much below the level of the surface (even below the level of the cube) and it's an instable position: I don't dig a potential on the middle of the surface, but the edge of the cube are bending down and make me slide out of the surface. I have the feeling of the following scheme : 
Modification of the strategy	I will apply a light force and move around the surface to see if there are instabilities at a small scale and some friction on the surface.
Result	I make some circular movements on the top surface of the cube. It seems to be isotropic. I can't feel any rasping.
Modification of the strategy	I feel try to check if the other surfaces of the cube are similar.
Result	On the front surface, I feel a kind of grain. On the right-side surface, it's much more clean and stable than on the 2 other surfaces and it's stiffer.
Experience report	The contact forces are rather high and the contact edge is clear. However the feeling of stiffness and rasping are different on the 3 surfaces. A hard pressure on the middle of the surface will not involved to get into the cube, but to be sweep off from the cube.

Experience report IIc

Property to target	Exploring an object: feeling the edges and corners of the cube.
Strategy planned	I will explore an edge of the cube and try to understand the feeling of "sweep off" that I had when I pressed on the cube surface.
Result	I brush the edge from inside to outside the surface. The feeling is sharp and clean. I try to go from a surface to the other. I can't stay on the edge. I can't reach directly a surface from another in a continuous movement as I could do it with a real cube. Instead, I sweep out of the surface in the free space. The feeling is like a gripped string. I can feel the edge bowing before it releases. It's just like if I explore the side of a piece of paper using a pencil. The effect is symmetrical (and reversed) when I go in the opposite way.

	
Modification of the strategy	I will now explore a corner of the cube to check how I can feel and if the edges are the same nearby a corner.
Result	I still can feel the edge very sharp, and with the same effect of "knife's blade", but the rigidity is maybe a little higher. I can't find directly the corner, I just the succession of the 3 edges. I can imagine the position of the corner, moving with a fast circular movement around the 3 edges.
Experience report	The boundary of a traditional cube is typically "visual". What I feel here is a kind of transcription of this visual bounds, I don't feel a continuous contact as I would with a real cube in a instrumental manipulation (using a pencil for instance). I feel some string or knife's blade effects on the edges, probably due to the geometrical formalism of the mock-up.

Experimenter report on the system.

Experimental configuration(s):

Simulation of the direct interaction between a manipulation point (representing the haptic device point) and a fixed and full 3D cube, in a 3D empty space.

Global strategy followed.

I mostly try to figure out the limitations of the system, like the inner elasticity/viscosity of the arm, the quality of the hard contact and of the sharp area (edges), as well as the free motion:

- Free space motion behaviour

The motion in 3D space can be done in a very large scale (several dozens of centimetres). The system is difficult to move left-right at high frequency (inertia). There is also some viscosity on this axis (the system stops by itself on a short distance). The force field is not isotropic in the forward-backward/top-bottom plan. There is a kind of elliptic guidance in this plan for a given force.

- Exploring an object: contact with the cube surface

The contact forces are rather high and the contact edge is clear. However the feeling of stiffness and rasping are different on the 3 surfaces. A hard pressure on the middle of the surface will not involved to get into the cube, but to be sweep off from the cube.

- Exploring an object: feeling the edges and corners of the cube

The boundary of a traditional cube is typically "visual". What I feel here is a kind of transcription of this visual bounds, I don't feel a continuous contact as I would with a real cube in a instrumental manipulation (using a pencil for instance). I feel some string or knife's blade effects on the edges, probably due to the geometrical formalism of the mock-up.

General opinion on the system

The LHIfAM system is based on an arm structure, closed to the PHANToM, but a range of one meter. Firstly, I'm not sure to understand the reason of working at a large scale, since working at smaller scale but with higher accuracy is morphologically analogous. For such a large working space, the haptic rendering is very good in accuracy and force rate. It seems also very reliable, no noise and no bugs. However, working at this scale brings some drawbacks difficult to compensate: the elasticity and viscosity of the arm is high and we feel it during the manipulation, as if we had something attached to our arm, preventing us from acting easily and fast. Although it's not clear to me, I think this device is surely interesting to manipulate scenes in the case where having a large spatial displacement in the user space is important. It would be worth to compare the pros and cons in user space displacement range (technically vs. haptically speaking).

CEIT

The user handles the robot's end effector and simply moves it. The present robot position is conveyed to the virtual environment and the contact forces in the virtual environment are sent back to robot's arm.
The scene tested consists of a virtual cube. So a free test, a contact test and corner test can be completed.
Firstly, the free movement test is done without inertia compensation in Z-axis. Obviously, the inertia in Z-axis is so high that some kind of compensation is required. The inertia that is felt in X-axis and Y-axis is negligible.
The second step is to analyse the inertia compensation in Z-axis: After activating the inertia compensation, the operator feels that device's behaviour is very isotropic.
The impact test is felt as stiff rubber stiffness (the virtual stiffness was actually 1500Nm). However, it is completely stable.
There are almost negligible instabilities in the direction of the inertia compensation is done.
The flat surfaces are felt as flat surfaces.
The corners are well perceived.
With a big mock-up some basic disassembly processes can be done.
The contact is unstable when pipes are tested.
In a still contact, if the penetration is high, a small tremble is felt.

DLR

Moving in free space

Actuators off

This test showed the low friction along every ax. The quite high inertia along the horizontal joint is good perceptible (about 3 times higher than other DOF).

Actuators on (active feed forward compensated)

- the inertia along the horizontal direction was reduced
- parasitic forces during the free space movement; probably reason: lack of gravity compensation
- inertia: is isotropic in the whole workspace center; in other position the gravity forces makes impossible to judge the inertia properties.

One point contact with a CUBE

Simulation of a rigid wall

- stiffness = 50N/mm
- static contact is stable
- stability is not influenced by the changing of the way to handle the endeffector. – it influences the subjective perception of the forces

Surface exploration with light forces

- the surfaces of the cube were explored exerting very light forces
- there was a directional dependent quality of contact: smooth while exploring the horizontal surface and the lateral surfaces of the cube; a small ripple was perceivable while "touching" the frontal surface.
- Possible reason for torque ripple: current controller with different parameters (not adapted to the motor) or noise sensitivity caused by the long motor cables;

Simulation of impact

- moving in quite fast way the haptic interface "against the virtual object" in order to verify the stability of elastic response: In this case there was a directional behavior of the device when "hitting" the horizontal and lateral surface the contact was stable, while hitting the frontal surface the elastic response was bigger

Controlling the engine model

- when the engine model is loaded (high amount of polygons) the haptic device reacts very 'nervous' and unstable when trying to slide along curved planes and in situations of multiple contacts; the main disadvantage in this situation are the missing torque feedback commands (only 3 DOF feedback). Due to this situation the handling of the tools (ratchets) is implemented in a less intuitive manor.

Sources

Borro, D., Savall, J., Amundarain, A., Gil, J. J., García-Alonso, A.,Matey, L. (2004). "A Large Haptic Device for Aircraft Engines Maintainability," in *Proceedings of the IEEE Computer Graphics & Applications (to appear in)*, November.

Savall, J., Borro, D., Amundarain, A., Martin, J., J. Gil, J.,Matey, L. (2004). "LHIfAM - Large Haptic Interface for Aeronautics Maintainability," in *Proceedings of the IEEE International Conference on Robotics & Automation (audiovisual material)*, New Orleans, LA, USA, April 26 - May 1.

Savall, J., Borro, D., Gil, J. J.,Matey, L. (2002). "Description of a Haptic System for Virtual Maintainability in Aeronautics," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, EPFL, Lausanne, Switzerland, pp. 2887-2892, September 30 - October 4.

6.19 UNEXE

6.19.1 Exeter Tactile Array 100

Device description by : UNEXE on 21/12/2004.

General Description of the device

The stimulator array described in this technical sheet has been designed to create "lifelike" spatiotemporal patterns of tactile stimulation on the skin. The intention is not to reproduce the topology of "real" surfaces – rather it is to reproduce an appropriate excitation pattern over the various populations of mechanoreceptors in the skin. The spatial resolution required for stimulus presentation is thus related to the density of receptors, and is effectively determined by the spatial acuity for tactile perception – around 1 mm on the fingertip for "real" stimuli such as gratings. This device has 100 piezoelectric-bimorph drive elements linked to 100 contactors arranged on a square matrix (1 mm _ 1 mm spacing) over an area of 1 cm^2. The plane of the stimulating surface is horizontal in normal use, with motion of the contactors normal to this surface. The 10 _ 10 square of moving contactors is surrounded by a ring of 44 fixed contactors, giving a 12 _ 12 array overall, designed to cover the fingertip. The fixed contactors are included to ensure that each of the moving contactors is surrounded on all sides by other contactors and is thus subject to a similar mechanical load from the skin.
The contactors are the circular free ends of L-shaped wire link (brass, 0.6-mm diameter) attached to the bimorph elements. Drive voltages to the bimorphs cause them to bend and this results in movement of the contactors. The wire links are electrically insulated from the bimorphs to avoid any possibility of electrotactile stimulation. To ensure accurate spacing of the contactors, the links run through a low-friction (PTFE) plate containing a matrix of 0.8-mm holes at 1 mm _ 1 mm spacing. The surface formed by the contactors lies 1 mm above the upper surface of the PTFE plate. In normal use the contactors maintain contact with the skin but the PTFE plate is clear of the skin.

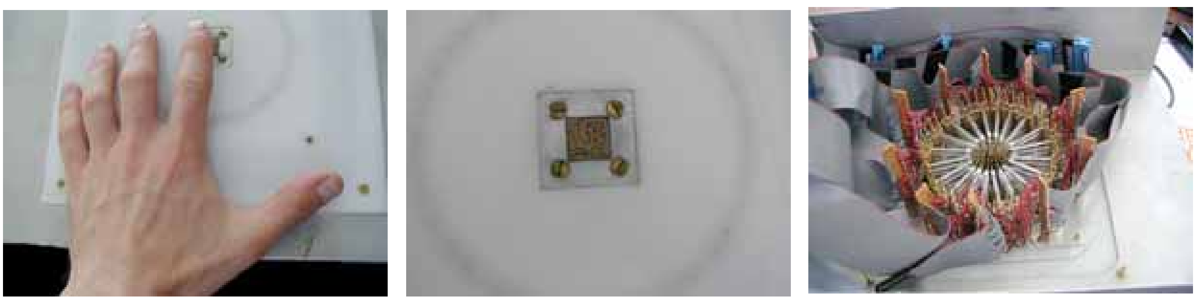


Figure 6.54 Exeter Tactile Array

This is an operational research tool which was not intended for commercial applications.

Technical points

Mechanism

Size of workspace	Fingertip display
Geometry of workspace	10mm _ 10mm square
Spatial reference	Fingertip
Number of degrees of freedom	100 independent actuators
Isotropy of workspace configuration or not, in terms of accessibility	N/A
Characterization of the system in a passive state	N/A
Special effects coming from the morphology (such as non isotropic inertia).	N/A
Material of structure	Aluminium and brass
Type, material and other characteristics of joints (if any)	N/A
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	N/A

Signal Processing

Type of local treatments	No feedback mechanism

Actuation

Technology of Actuators

Physical principle	Piezo electric
Specific technologies for the above category	Bimorph bending elements
Type of Commutation system (if any)	N/A
Gear or low-level mechanisms (if any).	N/A

Power driver system

Technology of the power modulator	High power audio-type amplifiers (85Vpp)

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	
Max continuous force/torque exerted	
Linearity	
Bandwidth	20-400 Hz
Stroke / Motion range	0.55 μm V^{-1} at 40 Hz ,0.065 μm V^{-1} at 320 Hz
Frequency response or resonance effects	Resonant frequency ~140 Hz Driven off resonance.

Tactile Component

Number and geometry of contactors	100 pins (0.6mm diameter) in 1mm spaced square grid
Area stimulated	1cm^2
Stimulation method	Vibrotactile, normal to skin surface
Parameters under hardware/software control	Independent control of amplitude and relative phase of 40 Hz and 320 Hz sine waves for each pin. Max length of stimuli 2s. Resolution 1/40th s.

Other properties

Price	N/A
Weight	0.75 kg (stimulator array)
Whole dimensions of the system	150 × 150 × 75 mm (stimulator array)

6.19.2 Exeter Five Finger Array 125

Device description by : UNEXE on 21/12/2004.

General Description of the device

This device is the next generation from the High-Density Array. The intention was to make a more modular system with improved output, which was capable of addressing multiple digits at the same time.
It makes use of the same 128 channel DAC system (with external clock) as the original array, but has improved amplifiers and has a pseudo-real time computer control system. This allows stimuli of unlimited length to be presented, or can be used for active exploration experiments.
The stimulator heads have been designed to provide more flexibility in experiment design and to facilitate easier servicing. New, larger bimorph elements have been used which have displacement and force ceilings far greater than the High Density Array.
Each of the 5 heads has a grid of 5 _ 5 active pins, at 2mm spacing. This is surrounded by a guard ring of 24 fixed pins, giving a 7_7 array.
An extra head has been mounted on a standard optical mouse for use in active exploration/co-location experiments.

Figure 6.55 Exeter Five Finger Array 125

This system is a research tool. However, the modular nature of the stimulator heads and the flexibility of the control software make this a suitable prototype platform for future devices incorporating tactile and force-feedback elements.

Technical points

Mechanism

Size of workspace	~ 200mm _ 150mm, or 5 fingertips
Geometry of workspace	Rectangular
Spatial reference	Fingertip
Number of degrees of freedom	125 independent actuators in a planar configuration, in a 2D workspace
Isotropy of workspace configuration or not, in terms of accessibility	N/A
Characterization of the system in a passive state	N/A
Special effects coming from the morphology (such as non isotropic inertia).	N/A
Material of structure	Perspex frame, brass link wires
Type, material and other characteristics of joints (if any)	N/A

Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	N/A

Actuation

Technology of Actuators

Physical principle	Piezo electric
Specific technologies for the above category	Bimorph bending elements
Type of Commutation system (if any)	N/A
Gear or low-level mechanisms (if any).	N/A

Power driver system

Technology of the power modulator	High power audio-type amplifiers (90Vpp)

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	
Max continuous force/torque exerted	
Bandwidth	20-400 Hz
Stroke / Motion range	1.6 μm V^{-1} at 40 Hz , 0.096 μm V^{-1} at 300 Hz
Frequency response or resonance effects	Resonant frequency ~85 Hz Driven off resonance.

Tactile Component

Number and geometry of contactors	125 pins (0.6mm diameter) in 2mm spaced square grids
Area stimulated	5 _ 1cm^2
Stimulation method	Vibrotactile, normal to skin surface
Parameters under hardware/software control	Independent control of amplitude and relative phase of 40 Hz and 320 Hz sine waves for each pin. Unlimited length of stimuli. Resolution 1/40th s.

Other properties

Price	N/A
Weight	0.75 kg (stimulator arrays)
Whole dimensions of the system	200 × 200 × 75 mm

Sources

[1] IR Summers and CM Chanter, "A broadband tactile array on the fingertip", Journal of the Acoustical Society of America 112 (2002) pp. 2118-2126

6.20 MEDIALAB

6.20.1 MESH

Device description by: MediaLab on 02/12/2004

General description of the device

The first revision of Mesh was completed in December 2003. It saw its second revision in October 2004 and currently finished its third revision. The first revision had tilt sensing and one channel of vibrotactile display. The second and third revision share the basic functionality described in this sheet, with the third revision fixing technical short-comings of the second for commercial production.
The application domain is hand-help HCI. It is housed in an Ipaq PCMAA expansion pack. See the picture and schematics for details.
The product is now a commercialized system.

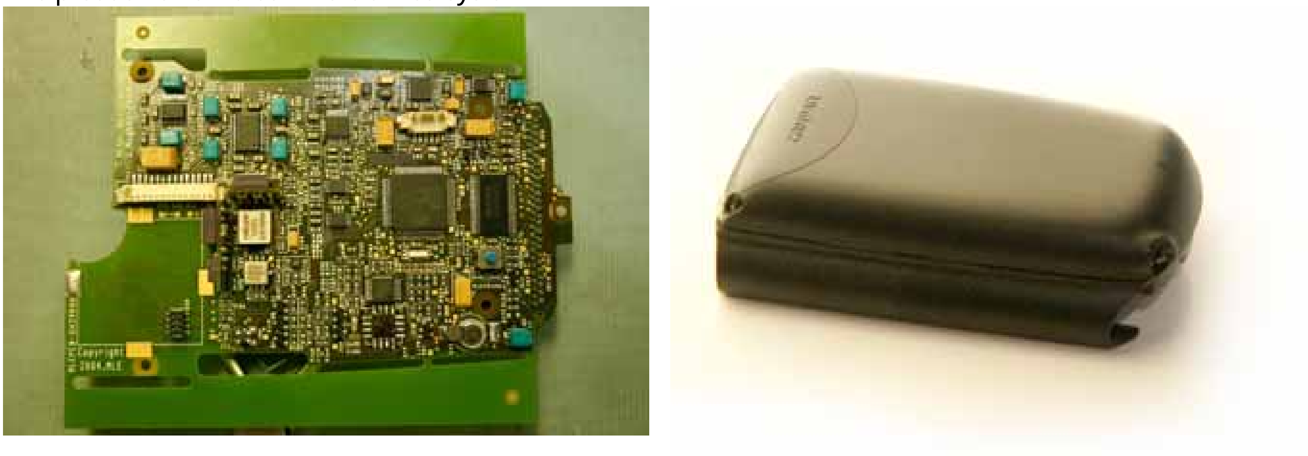


Figure 6.56 Location of Mesh device in a mobile phone

Technical points

<u>Mechanism</u>

Size of workspace	Hand
Geometry of workspace	Hand
Spatial reference	Body
Number of degrees of freedom	3 actuation/ ~30 sensing
Isotropy of workspace configuration or not, in terms of accessibility	N/A
Characterization of the system in a passive state	N/A
Special effects coming from the morphology (such as non isotropic inertia).	N/A
Cinematic configuration type	Hybrid
Structure of mechanism (internal cinematic configuration)	Linear Vibration Transducer
Morphology of the system.	N/A
Material of structure	Plastic
Type, material and other characteristics of joints (if any)	N/A
Frictions: Maximum force level Non-linearities: dry friction, viscous friction	None
Intrusion of mechanism in visual space of the user	None
System statically balanced	N/A

Signal Processing

Number and structure of the signals ports.	(a) 3 axis acceleration (linear), (b) 3 axis angular velocity, (c) 3 axis magnetic field strength, (d) 2 electric field strength, (e) 1 GPS
Type of coding and type of medium.	(a) 14 bit linear (b) 14 bit linear (c) 12 bit linear (d) 12 bit linear (e) see data sheet
Bandwidth or sampling rate.	(a) 40Hz (b) 40 Hz (c) 20 Hz (d) 20 Hz (e) see data sheet
Type of the local treatments, if any.	Open Loop
Functional properties of the local loops	N/A
Technology of the local treatments	N/A

Actuation

Technology of Actuators

Physical principle	Electromagnetic
Specific technologies for the above category	VBW32 vibrotactile display
Type of Commutation system (if any)	NONE
Properties of the Commutation System	N/A
Gear or low-level mechanisms (if any).	N/A
Backlash	N/A
Backdrive forces	N/A

Power driver system

Technology of the power modulator	Class D Fullbridge MAX4295
Low level control loop	None

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	N/A
Max continuous force/torque exerted	N/A
Linearity	10%
Bandwidth	1000Hz
Stroke / Motion range	N/A
Max speed (due to intrinsic limitation or to the driver)	N/A
Frequency response or resonance effects	Peak 250Hz 6dB/Octave fall-off symmetric
Efficiency	50%
Endurance	MTBF = 100000 hours

Sensing

Type of sensing	(a) Accelerometer (b) Gyroscope (c) Magnetic field sensor (d) electric field sensing (e) GPS
Physical principle of the sensors	(a) ADXL311 MEMS (b) ADXRS300 MEMS (c) HMC1053 (d) custom (e) TRIMBLE LASSEN SQ, see data sheets
Resolution	(a) 14 bit (b) 14 bit (c) 12 bit (d) 12 bit (e) see data sheet
Bandwidth, max data rate (in the case of sampled digital output)	(a) 40 Hz (b) 40 Hz (c) 20 Hz (d) 20 Hz (e) see data sheet
Range of measurements	(a) +/- 2*9.81 m/s^2 (b) 640 degrees/s (c) +/- 0.5*10^-4 T (d) 0-20 pF (e) see data sheet
Location in the haptic system – relation / link with	In Hand

the geometry of the mechanism	

Other properties

Price	1000 Euros
Weight	150 grams
Whole dimensions of the system	32x85x130 mm
Spatial constraints	N/A
Power consumption	2 Watts
Thermal dissipation	N/A
Security and protection systems, if any	N/A

6.21 Technical University of Munich (TUM)

6.21.1 VISHARD10 (Virtual Scenario Haptic Rendering Device with 10 DOF)

Device description by INPG on 07/01/2005

General Description of the device

Brief history: A well known deficiency of all non-redundant robots based on serial kinematics with revolute joints is the existence of interior singularities within the workspace. Whereas in common industrial applications it is usually allowed to drive the robot through such singularities it is necessary to circumvent these locations in haptic systems. Moreover, in regions close to singularities the dynamic properties of the robot are degrading. As a result large areas of the device workspace are not available for haptic simulations. Also, an angular workspace of 360° around each axis is in general foreclosed for non-redundant robots. These fundamental limitations are the motivation for the design of VISHARD10 (Virtual Scenario Haptic Rendering Device with 10 DOF), a haptic device with kinematical redundancies. Beneath the increase of workspace the redundandant degrees of freedom offer a potential for collision avoidance and improvement of the dynamic properties and output capability.

Domain of application: The main design objective for the new hyper-redundant haptic interface is to provide a versatile haptic display with distinct advantages compared to existing solutions with respect to universal applicability for a variety of applications; large workspace free of singularities; high payload to accomodate various application specific end-effectors as e.g. surgical tools like drills, scalpels or scissors, to mount tactile stimulation actuators for combined kinesthetic and tactile feedback.

Another goal of this prototype is to provide a benchmarking testbed for the development and feasibility studies of novel haptic applications.

Figure 6.57- ViSHaRD10

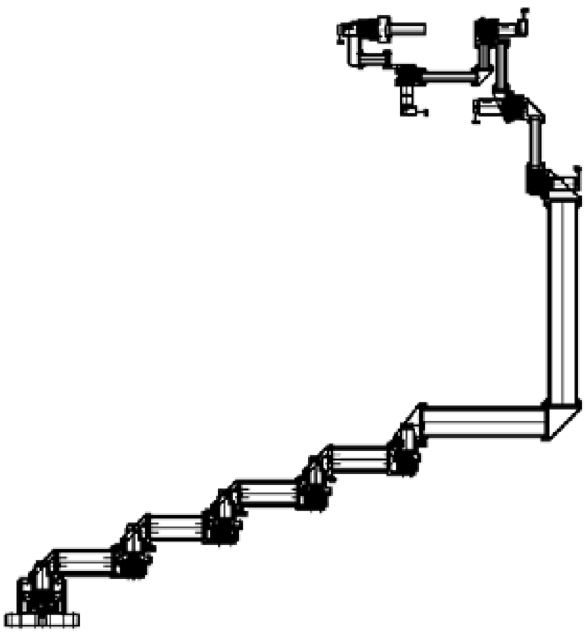


Figure 6.58 - Assembly drawing of ViSHaRD10

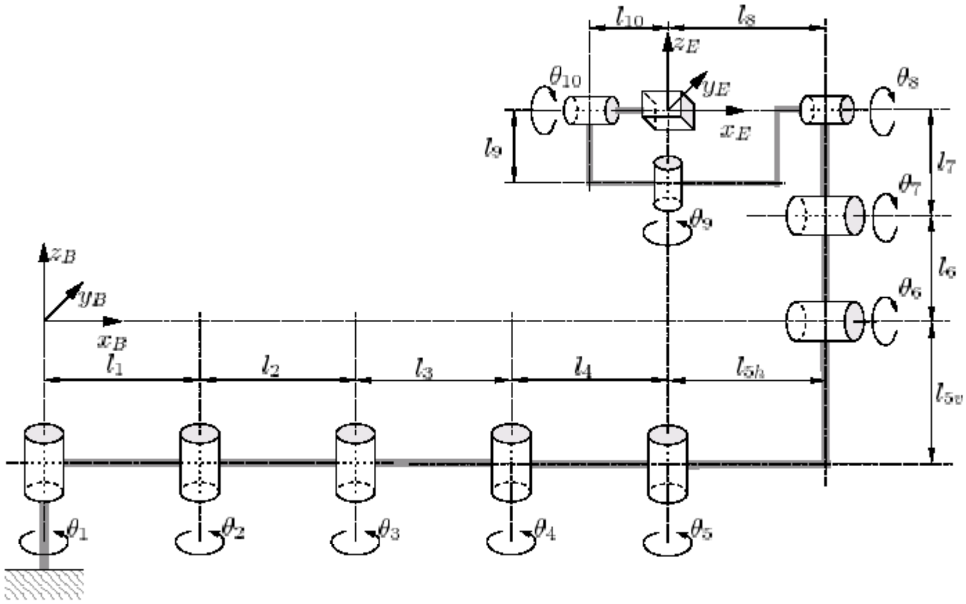


Figure 6.59 - Kinematical model of ViSHaRD10

The kinematic structure of the hyper-redundant design with 10 DOF, ViSHaRD10, is depicted in the figure below, the link length design is summarised in the table below. It shows the reference configuration with all joint angles θ_i defined to be zero.

The first five joints are arranged in a SCARA configuration with vertical axes avoiding an active compensation of gravity. This segment is assigned for the positioning of the end effector in the x-y-plane. Joints 6 and 7 are assigned to adjust the height of the end-effector. Joint 5 is used to prevent singular configurations in the wrist formed by joints 8, 9, 10.

The axes of joint 5, 8, 9, 10 intersect at one point which is located 5 cm in front of the force-torque sensor (assuming that the motion of joint 6 and 7 is controlled accordingly). This enables the operator to grip the end-effector at the point where the angular DOF are mechanically decoupled from the translational ones as for example desired for simulations involving direct haptic interactions with the finger or hand. Alternatively, the user can hold the device at a point behind to simulate the exploration of a virtual environment with the tip of a tool.

Link lenth design of ViSHaRD10

Link i	Length
l1 = l2 = l3 = l4	0.25 m
l5 = l8	0.47 m
l5V	0.71 m
l6 = l7	0.212 m
l9	0.15 m
l10	0.15 m

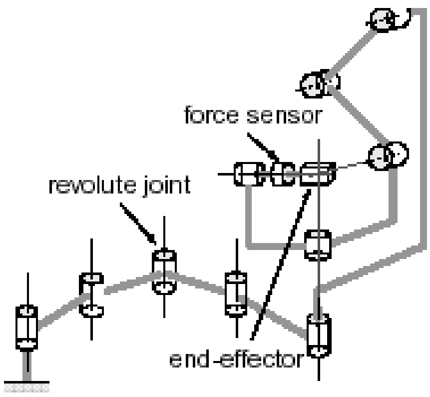


Figure 6.60 - Hyper-redundant haptic device ViSHaRD10

Level of achievement: prototype, commercialized system, etc.

The work on the hyper-redundant prototype completed so far includes: _

Study of standard redundant kinematical robot designs

Development of a prototype haptic interface with ten actuated degrees of freedom; completion of the engineering drawings
_ Completion of the mechanical parts manufacture, assembly of the prototype
Investigation of control strategies along with inverse kinematics solution techniques; numerical studies evaluating the performance of local redundancy optimisation techniques
Future developments: The planned activities for the next project year are
_ Wiring and start-up of the prototype
_ Implementation of the control algorithms
_ Psychophysical evaluation
_ Expansion of the system by an integration of tactile actuators in order to provide collocated kinesthetic and cutaneous haptic feedback
Experimental results for the performance evaluation of VISHARD10 will be provided within deliverables D4.4, D4.5.
The two main schemes of local control loops are the impedance control loop and the admittance control loop:

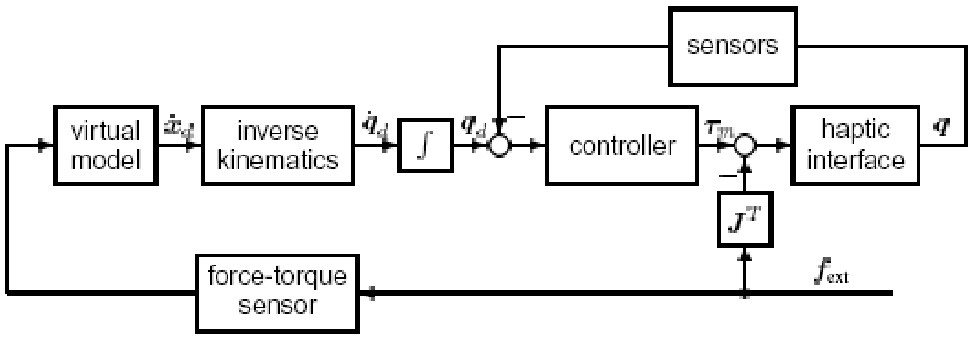


Figure 6.61 General control scheme of ViSHaRD10

Technical points

Mechanism

Size of workspace	Cylinder ø1.7 m * 0.6 m
Geometry of workspace	Cylinder ø1.7 m * 0.6 m 360° for each rotation
Spatial reference	
Number of degrees of freedom	3-DOF translation, 3-DOF angular motion
Isotropy of workspace configuration or not, in terms of accessibility	
Characterization of the system in a passive state	
Special effects coming from the morphology (such as non isotropic inertia).	
Cinematic configuration type	Serial
Structure of mechanism (internal cinematic configuration)	Joints 1, 2, 3, 4, 5 in SCARPA configuration; joins 6 and 7 mimic a prismatic joint; joints 8, 9, and 10 (in conjunction with joint 5) form a 4R spherical wrist of type roll-yaw-pitch-roll.
Morphology of the system.	
Material of structure	
Type, material and other characteristics of joints (if any)	See Structure of mechanism (above)

Actuation

Technology of Actuators

Physical principle	DC-motors coupled with harmonic drive gears
Backlash	0

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	170 N peak force, 13Nm peak torque (pitch, yaw), 4.8 Nm peak torque (roll)
Max continuous force/torque exerted	
Max speed (due to intrinsic limitation or to the driver)	>1 m/s

<u>Sensing</u>

Type of sensing	Six-axis JR3 torque-sensors ; Joint angles measured by digital MR-encoders with a resolution of 4096 count per revolution
Physical principle of the sensors	
Resolution	Varies from 50:1 to 160:1
Bandwidth, max data rate (in the case of sampled digital output)	8 kHz
Range of measurements	
Location in the haptic system – relation / link with the geometry of the mechanism	

<u>Other properties</u>

Weight	23 kg (weight of moving parts)
Spatial constraints	Mechanical singularity when joints 8 and 10 have the same orientation. This can be avoided by rotation of joint 7

Sources

[1] M. Ueberle : "Design of a Redundant Kinesthetic Feedback Device" D4.3/T4.2 WP4 : New Generation of Force Feedback Devices, 2003
http://www.touch-hapsys.org/
[2] M. Ueberle , N. Mock and M.Buss, "Towards a Hyper-Redundant Haptic Display", Proceedings of the Workshop on High-fidelity Telepresence and Teleaction , jointly with the conference HUMANOIDS, Munich, 2003

6.22 UNIPI

6.22.1 Haptic Black Box

Device description by: INPG on 05/01/2005.

General Description of the device

Definitions: Rheology is the science that describes the interrelation between force, deformation and time of matters. Smart materials, such as rheological materials, exhibit a noticeable change of their physical behavior when they are excited with proper external stimuli. Rheological fluids, also termed controllable fluids, or rather Electro-Rheological (ER) and Magneto-Rheological (MR) fluids, are a particular class of smart materials, capable to change their rheological behavior when an external electric or magnetic field is applied.
Brief history: The initial discovery of rheological fluids is credited to Willis Winslow who described in the 1940s, the effects on Electrorheological fluids. And in 1949, Jacob Rabinow described Magnetorheological fluids effects and developed the first devices. A first non-immersive haptic prototype based on MR Fluids has been described by this research team : the Pinch Grasp (PG) display. Followed by, a preliminary immersive haptic interface based on MR Fluids : the Haptic Black Box (HBB) display.
Domain of application: An important application of rheological fluids is in the field of vibration control, particularly in automotive area and aerospace industry.
A few examples of ER fluids in tactile display devices include a prototype tactile graphic I/O tablet for blind people,. the MEMICA glove for medical teleoperation (acronym for MEchanical MIrroring using Controlled stiffness and Actuators), whose components are miniature electrically controlled stiffness (ECS) elements and electrically controlled force and stiffness (ECFS) actuators that are based on the use of Electro-Rheological Fluids
Physical description: Rheological fluids generally are non-colloidal suspensions of polarizable micron-sized particles in a synthetic liquid and exhibit a rapid, reversible and tunable transition from a liquid to a near-solid state upon the application of an external field. More specifically, Electrorheological and Magnetorheological fluids are materials that respond to an applied electric and/or magnetic field with a change in rheological behavior. Typically, this change is manifested by the development of a yield stress that monotonically increases with applied field. The phenomenon is reversible (ie the fluid can be returned to its liquid state just as quickly by the removal of the field)

The Haptic Black Box (HBB) described here is composed of a plastic box (20*20 cm) containing the Magneto-Rheological Fluid (commercial MRF 132-LD by Lord Corporation©, Cary NC, USA) and 16 excitation coils vertically placed below the box. Each coil is built with 305 turns of enameled copper wire, (Autovex 180 Pirelli), with a low thermal resistivity, arranged in 5 layer of 61 turns around a cylindrical carbon steel core (AISI 1015) of 21 mm in diameter (taking into account the thickness of two rubber layers of 0.85 and 0.15 mm respectively) and total length of 150 mm. The electrical resistance of a coil is 0.25Ω at 27°C, and the inductance is 5.25 mH at a frequency of 50 Hz.

The ferromagnetic core is commonly used for screws and bolts production. Turns are not in direct contact with the core, but they are separated by a rubber support covered with a layer of Nomex which is a special insulating material for voltage transformers. This precaution assures a good thermal and electrical isolation. In order to minimize the dispersed flow beyond the workspace and to guarantee the safety of the user, the solenoids are connected together by means of an AISI 1015 steel ring. By separately tuning the current flowing into the 16 coils, it is possible to reproduce figures with desired shape and compliance.
A real time control strategy is obtained by using two acquisition cards interfaced to a computer. One is used as input card to acquire signals from Hall sensors (UGN3503U sensors, produced by Allegro, chosen for reliability and cheapness.) witch allow to control the magnetic field.The other card is used as output with 16 analogical channels. The output signals are used to drive a power circuit able to generate high electric current for the solenoids.

Pictures or schemas

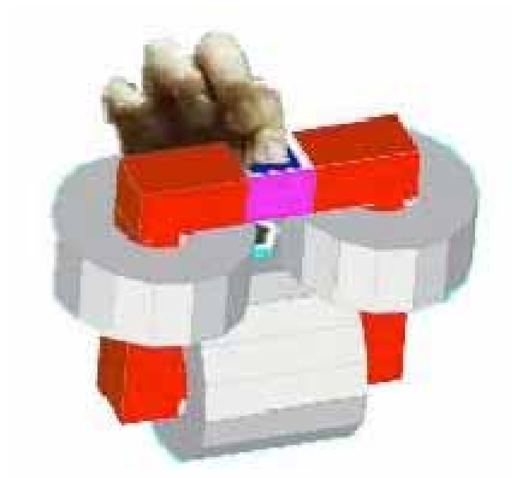


Figure 6.62 -Design of the Pinch Grasp display

Figure 6.63 - Haptic Black Box composed of 16 vertical solenoïds

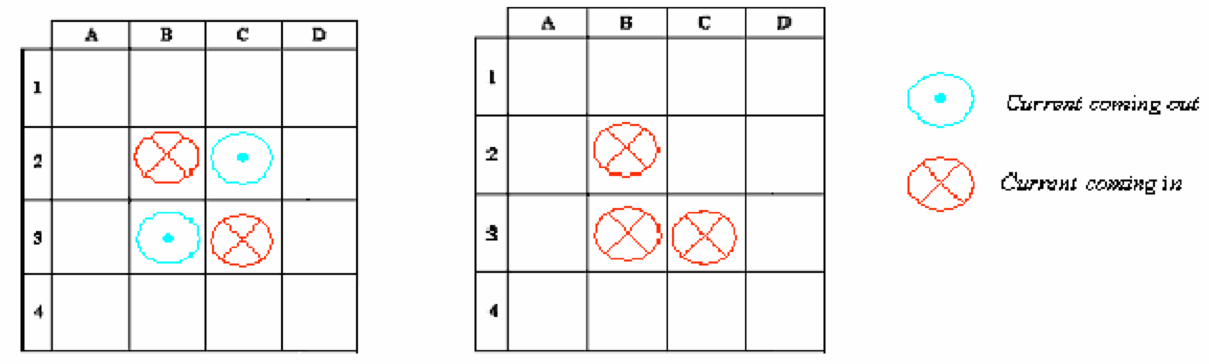


Figure 6.64 Set of solenoids activated in order to reproduce different shapes in Haptic Black Box work: square (a) and triangle (b)

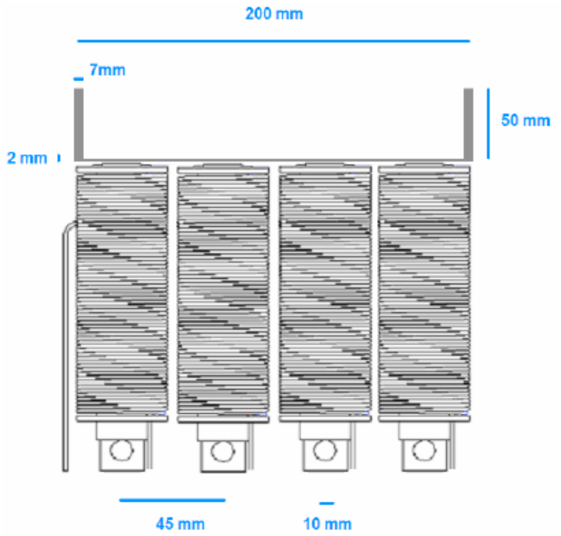


Figure 6.65 - Coils and mechanical design dimensions of the Haptic Black Box

Level of achievement: prototype.
A HBB (Haptic Black Box) with 16 cilinders, which allows to simulate rough shapes in a 2-dimensional plane (a 4*4 grid).

Future developments: Much work is yet to be done to improve real-time rheology simulation of virtual objects by acting on both shape and softness. Further development will also lead to increased 2D-resolution (which will improve realism), and 3D arrangements.

Technical points

Mechanism

Size of workspace	Cartesian plane 18*18 cm with 16 quantized points (note : basin is 5 cm deep, although rheological perception is not controled vertically)
Number of degrees of freedom	1
Characterization of the system in a passive state	Viscosity of fluid is similar to water (50-1000 mPa)
Cinematic configuration type	other
Structure of mechanism (internal cinematic configuration)	16 vertical solenoids underneath a basin containing the MR fluid
Material of structure	MR fluid is commercial MRF 132-LD by Lord Corporation©,

Actuation

Technology of Actuators

Physical principle	Magnetic field generated by solenoids
Specific technologies for the above category	305 turns of enameled copper wire arranged in 5 layer of 61 turns around a cylindrical carbon steel core of 21 mm in diameter and total length of 150 mm

Functional Characteristics of the Actuation system

Max force/torque exerted at peak	Yield strength of 100 Kpa attained in 10 msec when maximum magnetic fiels is applied.
Max speed (due to intrinsic limitation or to the driver)	Response time is 1-10 ms

Sensing

Type of sensing	No sensors (except Hall sensors for magnetic field measurement)

Other properties

Whole dimensions of the system	Basin + solenoids : 20 * 20 * 20 cm
Security and protection systems, if any	Maximum magnetic field generated : 0.6 T (2T is used in medical examinations). A magnetic cage is used as well. low frequencies signals (down to 60 Hz) and compatible levels of magnetic field magnitude have been used.

Sources

[1] N. Sgambelluri, R. Rizzo, E.P. Scilingo, A. Bicchi : "Specifications and Prototype of Rheological Device" D4.6/T4.3 WP4 : New Generation of Force Feedback Devices, 2003
[2] http://www.touch-hapsys.org/

6.23 Université d'Evry Val d'Essonne (UEVE), Laboratoire Systèmes Complexes (LSC)

6.23.1 A multi-level haptic rendering concept

Description device by: INPG on 06/01/2005.

General Description of the device

Brief history: Most current "haptic devices" are actually either tactile or kinesthetic devices. The concept proposed here is to distribute haptic feedback in a three-stage rendering interface, respectively for shape, surface-roughness and texture.
Similar concepts have already been proposed in scientific literature. Examples include combining a 2D planar pantographic device with a braile cell display ; blending vibration feedback with force feedback (and also with texture) ; and combining an actuated pins texture device with a kinesthetic PHANToM device.
Physical description: The long term issue of this work is to achieve a note-book size haptic device capable of rendering both kinesthetic and tactile information. The device proposed here is further combined with an LCD horizontal screen to provide visual perception as well.
The lower level (for shape) stage would be achieved by a compact XYZ Cartesian device. The intermediary level (for roughness) would be a low-density actuated pins device, on top of which the third level (for fine texture) might be a flexible membrane

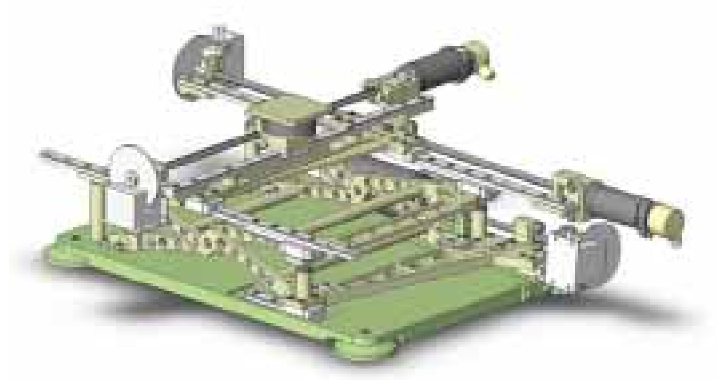


Figure 6.66 Design for the kinesthésic stage of the haptic device

Level of achievement and future developments: The work described here is still in a conceptual phase. The low level stage design is presented and ideas with ongoing investigation for the other two stages are discussed.

Technical points

Mechanism

Size of workspace	Notebook sized
Number of degrees of freedom	3

Source

[1] A. Kheddar, A. Drif, J. Citérin, B. Le Mercier "A Multi-level haptic rendering conceptt", Proceedings of Eurohaptics 2004, Munich, Germany, June 5-7, 2004

Commercial devices

Some commercial devices are presented in the following from a technical point of view.

6.24 MIT AI Laboratory, Sensable

6.24.1 Phantom hatipc interface Model: Desktop

Device description by : INPG on 03/06/2004.

General Description

History: The first PHANTOM® haptic device was designed and built in the early 1990s by Thomas Massie and Dr. Kenneth Salisbury. Massie, an undergraduate student at MIT at the time, and Dr. Kenneth Salisbury, then a principal research scientist at MIT's Artificial Intelligence Laboratory, worked together to combine robotic and haptic technologies to "reach into the computer display" and touch and manipulate 3D data. What began as a thesis project was validated when demand for the PHANTOM device began to spread through MIT and the research communities of other leading institutions. SensAble was formally incorporated in 1993. The **PHANTOM Desktop™** is introduced 1998.

Domain of application: Remote virtual and physical environments, probing virtual objects.

Selected Types of Haptic Research, the FreeForm® Modeling™, and the FreeForm® Modeling Plus™ systems.

Physical description: The PHANTOM is a convenient desktop device that connects the user by inserting his index finger into a thimble. It is a passive, 6DOF “thimble-gimbal”.

The PHANTOM Desktop provides precision positioning input and high fidelity force-feedback output. Portable design, compact footprint, and simple parallel port interface ensure quick installation and ease-of-use.

Level of achievement: PHANTOM Desktop is a commercial product.

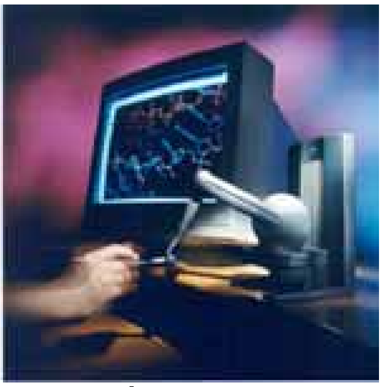
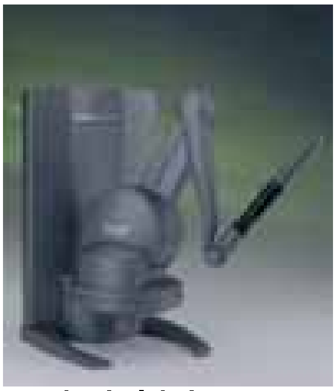



Figure 6.67 PHANTOM Desktop mechanical design

Future developments:

1999 FreeForm® Modeling™ system shipped
2002 FreeForm Modeling system Version 5
2002 FreeForm Modeling system Version 6 speeds digital pipeline
2003 FreeForm® Mold™ system Version 1.0 shipped
2003 FreeForm® Concept™ system Version 1.0 with PHANTOM® Omni™ device shipped
2003 FreeForm® Modeling Plus™ system Version 7.0 including mold design and photo-realistic rendering shipped
2004 GHOST® SDK v4.0 - Linux Update Feb-04 shipped
2004 3D Touch™ SDK and Haptic Device API (HDAPI) shipped
2004 PHANTOM® Omni™ Developer Kit shipped
2004 FreeForm® Modeling Plus™ system version 7.1 with mold design enhancements

2004 3D Touch™ Developer Challenge with $800 PHANTOM Omni Developer Kit
2004 OpenHaptics™ toolkit v1.0 shipped
2004 FreeForm® Concept™ v2.0 shipped

Technical points

Mechanism

Size of workspace	160 W x 120 H x 120 D mm
Geometry of workspace	
Spatial reference	Desk-top
Number of degrees of freedom	6-DOF positional sensing
Isotropy of workspace configuration or not, in terms of accessibility	
Characterization of the system in a passive state Stiffness: Inertia (apparent mass at tip):	X axis > 1.86 N / mm. Y axis > 2.35 N / mm. Z axis >1.48 N / mm. 45 g
Material of structure	Molded-rubber stylus, Aluminium linkages Metal components and injection-molded, carbon fiber reinforced plastics
Type, material and other characteristics of joints (if any)	A passive gimbal attached to a thimble
Frictions: Maximum force level Non-linearities: dry friction, viscous friction	< 0,1N (static back-drive friction)
System statically balanced	< 0,2N for all points within the workspace
Signal Processing	
Number and structure of the signals ports.	Parallel port, PCI (NT, Win2K), Irix or ISA (NT) interface card
Type of the local treatments, if any.	Impedance local loop
Functional properties of the local loops	
Technology of the local treatments	Intel-based PCs

Actuation

Technology of Actuators

Physical principle	
Specific technologies for the above category	
Commutation system (if any)	DC brushed motors
Backdrive forces	0,06N

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak** at nominal (orthogonal arms) position	7,9N
Max **continuous** force exerted (24h)	1,75N
Motion range	Hand movement pivoting at wrist

Sensing

Type of sensing	Force/Torque
Physical principle of the sensors [Stylus gimbal]	x, y, z (digital encoders) [Pitch, roll, yaw (± 3% linearity potentiometers)]
Resolution (Spatial resolution)	0,02mm

Other properties

Price	$13,295USD
Weight	<75g
Whole dimensions of the system (area occupied on a desk)	143 W x 184 D mm

Sources

[1] Thomas H. Massie and J.K. Salisbury, "The PHANTOM Haptic Interface: A Device for Probing Virtual Objects", Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov., 1994
[2] http://www.sensable.com/
[3] Phantom_ghost.pdf
[4] PHANTOMDesktopandOmniComparison.pdf

6.25 Immersion Corporation

This company offers various haptic devices, but seem targeted mostly at the gaming market [1]. They also advertise a "Laparoscopic Impulse Engine." From their web page [2] one can see that they have several patents, developed chips for "simulating feel sensations", and also deal in the software side by producing foundation classes.

6.25.1 Immersion laparo-simulator used as master-slave System

General Device description

The Immersion Laparoscopic simulator is a device made by two independent haptics interfaces. It is composed by two robotic arms that reproduce the kinematic structure of a laparoscope. Every haptic device has 4DOF, all actuated (a spherical wrist plus a prismatic joint). The actuation is made with DC motors and cable transmission without using force sensor.
The system in this case was used for testing remote teleoperation control algorithm and communication protocols. The arms of the device were working as master-slave bilateral system: one arm was following the other arm's movements symmetrically.
Applications: This device is commonly used for laparoscopic simulation within the filed of training and teaching of surgery procedures. In this case it was used as a master-slave teleoperation system for testing the stability of the control algorithm inserting delays in the communication loop.

Subjective evaluation

PERCRO

Moving in free space

The device was tested in free space motion without any active motor. The friction forces are quite low due to the cable transmission system. The inertia was quite high if compared to the dimension of the device. This was probably caused by two of the motors that are not located at base of the mechanism but they are fixed on the moving links.

Symmetrical Teleoperation

The spherical of both laparoscope simulators were controlled with a teleoperation algorithm. The movements of the first were reproduced on the second allowing also the force feedback effect.
Firstly the teleoperation system has been tested in free movement. The system is stable in every position also changing the way to handle the device. Moreover there were no difference in using the first or the second arm as master or slave.
In this configuration it was possible to test the fidelity of the force communication by hitting one of the two devices, while keeping in the other hand the other HI arm. The sensibility of the force transmission was quite low, in fact the force feedback was perceivable only by exerting a big amount of force on the slave device.

Sources

[1] http://www.cs.utah.edu/~tthompso/haptics.html
[2] http://www.immersion.com/products/

6.25.2 Programmable rotary actuator PR-1000

General Device description

Pr-1000 is a small passive rotary actuator. It is in a bi-directional clutch based on friction and his shape is very similar to the common potentiometers. This is an all embedded system (controller, sensors, actuator, driver etc...) and it presents two modalities of working: it can be switched on and off by

pushing the rotary knob along his axis. It is possible to program the haptic behaviour of the actuator by means of a USB port using a specialized software (developed by Immersion). The cost of PR-1000 will be very low (around 3-4$) but unfortunately also its quality seems to be cheap.
Applications: This device can be used as a rotary selector programming different haptic feedback simulating dented selector, hard stroke stops, dampers and constant forces. PR-1000 could find application in every device in which are present rotary selectors (car interiors, medical equipment, Audio& Video Devices,).

Subjective evaluation

PERCRO

This test as been done with the proposed set up. The user were holding a cylindrical knob (diameter 30-40mm) directly attached to the actuator axis.

Moving in free space:

The friction seems to be very high (~7mNm). Moreover a low speed rotation generate a feeling of high frequency stick and slip effect. This effect raise if a torque is exerted.

Simulation of a hard wall:

The hardness of the wall (one degree of freedom) is quite high thanks to the high value of the peak torque (~100mNm) and the contact is intrinsically stable (passive system). The frequency response must be quite high in fact, hitting the wall at higher speed, its hardness almost the same.

Simulation of rotary notch:

The notch are well perceivable also at high speed of rotation (due to high frequency response). At lower speed the repeatability of the feeling of every dent become worst, the rotary selector block off on some dent and requiring an higher force to be moved.

6.25.3 Programmable rotary actuator PR-5000

General description of the device

PR-5000 is a mixed passive and active rotary actuator composed by a clutch and a low cost motor. As the PR-1000 it is an all embedded system but it is very much bigger (~8x8x10cm box). It can be programmed with four modalities of working selectable by some buttons. The device can be switched off by means of pushing the knob along its axis.

Subjective evaluation

PERCRO

Moving in free space:

PR-5000 presents lower friction of the PR-1000, the feeling is smoother also at low speed and also while a torque is exerted.

Simulation of a hard wall:

The hardness of the wall is quite high but not much higher than the PR-1000. Being an active actuator it can simulate also the elastic behaviour of the wall.

Simulation of rotary notch:

In this case it was possible to test two different shape of notches different from the length of their angular amplitude. Both modalities give a good feeling of dented cues. The modality with bigger amplitude seems to be at stability limit, in fact if the grasping of the device was left while passing from a dent to another the knobs start an oscilation and stops after 3-4 periods.

6.25.4 Vibetonz

General description of the device

Vibetonz isn't a real haptic interface in fact there is no bilateral interaction between the user and the computerized environment. This device is a simple voice coil actuator installed in a Portable Telephone that is able to transmit vibration to the user hands. The software developed by immersion allow to program, trough an easy-to-use graphical interaction, the amplitude and the duration time of the vibration signal (at fixed frequency).

Subjective evaluation

PERCRO

Stimulation with variable amplitude

The user hold in his hand the portable telephone and can feel the vibration programmable in amplitude and time.

Stimulation in synchronization with music

The vibration can be programmed in synchronization with the telephone melody. It can be programmed to vibrate while a particular instrument or is playing enhancing the quality and the enjoyment.

6.26 FCS Robotics

6.26.1 Haptic master

Device description by : INPG on 07/12/2004.

General Description

The *Haptic* Master is a commercial device developed at FCS Robotics, a division of FCS Control Systems B.V. located in Schiphol, NETHERLANDS.

History: Control Systems originated in the late 70's by applying Fokker's aircraft expertise in challenging ground-based control systems. Their first product line was control loading equipment used in flight simulators to replicate the forces which act on the pilot's controls. They have a patent on the force-loop technology.
FCS Robotics is a division of FCS Control Systems, and entered the field of force-controlled medical equipment in 1997. The products of the FCS Robotics division are centered around the Haptic Master.
Domain of application: Virtual reality (when stiff, heavy or curved stiff objects must be render, virtual design and assembly tasks), haptics research (to perform man-machine interaction measurements: finger or arm movements) , rehabilitation and neurological research for moving around the human limbs(e.g. the arm).
Physical description: The *Haptic*Master is a 3-DOF, force controlled haptic interface. The hardware contains the robot arm and the control box. The programmable robot arm can end with different end-effectors. *The standard end effector* comprises a simple bal grip with a push button and can be connected to software applications. *The passive end effector with 3DOF orientation measurement* is a universal clamp and can be used for applications requiring the measurement of 3 additional degrees of freedom. *The gearshift end effector* is an example of a custom-built end effector for a specific application.
The kinematic chain allows rotation of the base, while the arm can make up/down, respectively in/out movements.
The Haptic Master is controlled by means of Haptic API interface, which allows also to create virtual haptic worlds.
Level of achievement: Commercially available device.
Future developments: The end effectors will be developed to facilitate different applications and the HapticAPI will be functionally extended to support software interfaces of third parties and incorporate triangularization, dynamic environments, etc.

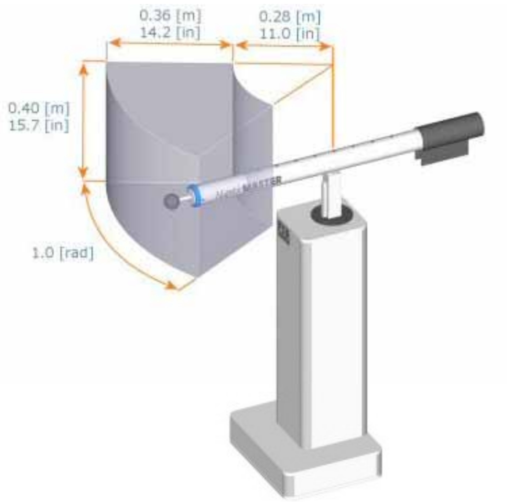


Figure 6.68 FCS *Haptic*Master workspace

Figure 6.69 FCS *Haptic*Master and different end effectors

Technical points

Mechanism

Size of workspace	80 x 10^{-3} m^3
Geometry of workspace	A volumetric workspace (Fig. 1)
Number of degrees of freedom	3-DOF
Characterization of the system in a passive state	Simulated stiffness: 10-50 kN/m Simulated equivalent inertia: 2kg
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	- Friction in joints is 0,001N, reduced by the control loop

Signal Processing

Type of coding and type of medium.	100/10 MBIT ethernet
Bandwidth or sampling rate.	2500Hz
Type of the local treatments, if any.	Admitance local loop. The general control loop scheme comprises an outer loop and an inner servo loop. A virtual model converts the force sensor signal to a Position/Velocity/Acceleration setpoint vector. The inner servo loop controls the robot to the PVA setpoint values.
Functional properties of the local loops	The transfer function for the up/down movement is straight till 10Hz with a less than 5db amplitude from 10 to 25Hz.
Technology of the local treatments	The haptic render and the robot control loop run on a dedicated industrial PC with VxWorks real-time operating system. HapticAPI software.

Actuation

Technology of Actuators

Backlash	Device designed for 0 backlash

Power driver system

Low level control loop	An internal model, which contain a mass to avoid commanding infinite accelerations, calculate the Position, Velocity and Acceleration from the force exerted by the human hand. The PVA vector is commanded to the robot, which makes movements by means of a conventional control law.

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	Maximum force: 250N
Max **continuous** force/torque exerted	Nominal force: 100N
Max speed (due to intrinsic limitation or to the driver)	1m/s

Sensing

Resolution (Spatial resolution)	Position resolution: 4 –12 µm Force sensitivity: 0,01N

Other properties

Price	42 500 euro, HapticAPI software: 1000 euro
Weight (Effective mass)	
Whole dimensions of the system	Console height: 0,8 m
Power consumption	500W (voltage requirement: 90-264Vac)

Sources

[1] R.Q. Van der Linde, P. Lammertse, E. Frederiksen, B. Ruiter, "The HapticMaster, a new high-performance haptic interface", Proceedings of Eurohaptics 2002
[2] http://www.fcs-cs.com/robotics/products/hapticmaster

6.27 Haption

6.27.1 Virtuose 6D40-40

General Description of the device

The class of products VIRTUOSE are commercialized by HAPTION, a spin-off of CEA (French Nuclear Research Agency).
History: HAPTION has 30 years experience in designing, manufacturing and selling haptic devices. Their models are situated in the VIRTUOSE family. The VIRTUOSE 6D35-45 offers force-feedback on all 6 degrees-of-freedom together with a large workspace and is recommended [1] for scale 1 manipulation of virtual objects such as assembly/disassembly simulation, ergonomic studies, or maintenance training. The VIRTUOSE 3D15-25 is a 3D haptic interface (3-dof with force-feedback and 3-dof with position sensors). The VIRTUOSE 6D40-40 new generation master arm for tele-operation with force-feedback.
Domain of application: Virtual reality, tele-surgery, teleoperation in hostile environment, functional rehabilitation, medical training.
Physical description: The VIRTUOSE 6D40-40 is master arm for teleoperation.
Level of achievement: Commercial device.

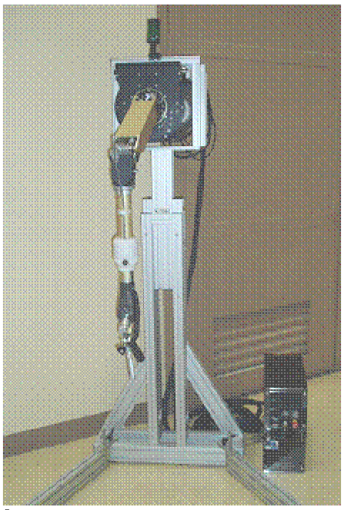


Figure 6.70 VIRTUOSE 6D40-40

Technical points

<u>Mechanism</u>

Geometry of workspace	A cube of 400mm on each side
Number of degrees of freedom	6 DOF
Characterization of the system in a passive state	Stiffness: 4000N/m
Cinematic configuration type	Serial

<u>Actuation</u>

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	Force: 40N, Torque:3Nm
Max **continuous** force/torque exerted	Force: 10N, Torque: 1Nm
Stroke / Motion range	Body rotation: 80°, Shoulder: 80°, Elbow: 130°, Azimuth: 238°, Wrist elevation: 180°, Wrist Rotation: 160°, Gripper: 60mm.

<u>Sensing</u>

Type of sensing	Position
Resolution (Spatial resolution)	Translation: 200µm, Rotation: 0.006°
Range of measurements	

<u>Other properties</u>

Price	
Weight (Effective mass)	
Whole dimensions of the system	Length of axes: Arm: 400mm, Forearm: 400mm

Sources

[1] http://www.haption.com

6.28 Force dimension

6.28.1 The Delta Haptic Device

Device description by : INPG on 27/05/2004.

General Description of the device

The Delta Haptic Device system meets the high standards required for industrial applications by combining high strength, high stiffness and high sensitivity. This system is based on the patented Delta robotic structure, which provides three translational degree-of-freedom.
A dedicated mechanical wrist plug-in provides three rotational DOFs and is based on the PARAMAT structure.

Figure 6.71 –The Delta Haptic Device

History of Force dimension compagny:
2004
Major projects in medical simulations (e.g. surgery) and teleoperation applications were successfully accomplished. | Various OEM partnerships with software and hardware vendors in different application fields were launched. | The first stages of a worldwide reseller and distributor network were put in place. | A co-operation with Nice Ventures for worldwide marketing and sales was initiated. | A joint partnership with Nanonis, a scanning probe microscopy (SPM) application expert company, was formed to build an integrated haptic force feedback system for nanotechnology applications.
2003
The OMEGA 3-DOF, a powerful and user-friendly desktop haptic device was successfully introduced to the market. | The device's commercial success was outstanding; it was sold across continents to numerous high-tech industries. | Force Dimension won the Swiss Technology Award for its nanomanipulation application.
2002
The first powerful 6-DOF rotational and translational haptic device, the DELTA 6-DOF, was built and sold to the market.
2001
Force Dimension was founded, introducing the DELTA 3-DOF, a patented system, to the market. | The first haptic device from Force Dimension was sold to Singapore.
1998
The four founders of Force Dimension joined the VRAI group. | Their scientific research work was the foundation of a revolutionary new haptic device.
1993
VRAI group (Virtual Reality and Active Interfaces) was founded at the Swiss Federal Institute of Technology (EPFL) specializing in virtual reality, minimally invasive surgery, sensory feedback for autonomous systems, agent-based user interfaces, and micromechanical devices for medicine and defense.

Applications: The first application for the device consisted of a VR simulation: the 6 DOFs of a virtual cube are mapped with the 6 DOFs of the Delta nacelle. The interaction between the cube and a virtual rigid plane allows the user to "feel" the contact impact, i.e. forces and torques imposed on the cube.
The Delta device has been used for teleoperation manipulation too (the KoalaDriver demo): the device is used to rate-control the motion of a mobile robot. Infrared range sensors on the robot are mapped onto a virtual envelope that constraints the nacelle movement to the directions that are safe for the robot. When an obstacle is encountered, the system renders a force opposing the user command to go towards the danger.
Level of achievement: A spin-off company from the Swiss Federal Institute of Technology in Lausanne (Force Dimension: http://www.forcedimension.com) is responsible for the development, production and commercialization of the device. Three versions are available:

- 3-dof OMEGA Haptic Device
- 3-dof DELTA Haptic Device
- 6-dof DELTA Haptic Device

The version discussed below is the 6-dof DELTA Haptic Device.

Technical points

<u>Mechanism</u>

Size of workspace	Cylinder ∅360mm x 300mm Rotation +/-20° for each axis of rotation
Geometry of workspace	Cylinder, no effets of the rotation on the geometry
Spatial reference	Desktop
Number of degrees of freedom	6: 3 translational + 3 rotational
Characterization of the system in a passive state	Low inertia (furthermore compensated by data integration in the control loop) Low friction forces (furthermore compensated by data integration in the control loop) Backlash is avoided through elastic preconstraints Stiffness14.5N/mm in closed loop
Special effects coming from the morphology (such as non isotropic inertia).	- inertia is (said to be) very small due to the parallel architecture.
Cinematic configuration type	Parallel: three double-bar parallelograms rely the platform to the base of the device, which forces the platform to always be in a plane parallel to the base plane of the device.
Structure of mechanism (internal cinematic configuration)	A wrist is fixed to the platform structure to provide the 3 rotational DOFs: the structure decouples the translations from the rotations provided by the wrist.
Frictions: - Maximum force level - Non-linearities: dry friction, viscous friction	Max force level: 25N Max torque level: 0.2Nm
Intrusion of mechanism in visual space of the user	No

<u>Signal Processing</u>

Bandwidth or sampling rate.	Control data refresh rate > 1kHz (video) refresh rate >25Hz No information about force interaction bandwidth

Type of the local treatments, if any	Friction forces and inertia compensation through integration of data in the control loop.
Technology of the local treatment	Interface standard PCII/O

Actuation

Technology of Actuators

Physical principle	-
Gear or low-level mechanisms (if any).	None (expected)
Backlash	No backlash due to elastic preconstraints
Backdrive forces	System is supposed to allow very low backdriveability due to parallel architecture and absence of gear

Power driver system

Technology of the power modulator	-
Low level control loop	- position loop?

Functional Characteristics of the Actuation system

Max force/torque exerted **at peak**	-
Max **continuous** force/torque exerted	20N, torque: 0.2 Nm

Sensing

Type of sensing	-
Physical principle of the sensors	-
Resolution	0.1mm in translation (commercial version: 0.03mm) 0.004° in rotation (0.04° commercial version).
Bandwidth, max data rate (in the case of sampled digital output)	Bandwidth of control lop is assumed to be > 1kHz
Range of measurements	-

Other properties

Price	-
Whole dimensions of the system	600mm (height) x 700mm (width) x 400mm (depth)
Power consumption	Universal 110/220volts Consumption: -
Security and protection systems, if any	Software securities: speed velocities, structure position limits and low force update checked.

Sources

[1]Grange S., Conti F., Routiller P., Helmer P., Baur C., "Overview of the Delta Haptic Device", Eurohaptics'01, Birmingam, England, July 2001
[2]Grange S., Conti F., Routiller P., Helmer P., Baur C., "The Delta Haptic Device", Mecatronics 2001, Besançon, France, July 2001
[3]Grange S., Conti F., Routiller P., Helmer P., Baur C., "the Delta Haptic Device as a nanomanipulator", SPIE Micorrobotics and Micorassembly III, Boston, MA, Nov 2001
[4]www.forcedimension.com

6.29 MPB Technologies

6.29.1 FREEDOM 6S

General description of the device

This device is a competitor to the Phantom with a workspace of 22cm x 24cm x 22cm. Unlike the Phantom [1] this is a 6dof device, both input and output. It doesn't map to one model of the Phantom though. It has a max force of 2.5N and 125mNm torque. Its resolution is the same as the Phantom at 0.02mm. The stiffness is around 1.3N/mm and the inertia of th etip is 150g. Like the Phantom it has a 1kHz update rate. They also make a 3dof device, which is not the same device without torque sensors. Their web page did nt give specifications but did supply an image. This device is not at all like the Phantom ot the Freedom 6S. It appears to use three orthogonal tracks that the end-effector, located in the center, must follow along on.

Figure 6.72 Freedom 6S device

History: Monreal, QC, Canada – December 10, 2002 – At the CANARIE 8th Annual Advanced Networks Workshop: MPB Technologies, Inc., in partnership with the National Capital Institute of Technology of Ottawa Canada (NCIT), the Commonwealth Scientific & Industrial Research Organization (CSIRO) of Canberra Australia, Algonquin College of Ottawa, and the University of Ottawa, has successfully demonstrated the very first live simulated surgical gall bladder extraction using MPB's "touch-sense" Haptic Technology over a high speed Fiber Optic telecommunication network linking Canberra, Australia to Montreal, Canada.

Technical description

Freedom 6S is a 6DOF (all active), desktop type, cable actuated haptic interface. It is an impedance controlled haptic device that makes no use of any force sensors. The transmission of the forces is achieved by means of Spectrum® cables. The kinematic is mixed (serial-parallel). The actuators are high performance maxon DC motors and maximum force are not very high (~2.5N at 60min) but the force resolution and the friction are very low. The user interact with this haptic device trough a pen type end-effector.

Applications

This device can be used in several filed (all the typical field of application of desktop type HI): Teleoperated Surgery (as master manipulator), Medical Simulation, Virtual Assembling, application for impaired people etc...

Subjective evaluation

PERCRO

Moving in free space

The perceived inertia of this device is very low but the mechanism has not gravity compensation algorithm. It is statically balanced at center of the workspace. This fact lead the user to grab the pen with higher forces (in order to keep the grasping stable), making him unable to exploit the very high force resolution of this HI.

The friction is very low and the backlash is near zero.

Box in a corner

- Stiffness of contact: the contact is not very stiff due to the controller and the tendon transmission compliance. But the most pestering fact was an high frequency noise that was generated while some of the motors were active (this noise is not present on the other models of this haptic device).
- Stiffness of against rotational motion: the “torque stiffness” evaluated putting the box in the corner and trying to rotate it against the walls is large enough to give a realistic sensation.
- Stability of contact changing the point of grasping: the contact remain stable also if the impedance of the user change (changing the way of grasping the end-effector) also if it lower almost up to zero.
- Ripple during soft exploration of the surfaces: This interfaces don’t presents almost any ripple during the exploration of surfaces with light forces of interaction.
- Beat against the simulated wall: It was verified the stability of the system during a hit against a simulated hard wall. The stability was tested but the mechanism makes a strange high frequency vibration that makes a sounding noise.

UNEXE

<u>Appraisal</u>

Free movement exhibited very little inertia. Surfaces and motion were very smooth – a world apart from the Phantom I had been using a few hours earlier.
However, the forces capable of being exerted by the Freedom are quite low, and “hard” surfaces felt quite spongy.

CEIT

The user handles the robot’s end effector and simply moves it. The actual robot position is conveyed to the virtual environment and the contact forces computed in the virtual environment are sent back to robot’s arm.
Three virtual environments are tested:
1st The mockup is an orographical 3D map of the Earth. The tool is a sphere.
2nd The mockup is a sphere. The tool is a prismatic polyhedron.
3rd The mockup is a virtual elastic membrane. The tool is a sphere.
Notice that although the device can display torques, all tests are force feedback tests; that is to say, no torque-feedback tests. The robot has no gravitational compensation.
The inertia felt in free movement test was high compared to the low weight of the device. The workspace is not big. This constraint becomes more noticeable when the operator wants to orientate the tool to a specific direction. The workspace is mechanically limited in order to prevent robot from reaching singular configurations.
The contact test was shown a high stiffness (the virtual stiffness was actually 700Nm, and the virtual damping was 6Ns/m). With these parameters, the contact was stable but a small noise/vibration could be heart.

DLR

The impression in free movement is very good. Less friction to feel and the inertia impression is due to the well balanced mechanic design very small and isotropic. The mechanic range in the wrist sometimes ends in some collision problems due to the guidance of the pulleys.
When the motors are actuated, very high bandwidths lead to a very realistic display of hard contact in all of the 6 DOF’s. At very high stiffness the mechanic design of one of the ‘elbow’ actuators causes with the frequency of the movement a resonance problem (very noisy). Since this is not often a possible working issue of the device, it’s not disturbing significantly the good performance of the device.
The remote placed control electronic of the device cause some noise and are heating up in a short time. This can influence the force impression at fine force-feedback actuation.
The driver and the presented application have not been adapted and fitted exactly to the different purposes of the demonstration desktop (performance is not too good, when sliding over the earth

surface, see also picture, and displaying the texture of the continents) which can influence in a negative mode the performance possibilities of the device (MPB is not developing applications for customers).

Sources

[1] http://www.cs.utah.edu/~tthompso/haptics.html
[2] http://www.mpb-technologies.ca/mpbt/haptics/hand_controllers/freedom/freedom.html
[3]http://www.mpb-technologies.ca/mpbt/haptics/hand_controllers/freedom/f6_news_touching.html

7 CONCLUSION

The last 15 years developments of haptic devices have given rise to a wide and multiform technologic space and a first result of the investigation of this 1rst WP period is a better evaluation of this complexity. It is clear that this parameter was completely under-evaluated at the beginning of the project. This complexity relies on several aspects :
1) The diversification of application domains.
2) The difficulties to clearly understand and specify the functionalities of haptic interfaces, in particular because of the relative lack of knowledge on the human aspects concerned.
3) The multidisciplinary aspect of the technologies involved.
The methodology for gathering material as briefly exposed in the introduction and in the corresponding parts (5) consisted in using 2 types of sources (1) publications (scientific, technical, commercial) and (2) direct experimentation and evaluation of devices.
This last task is obviously time consuming and expensive and it has been carried only on more representative systems. It is however very important because it allows to overcome lacks or biases of the publication system the most evident being that the haptic synthesis result cannot be enclosed in any existing medium and that no objective and powerful criteria exist yet today to qualify such haptic synthesis results.
This material has been structured into technical sheets that gather technical data and evaluation reports when these evaluation reports exist.
The objective was to reach an exhaustive technical data-base including not only commercial systems but also laboratories devices and historical prototypes (that may have disappered). This work will continue in the 2nd period. Achieving exhaustivity and maintaining this exhaustive data-base is quite possible since the haptic science is relatively young (early haptic developers are still alive) and identification of new developments are facilitated by the tendency of the haptic community to get a more and more clear social identity for exemple through specialized conferences.
The analysis were structured according 3 directions: (1) applications, (2) functional analysis and (3) technology of components. Although this analysis work is far from being completed each of these axis reveals a dimension of the multiform aspect and complexity of the discipline.

1) Applications.

The application analysis reveals a diversification of the uses of haptics interfaces simultaneously in the two well identified categories of applications that are classical teleoperation and simulation but also in the new domains like HCI , automotive and general man machine interaction. This tendency is coupled to the fact that the concepts related to haptic systems are todays more clear and socially recognized than in a previous period (the beginning of 80s) in particular thanks to the commercial diffusion of several systems since 1993.
Our objective is first to observe the widest field of domains were haptic interfaces are used. In each case to characterize the tasks in which the haptic device is used and identify if a specific technology has been developed or if this application reveals a new technological issue.
Such investigation must continue in particular for specialized tele-manipulation domains mentioned in part II. For the same applications get a more precise task analysis and quantitative specification and more general haptic needs.

2) Functional analysis.

This sections (3) deals with the functional characterisation of an haptic interface with a double objective. First we were interested in the external specification as demanded by the application. It appears that this first level is rarely explicated in an independent way from the technical realization. The second objective relates to the analysis of the inherent technical constraints and in which ways these constraints limit the realization of the specifications or interact with them. In order to clarify this

point it is in particular necessary to investigate the important works that have been carried on haptic control issues since the beginning of the 90s.
A great amount of work is still necessary to clarify these two points but it already appears that these two objectives are rarely distinguished by the haptic developers and that the only general framework that seems to be employed for this double issue seems to be the classical input-output box formalism of control science.
Another difficulty is due to the lack of knowledge on the low level of the human system (bio-mechanics and low level sensori-motor).
A relative general approach that has been followed by haptic developers to overcome this difficulty has consisted in defining criteria to be satisfied whichever the human behaviour would be in the field of passive systems. This approach leaded in general to over-constrain the system.
Such tool in order to precise some nonevident requirements in particular concerning temporal properties that could be enhanced by the physical analysis of human object interaction on basic representative tasks. Specially designed haptic systems may be helpful for the experimental part of such investigations.

3) Technology.

According to the technical sheet structure we have distinguished :

a. mechanical
b. actuators with eventual low level mechanical transmission
c. sensors
d. local control loops data paths and some aspects of computing.

Each of this parts correspond to a specific technological discipline and it is here the 3rd dimension of the haptics interfaces complexity or diversity.

Each of these domains has its own methodology conceptual an material tools, that inherit of demands from more standard applications. It is the case of actuation and sensing components but also of mechanical and control conceptual tools that greatly inherits from robotics.
The next steps of the WP concerning this technological analysis may be driven by the following conjecture :
Haptics while having its own needs remains a marginal application in these technological disciplines and does not constitutes a sufficient balance to modify the usual codes of practices and to stimulate more “haptic fitting” technological developments and researches.
Consequently the field does not completely benefit from fundamental progress and potentialities of these disciplines when they exist. Moreover in many cases haptic developers adapt their specifications to the state of the technology and thus create implicitely practices and standards that limit artificially the level of technical exigencies that haptic system could need in general.

As the haptic systems science is a young discipline that is beginning to constitute its own knowledge system it is particularly important to clearly distinguish the “conjunctural” constrains from more “fundamental” ones for example related to physical principles involved in device or from higher level overview on the tendencies of the corresponding technological domain.

ORIENTATIONS FOR A ROADMAP.

Technical developments
On actuation.
General properties to improve. Force/speed ratio to mach direct drive requirements, bandwidth, linearity, power/weight ratio, linearity, parasitic force reduction (commutation, reluctant forces, friction)

- Classical electromagnetic systems.
- New electromecanic transducers: piezzo-electric
- Mechanical amplification
- Specific actuators for tactile devices

On sensing
General properties to improve: resolution, bandwidth, linearity, better integration in power components
- improvement of optical sensors.
- force sensors: exploit micro-mechanic technology for better integration in mechanical components. Develop integrated electronics to improve data transmission quality.

On mechanical
Critical dynamical properties to improve: rigidity, lightness, friction joints. Critical problems to overcome : isotropic behaviour, rotational forces (torques) retitution.
Adaptation of the kinematics morphology to the application specification: workspace size, number of axis.
- Flexible morphologies.
- Specific prototypes for torque restitution evaluation.

Control loops.and data teatment system.
General properties to improve.
Flexibility in conjunction with mechanical system flexibility.
Related to general issues in transparency/stability compromises.
Standard for Haptic device link support.
- evaluation of various existing technology employed in haptics.
- Evaluation of the adequacy of existing and future standard for computer peripherals.
- General computer architecture specification for haptics.

Integration of tactile interfaces.
The current generation of RGIs typically provides inadequate representation of touch sensations Development of an effective tactile interface for incorporation into these interfaces will provide a significant enhancement. Some existing research prototypes may be too sophisticated for direct development into commercial devices, because of cost limitations, but “cut down” versions offer exciting possibilities. A significant gap in the knowledge base is the poor understanding of the transduction processes which link real objects and the mechanoreceptor excitation patterns produced when these objects are explored by the sense of touch – an understanding these processes is required in order to accurately specify virtual touch sensations in software.

Analysis of needs.
Overcome Methodologic bias tendencies :
- The first is to consider the problem at a too high level. That means to consider the human only like a data treatment system : cognitive level and sensori-motor only thus neglecting the bio-mechanical level.
- The second on the contrary is to consider the human in the same way as a passive robot load thus neglecting its sensitivity.

Perform investigation for better knowledge of the human low level system or identify if results already exist.

8 COMMENTED REFERENCES

(INPG)

CADOZ C., LUCIANI A., FLORENS JL. (1989). Responsive input devices and sound synthesis by simulation of instrumental mechanisms: the CORDIS system. *Computer Music Journal*, **8, N°3, pp. 60-73.**
This paper tends to prove the inherent limits of the rarely questioned basis of digital synthesis of sound, and proposes new instrumental models for synthesis. It critics the fact that the central goal of those

methods is the sound object itself and considers that the faculties of creativity of the traditional composers cannot be dissociated from an instrumental knowledge. Thus, it presents a new instrumental device composed by a trasducer which is applied to the three principal sensory channels (what implies building gestural, sonic, and visual computer peripherals) and a simulator of the actual instrument which controls the relationship between the magnitudes of the different senses. To do so, the designs of gestural devices and the CORDIS instrument simulator system are developed.

CADOZ (C), LISOWSKI (L), FLORENS (JL), "A modular Feedback Keyboard design" - Computer Music Journal, 14, N°2, pp. 47-5. M.I.T. Press, Cambridge Mass. 1990.

This article presents the Modular Feedback Keyboard (MFK), a gestural force-feedback transducer designed at ACROE. The authors first insist on the importance of the instrumental relationship for sound (or video) control using a computer. Then, they describe the MFK, focusing on its morphologic modularity, which allows a wide range of usages, and on the design of its components, notably the sensor-motor module and the covering. For historical and cultural reasons, the main morphology of the MFK is the keyboard, where the number of keys, their number of degrees of freedom and their morphology can be chosen according to specific needs. Other kinds of MFK configuration exist, like the one using a joystick-type controller. The MFK is used for the control of real-time music synthesis and image animation with physical modelling. Its principle could be extended to a large number of domains.

UHL(C), FLORENS JL, LUCIANI (A), CADOZ (C) - «Hardware Architecture of a Real Time Simulator for the Cordis-Anima System: Physical Models, Images, Gestures and Sounds» - Proc. of Computer Graphics International '95 - Leeds (UK), 25-30 June 1995 -, Academic Press. - RA Ernshaw & JA Vince Ed. - pp 421-436

This paper published in the "Computer Graphics International" conference deals with the issues raised by the introduction of computer as an element of the Instrumental Communication Interface, particularly in the real-time constraints and simulator hardware architecture requirements. Three bottlenecks are described then analysed: time constraints in the gestural transducer (TGR), in the simulation representation and its software computation, and in the input/output capabilities and its hardware computation. There is no practical application here but the specification of these issues on ACROE design (TGR and AP120-based simulator), resulting from the Sc.D. work of Claude Uhl.

CADOZ (C) & RAMSTEIN (C), "Capture, Representation and Composition of the Instrumental Gesture", International Computer Music Conference - Glasgow 1990.

In designing and constructing a computer tool for musical creation, the INSTRUMENTAL GESTURE is especially relevant for real time control of the sound synthesis processes by simulation of instrumental mechanisms. This study is based on the implementation of a complete system to enable the capture and memorisation of the instrumental gesture during play, i.e. when the instrumentalist / instrument relationship is established. Memorised gestural actions enable two new problems to be tackled. These relate to the representation and the processing of instrumental gesture. the concepts that emerge lead to the elaboration of a "gesture editor".

CADOZ C., WANDERLEY M., "Gesture and Music". in Trends in Gestural Control of Music. IRCAM Editeur. 2000. avec CDROM.

In this article, we comment on various definitions of the term gesture in the general literature of humanhuman and human-computer interaction and in the musica domain. Different propositions of gesture classifications are then discussed and topics from other disciplines, that are important to the discussion on gesture and music, are presented. Concepts developed by the first author related to instrumental gestures, such as energy continuum, gestural channel, and instrumental gesture typology are reviewed in this context. The introduction of case studies on acoustic instruments helps in supporting the theory. Finally, the role of non-obvious (ancillary or accompanist) gestures is discussed with respect to clarinet playing.

CADOZ.(C), «Le geste, canal de communication homme/machine. La communication instrumentale» - Technique et science de l'information. Volume 13 - n° 1/1994, pages 31-61

This paper focuses on the concept of 'gesture', its understanding in computer science and the deep changes the introduction of gesture devices brought in computer music.
At first, the gesture is presented as a channel, in the same and strong understanding than we can consider vision and audition as sensory channels. However, gesture represent maybe even stronglier the notion of sensory channel, since it is bilateral. Cadoz states that the hand is a perceptive and a sensory organ as well. Thus, he describes three primar gesture functions of the hand: the epistemic, the ergotic and semiotic ones.
Because of singular attributes of the gesture channel, and because of the particular mechanical phenomena (actually interactions) allowed by gesture, the specific interaction between a human and a manipulated object is described as the instrumental gesture. Its typology is then described.
A last, this paper describes the devices currently available that can interface the human gesture towards and from computer. These gestural devices make use of transducers, actuators, and sensors in order to submit gestural information from the human to the computer, and vice versa. This exchange of gestural information is indeed considered by Claude Cadoz as a instrumental communication.

FLORENS (JL), Expressive Bowing on a Virtual String Instrument, A. Camurri and G. Volpe (Eds.): Gesture Workshop 2003, LNAI 2915, pp. 487–496, 2004.
The physical model and its real-time computing with gesture feedback interfaces provide powerful means for making new playable and musically interesting instrumental synthesis process. Bowed strings models can be designed and built with these tools. Like the real bow instruments, they present a great sensitivity of the gesture dynamics. Beyond the musical interest of these synthesis process, the tuning possibilities of the gesture interface and the general context of the modular simulation system provide new means for evaluating and understanding some of the complex gesture interaction features that characterize the bowing action.

FLORENS (C), CADOZ (C), "The physical Model, Modelisation and Simulation Systems of the Instrumental Universe", In *Representations of Musical Signals***. G. De Poli, A. Picciali, C. Roads, Ed. MIT Press, 1991, pp. 227-268**
The authors provide in this paper a detailed description of the CORDIS-ANIMA system, which is designed to model manipulable, deformable and animated objects, i.e. objects which can be addressed to the visual, auditory and tactile-kinesthetic senses.

CADOZ (C), LUCIANI (A), FLORENS (JL), "Physical Models for Music and Animated Image. The use of CORDIS-ANIMA in *ESQUISSES a* **Music Film by ACROE" - ICMC 94 12-17 Sept Aarhus, Denmark. ICMC 94 Proceedings - 1994 pp. 11-18**
The multisensorial and retroactive simulation technique of physical objects, applied to sound and animated images creation, was introduced by the ACROE in 1978. Consequently, two fundamental research axes concerning the application of computer science to artistic creation have been studied: the instrumental gesture in the frame of the creator-computer relation, which gave rise to the development of Force Feedback Gestural Transducers (and recently of the Modular Force-feedback Keyboard), and modeling and simulation of multisensorial physical objects, which gave rise to the development of the CORDIS-ANIMA system. Thus, in the framework of computer science, artistic creation disposes of a material of a new nature. This material is based on a deep symbiosis between sound and image in the heart of phenomena and objects directly manipulated by hand and gesture. "ESQUISSES" was ACROE's first creation performed thanks to the CORDIS-ANIMA material. The purpose and the structure of t! he work are presented here, as well as its realization processes, the specificities of the implemented models for the sound and visual production, and their symbiosis. First, the CORDIS-ANIMA principle will be recalled.

9 ANNEXE

LIST OF HAPTIC DEVICES CLASSIFIED BY DATE OF PUBLICATION

The list is organized in chronological order and, for the same year of publication, in the alphabetical order of the university names.

N°	Place, University, Laboratory	System	Date of publication
1.	USA, University of Chicago, Argonne National Laboratory	1. Argone Arm [Goertz,54]	**1954**
2.	USA, General electric Co.	1. Handyman [Mosher,64]	**1964**
3.	USA, Beverlly Hills, CA, Northrop Corportion (Jones&Thousand)	1. Servomanipulator [Jones,66]	**1966**
4.	USA, University of North Caroline, Chapel Hill	1. GROPE-I [Batter, Brooks,71]	**1971**
5.	Europe, France, CEA	1. MA23 [Vertut,76] 2. Virtuose (Haption)	**1976** 1999
6.	Europe, France, ACROE	1. « Coupleur gestuel retroactif » [Florens,78] 2. « La touche » 3. CRM [Cadoz,88] 4. ERGOS [Florens,90]	**1978** 1981 1988 1990
7.	USA, University of Washington, Biorobotic Laboratory	1. Salisbury-JPL Master [Bejczy,80] 2. High Bandwidth Force Display (HBFD)[Moreyra,94] 3. Pen Based Force Display [Buttolo, 95] 4. Linear Haptic Display (LHD) – Excalibur [Adams,99] 5. Finger Haptic Display [Venema,99]	**1980** 1994 1995 1999 1999
8.	Japan, Tsukuba University, VR Laboratory	1. Feelex [Iwata,90] 2. Haptic Master	**1990** 1994
9.	USA, Carnegie Mellon University, Microdynamic Systems Laboratory (MSL)	1. Haptic Magnetic Levitation Device [Hollis,91] 2. WYSIWYF Display	**1991** 1996
10.	USA, North Western University, Laboratory of Intelligent Mechanical systems (LIMS)	1. 4-DOF haptic device (cobot) [Colgate,91] 2. Finger haptics 3. Cobotic hand controller 4. Unicycle (cobot) 5. Real time haptic stiffness display 6. Switch haptics 7. Extreme Joystick 8. 1-DOF device	**1991** 1996 1996
11.	Japan, Tokyo Institute of Technology, Precision and Intelligence Laboratory (PIL)	1. SPIDAR [Sato,91] 2. Both-Hand-SPIDAR 3. SPIDAR 8 4. SPIDAR-G 5. SPIDAR-G&G	**1991** 1994 1994 2000 2004
12.	Japan, ATR Communications Systems	1. Palmtop Display for Dexterous	**1992**

	Research Laboratories	Manipulation (PDDM) [Takemura,92]	
13.	USA, State University of New Jersey, Center of Advanced Information Processing	1. Rutgers Master II [Burdea,92] 2. Rutgers Master II “New Design”	**1992** 2002
14.	Canada, University of British Columbia, Department of Electrical and Computer Engineering (DECE)	1. MagicMouse [Salcudean,94] 2. Power Mouse [Salcudean,97] 3. 5DOF twin pantograph haptic pen 4. 3DOF twin pantograph haptic mouse	**1994** 1997 2000 2000
15.	Canada, McGill University, Haptic Laboratories (HL)	1. Pantograph [Ramstein,94] 2. Pencat [Hayward,01] 3. STReSS [Pasquero,03] 4. VBD(Virtual Braile Display) [Pasquero,04] 5. Morpheotron [Dostmohamed,94] 6. MicroTactus [Yao,04]	**1994** 1998 2003 2004 2004 2004
16.	USA, MIT AI Laboratory, Sensable	1. Phantom [Massie,94]	**1994**
17.	USA, MIT Boston, Touch Laboratory	1. Linear and Planar Graspers [Srinivasan,94]	**1994**
18.	Europe, Italy, Scoula Superiore Sant'Anna, PERCRO laboratory	1. Arm exoskeleton [Bergamasco,94] 2. Haptic Pen [Frisoli,99] 3. 3DOF joystick [Frisoli,00] 4. Hand exoskeleton [Frisoli,02] 5. Grab 6. Haptic Desktop [Solis,04]	**1994** 1999 2000 2002 2003 2004
19.	USA, Immersion Corporation	1. Impulse Engine 2000 [Jackson,95] 2. CyberForce 3. CyberGrasp 4. CyberTouch 5. CyberGlove 6. Impulse Stick 7. Laparoscopic simulatore 8. Programmable rotary actuator PR-5000 9. Programmable rotary actuator PR-1000. 10. Vibetonz	**1995**
20.	USA, Standford University, CCRMA	1. Moose [O’Modhrain,95] 2. vBOW	**1995** 2000
21.	USA, University of Colorado	1. 5 DOF Haptic Device [Lawrence,96] 2. Bow spring and tendon actuator design [Lawrence,05]	**1996** 2005
22.	Europe, Netherlands, FCS	1. FCS Haptic Master [VanderLinde,02]	**1997**
23.	USA, Southern Methodist University, Mechanical Engineering Departement	1. Master Arm Pneumatic Haptic Interface	**1998**
24.	Europe, France, Université des Sciences et Technologies de Lille, Laboratoire d’Informatique Fondamentale	1. Haptic Interface for Surgical Gesture Training [Chaillou,99] 2. DigiHaptic	**1999**

	de Lille (LIFL)		2003
25.	Europe, Germany, DLR	1. LWR 2. Joystick 3. Senso-wheelSD	**2001** 2003 2004
26.	Europe, Switzerland, Laussane	1. 3DOF Delta 2. 6DOF Delta 3. 3DOf Omega	**2001** 2002 2003
27.	Europe, Spain, CEIT	1. Lhifam	**2002**
28.	USA, MPB Technologies	1. Freedom 6S	**2002**
29.	Europe, UK, UNEXE	1. Exeter Five finger Array 125 2. Exeter Finger Array 100	**2002**
30.	Europe, Ireland, MediaLab	1. MESH	**2003**
31.	Europe, Germany, Technical University of Munich (TUM)	1. ViSHaRD10 [Buss,03]	**2003**
32.	Europe, Italy, UNIPI	1. Haptic Black Box [Bicchi,03]	**2003**
33.	Europe, France, Université d'Evry Val d'Essonne (UEVE), Laboratoire Systèmes Complexes (LSC)	1. Multi-level haptic rendering [Kheddar,04]	**2004**

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Glossary

	Items	Definition
1.	Action	
2.	Actuation	
3.	Actuator	
4.	Brushless	
5.	Coil	
6.	Commutation	
7.	Control	
8.	Controlability	
9.	Core	
10.	Coreless	
11.	Damping	
12.	Dipole	
13.	DOF Degree of Freedom	
14.	DSP Digital Signal Processor	
15.	Encoder.	
16.	Force	
17.	Force feedback	
18.	Haptic	
19.	Holonome	
20.	Hyperstatic	

21.	Immersive	
22.	Impedance/admittance	
23.	Inertia	
24.	Ironless	
25.	Isometric.	
26.	Isostatic	
27.	Isotonic.	
28.	Joint	
29.	Joint (cinematic sense)	
30.	LVDT Linear variable differential transformer	
31.	Mass	
32.	Motion	Used by [Martin Buss] to design either position, velocity and acceleration . The "motion" variable is dual of "force" variable.
33.	Condition Number	A measure of the degree of regularity of a Matrix. Applicable to a regular matrix with positive eigenvalues the condition number is defined by $\gamma = \sqrt{\lambda_{\max} / \lambda_{\min}}$
34.	Observability	
35.	Parallel/serial cinematic	
36.	Passivity	
37.	Physical-model	
38.	Prismatic (joint)	
39.	PWM Pulse width modulation	
40.	Reactance	
41.	Reactive	
42.	Reactivity	
43.	Reluctance	
44.	Robotics	
45.	Rotational (joint)	
46.	Sensing	
47.	Sensor	
48.	Signal	
49.	Sinusoidal commutation	
50.	Spherical (joint)	
51.	Stability	
52.	Stiff(system)	
53.	Supervisory control	
54.	Tactile	relating to the sense of touch, i.e., to perception of small-scale mechanical disturbance, distributed over the surface of the skin
55.	Telepresence	
56.	Telerobotics	
57.	Transparency	
58.	Vis-a-vis	
59.	Viscosity	