CHAPTER 4: Haptic Devices for Virtual Reality, Telepresence and Human-Assistive Robotics

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4.1 INTRODUCTION

Biomimetic systems attempt to copy the form or the behavior of biological systems to create efficient machines and processes. Since nature has had millions upon millions of years to perfect these systems it is logical to learn from these systems when designing machines and processes. Another way to use the tools that nature has built is to design machines that specifically incorporate a human into the system. These biologically-incorporated systems extend the capabilities of machines by adding a human component or extend the abilities of humans with the assistance of man-made devices.

The interfaces that are used when connecting these human and machine systems together are the human senses. These interface systems can truly be called bio-mimetic systems in that they are designed to respond to, or “mimic”, the reactions and sensations of a biological system, namely the human operator.

Various systems currently exist that provide information to the human senses of sight and hearing. Audio and video systems have been perfected over many decades so that it is now possible for a user to wear small devices, such as goggles and earphones, which will allow a user to see and hear various forms of information. Systems exist currently and others are being further developed that interface with a third human sense, the sense of touch. These systems are called *Haptic Systems* or simply *Haptics*. The inclusion of haptic systems, such as the ones presented in the following sections, allows for the creation of fully immersive environments that can provide a user with the three major inputs of visual, auditory and haptic information. These systems can be used for virtual reality and telepresence applications. The ability to generate visual, auditory and haptic stimuli makes it possible to accurately generate almost any environment that is desired in a believable and immersive manner.

Virtual Reality systems present a computer-generated visual and auditory experience that allows a user to be immersed within a computer generated “world” for various purposes. Used in conjunction with traditional computer input systems this can be used, for example, as a powerful design tool allowing a user to see objects that he or she is designing. The application to entertainment or training simulation systems is equally useful as it allows for the creation of an infinite number of immersive environments to suit any need. The addition of haptic systems to virtual reality will greatly increase its effectiveness at simulating real-world situations. One example can potentially include a medical training system using a simulator and virtual reality where a haptic system provides doctors with the “feel” of virtual patients. Figure 1 shows the schematic of such a medical simulation system, the visual display and the haptic gloves are combined to simulate, in this example, an abdominal aortic aneurysm surgery.

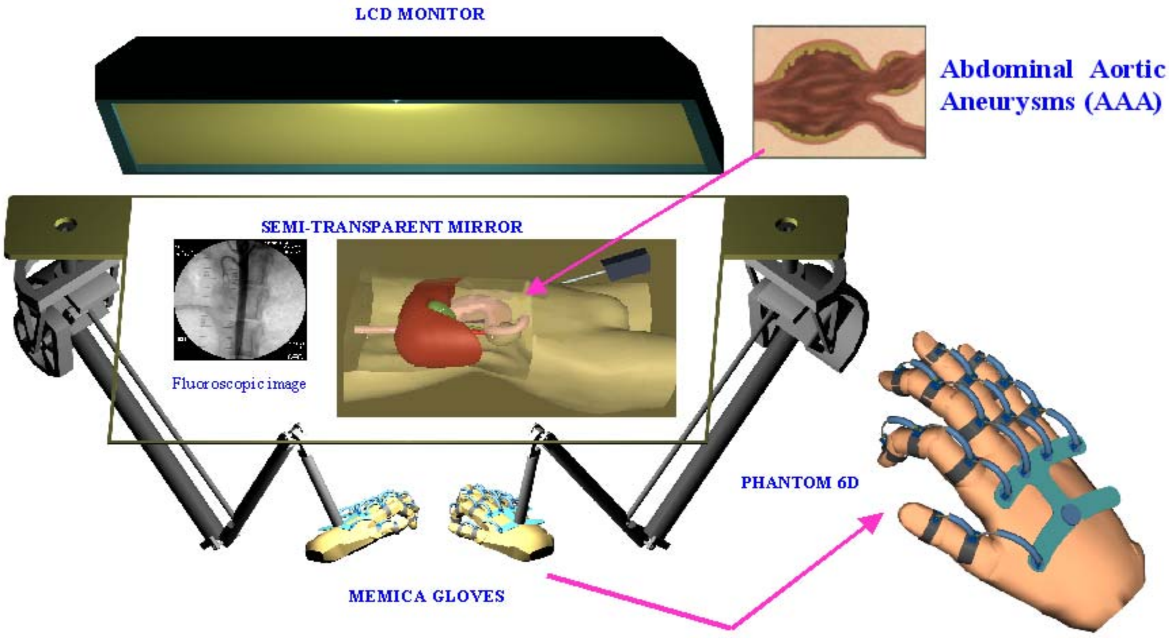


FIGURE 1: Virtual Reality for Surgical Training.

Tele-presence is a form of remote control for robotic systems, by which an operator interfaces with a robot, via visual, auditory and force feedback "as if he were there" at the remote site in place of the robot. Since the data processing and decision making power that a human is capable of far surpasses even the most advanced computer system, a human operator can control a robot in unknown or difficult situations more effectively than any computer program. The Mars Pathfinder mission from 1996, shown in the foreground of Figure 2, employed a simple form of tele-presense. The Sojourner rover sent visual and other sensor data to operators back on Earth who, in turn, sent instructions for the rover to carry out. The time-lag inherent in Earth to Mars communications required the rover to act semi-independently, but it can be imagined that if the rover were in near-instantaneous communications range it would directly act out the human-operator's instructions.

FIGURE 2: Mars Pathfinder Mission's *Sojourner* Rover shown on the surface of Mars inspecting a boulder (1996)

Human-Assistive devices use the force feedback component of a haptic system to generate forces for applications such as rehabilitation and muscle enhancement. Devices such as the exoskeletons presented in the following sections can be programmed to provide resistive forces to targeted body parts for use in rehabilitation. It can be easily imagined that a haptic glove can be used to support an injured hand while providing the opportunity for targeted exercises to the injured body parts. Assistive systems using similar exoskeleton devices can extend a person's muscle capabilities by following the user's movement and producing external forces proportional to the forces applied by the user.

This chapter will provide an overview of the state of the art in haptic research. The information will be provided in the following manner. Section 4.2 will give an introduction to the concept of haptics and the various applications that are foreseen for haptic technologies. Section 4.3 will review current technologies that are in development or production. Section 4.4 will introduce a new and promising form of haptic technology that uses a Smart Fluid to provide the force information. Section 4.5 will discuss some of the future work that will be and perhaps should be performed in the area of haptic research.

4.2 HAPTIC SYSTEMS

Haptic interfaces are devices that stimulate the sense of touch such as the sensory capabilities within our hands. The surge of computer capability and the desire for better ways to connect to computer-generated worlds has driven the creation and development of practical devices for haptic interaction. Until recently haptic systems only existed as demonstrations in research facilities. However, while research is still continuing, consumer-level haptic systems have been introduced. For example, force feedback gaming devices, such as joysticks and computer mice, have become available, while in the medical field, telesurgery or surgeon-directed robotic surgery has been gaining recognition.

The development of even more capable devices that can accurately reproduce a large range of haptic information is an important component for the technologies of virtual reality and telepresence. In medical applications it is vital that a surgeon be able to "feel" the difference between hard and soft tissues. For general robotic telepresence applications it is equally important that an operator be able to feel what the remote robot is touching, to allow the operator to run the robot in a more natural and responsive manner.

Telepresence systems and, even more simply, virtual reality systems, that incorporate a successful force-feedback component can be extremely useful for a wide variety of applications, for example:

- Space operations can benefit from a more robust control of robots, such as Robonaut, the robotic astronaut that is now in development. If Robonaut can be used with a telepresence system, it can be deployed in difficult or hazardous situations, in the place of an astronaut, with its operator, safely housed on a nearby spaceship or even on the ground, controlling its actions in a fluid, intuitive fashion. Figure 3 demonstrates the concept of remotely controlling Robonaut's operations.

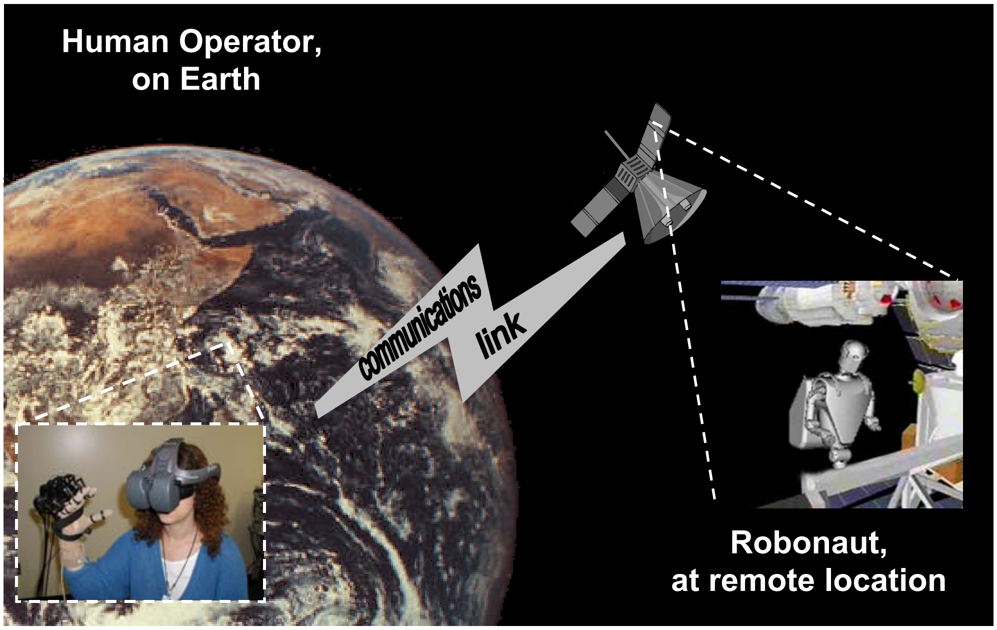


FIGURE 3: Example of Tele-Presence Control of Robonaut [NASA-JSC Website].
[Picture requires Permission]

- A force-feedback system could be used for rehabilitation purposes in space applications, as it can simulate gravitational forces, thus preventing the bone and muscle loss that are the result of extended operations in space.

- A virtual reality system that can reproduce realistic sensations can be used for training, for simulations or even for entertainment by allowing a user to fully interact with a virtual world.
- The system will have various medical applications as well. Medical students or field-medics will be able to train with virtual surgery, surgeons will be able to perform microsurgery by mirroring forces from the surgeon to the microsurgical tools, and surgeons will be able to perform surgical operations remotely in places where there are no surgeons, as with the case of the doctor at the South Pole research facility who was diagnosed with breast cancer but could not be evacuated from the site for a few months.

The successful creation of a completely immersive interface system that can accurately convey information to the senses of sight, hearing and touch is vital to the development of these and other systems.

Haptic technology is difficult to achieve convincingly because the human sense of touch is far more sensitive than the senses of sight or sound. In visual systems a picture needs to be refreshed at only 30 frames per second to trick the eye into thinking it is seeing continuous motion. However, the sense of touch requires that a sensation be updated 1000 times per second or more to relay a convincing tactile experience.

There are two main areas of application and research that are currently being developed by researchers in the haptics field - Virtual Reality/Telerobotic systems and Force Feedback/Tactile Display systems. Although both types of systems seek to simulate force information there are differences in the types of forces being simulated. Virtual reality and Telerobotic researchers seek to develop technologies that will allow the simulation or mirroring of virtual or remote forces by conveying large-scale shape and force information. Researchers in the field of Force Feedback and Tactile displays seek to develop a method of conveying more subtle sensory information between humans and machines, using the sense of touch.

Using the criteria of large- and small-scale force generation, haptic devices can broadly be categorized as follows:

Virtual Reality/Telerobotics: a) Exoskeletons and Stationary Devices;
b) Gloves and Wearable devices;
c) Point-sources and Specific Task Devices;
d) Locomotive Interfaces.

Feedback devices: a) Feedback input devices/ Force feedback devices;
b) Tactile displays.

The following sections present some of the current devices being developed from the categories listed above.

4.3 CURRENT DEVICES

Much research is being performed to create a viable Human-machine interface to use in Virtual Reality or Telerobotic systems. Various approaches have been taken to add touch information to these systems. The following section will present the categories of haptic devices that are in development - Exoskeletons and Stationary Devices, Gloves and Wearable devices, Point-sources and Specific Task Devices, Locomotive Interfaces, Feedback input devices/ Force feedback devices and Tactile displays.

Each category will be presented with a description of the basic concept behind the devices in the category followed by various example devices from that category. Although the devices presented are all examples of the fine work being done in the field of haptics technology the overview presented here should not be taken as a comprehensive list. Rather, the devices presented were chosen as representations of the different approaches that are available to achieve various forms of haptic information.

4.3.1 Exoskeletons and Stationary Devices

The first category of systems that are being developed for Virtual Reality and Telerobotic applications are the exoskeleton and stationary devices. The term exoskeleton refers to the hard outer shell that exists on many insects and other creatures. In a technical sense the word refers to a system that covers the user or that the user has to wear. Current haptic devices that are classified as exoskeletons are large and immobile systems that the user must attach him- or herself to. The benefit of exoskeleton devices is that their large size and immobile nature allow for the generation of large and varied force information without strict size or weight constraints. Various different approaches have been taken to provide force information in this manner.

Many of the exoskeleton devices that have been developed will provide force information along the whole arm or a similar area, using a variety of actuation methods. One example of this type of device is the Iowa State's Force Feedback Exoskeleton, shown in Figure 4, which uses magnetic fields to transfer force information to the user [Luecke and Chai, 1997, and VRAC Website].

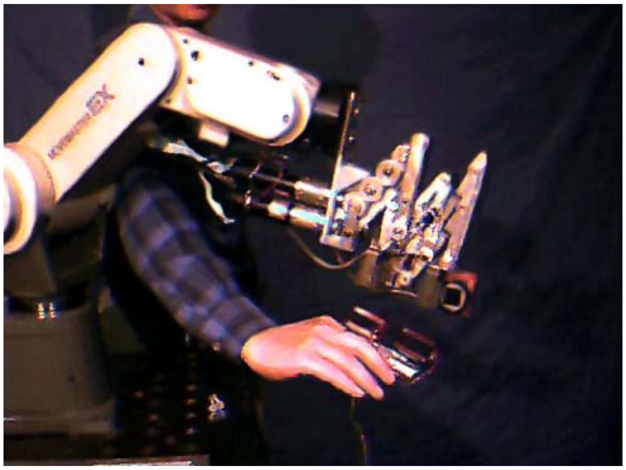


FIGURE 4: Iowa State Force Feedback Exoskeleton [VRAC Website].
[Picture requires Permission]

Other systems exist which provide haptic information to the arm, such as the commercially available CyberForce system from Virtual Technologies, Inc. shown in Figure 5, which attaches a haptic glove device to a force-feedback armature to provide hand and wrist force information [Immersion Corporation, Cyberforce, Website]. Forces are generated at the fingers by the use of a system of tendon-like cables.

FIGURE 5: CyberForce [Corporation, Cyberforce, website].
[Picture requires Permission]

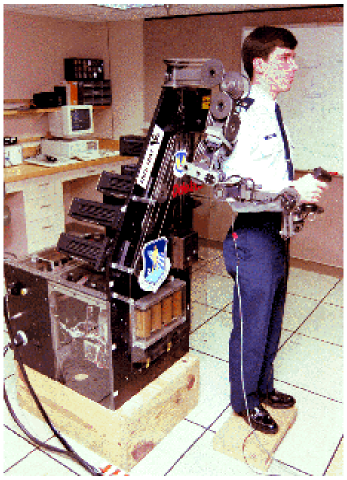


FIGURE 6: FREFLEX [Ohio University Website, Robert L. Williams].
[Picture requires Permission]

FREFLEX, the Force REFLecting EXoskeleton from Ohio University's Department of Mechanical Engineering [Williams, et al, 1998, and Ohio University Website], shown in Figure 6, is a system that provides information via a large stationary input device that follows the motions of the operator.

Researchers at the Systems Lab at Southern Methodist University have developed an exoskeleton device called the Master Arm that operates with pneumatic actuators [Hurmuzlu, et al, and ,Systems Laboratory Website]. The device, shown in Figure 7, consists of an aluminum manipulator with four revolute joints. It tracks the shoulder-elbow motions of the right arm of the operator. The manipulator is fixed at one end to a chair while the other end of the manipulator has a handle that is grasped by the operator. The device is strapped to the arm of the operator by using a set of inflatable cushions. Various length adjustments are used to accommodate different operators.

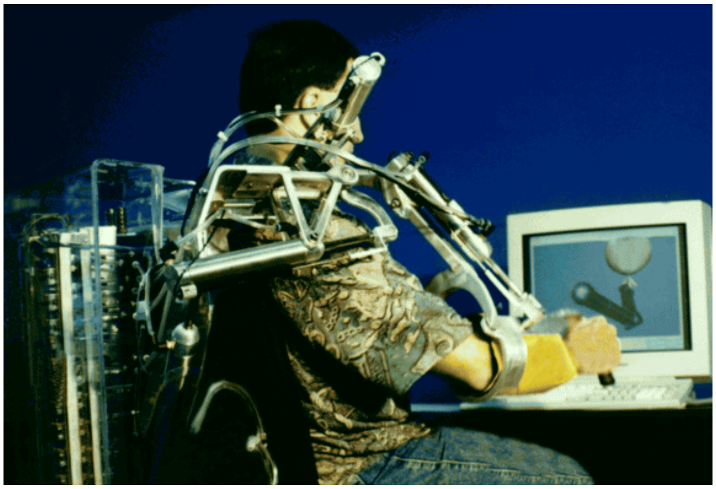


FIGURE 7: Master Arm, Southern Methodist University [Systems Laboratory Website].
[Picture requires Permission]

4.3.2 Gloves and Wearable Devices

The next important area of research is in the development of wearable devices that will be even more unencumbered than the exoskeleton systems described above. These devices are smaller exoskeleton-like devices that often, but not always, take the form of a glove. One major benefit of a wearable system is that the user can move more naturally without being weighed down by a large exoskeleton or other immobile device. Since the goal of building a haptic system is to be able to immerse a user in the virtual or remote environment it is important to provide as small a reminder of the user's actual environment as possible. The drawback of the wearable systems is that since weight and size of the devices are a concern the systems will have a more limited set of capabilities. There are many systems that are in development. The Master II from the Human-Machine Interface Laboratory at Rutgers, The State University of New Jersey [Bouzit, et al, 2002, and Human Machine Interface Laboratory Website], shown in Figure 8, is a glove that uses a pneumatic system to provide force information. The designers used only four actuators, leaving off an actuator for the smallest finger, in order to reduce the system's complexity. Other types of wearable devices exist that do not take the form of a glove, such as the WearableMaster, Figure 9, by the VR Lab at the University of Tsukuba, Japan [Virtual Reality Laboratory, Japan, Website]. It is a 3 Degree of Freedom, motor-driven joystick that is mounted on a user's arm.

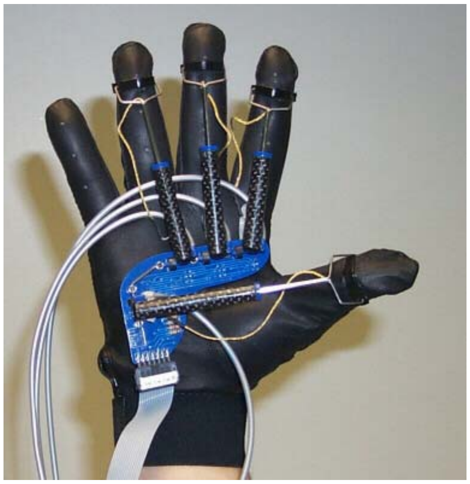


FIGURE 8: Master II, Rutgers University [Human Machine Interface Laboratory Website]. **[Picture requires Permission]**

FIGURE 9: Hand Held Force Display [Virtual Reality Laboratory, Japan, Website]. **[Picture requires Permission]**

Another force-feedback glove is the CyberGrasp system, developed by Virtual Technologies Inc., which is commercially available from Immersion Corporation of San José, California [Immersion Corporation, CyberGrasp, website]. The CyberGrasp system consists of two parts: The CyberGlove and the exoskeleton, seen in Figures 10 and 11 respectively. The CyberGlove is a lightweight glove with flexible sensors that accurately measure the position and movement of the fingers and wrist. The 22 sensor version of the CyberGlove features: two bend sensors on each finger, a sensor to measure the flexion of the distal joints on the four fingers, four abduction sensors, plus sensors measuring thumb crossover, palm arch, wrist flexion and wrist abduction. The active forces for the CyberGrasp system are provided by a lightweight exoskeleton system consisting of cable driven actuators that are worn over the CyberGlove. The CyberGrasp can provide 12N of continuous force per finger.

FIGURE 10: CyberGlove [Immersion Corporation, CyberGrasp]. **[Picture requires Permission]**

FIGURE 11: CyberGrasp Exoskeleton [Immersion Corporation]. **[Picture requires Permission]**

4.3.3 Point Sources and Specific Task Devices

The next category of Telerobotic and Virtual Reality systems is the Point-Source and Specific-Task Devices. This is a class of devices that are very specialized in either their technology or their application. Devices that provide any type of force information that may be required can be complicated and even extremely difficult to develop. Designing a device to perform a single type of task restricts the application of that device to a much smaller number of functions. However, it allows the designer to focus the device to perform its task extremely well.

These specific task devices have two general forms - single point of interface devices and specific task devices. An example of a single point of interface device is the Phantom, Figure 12 [Sensable Technologies], from Sensable Technologies. The Phantom has either a handle or a fingertip interface with an armature that provides up to six degrees of freedom, to a single point. Another single-point systems is the McGill University Pantograph shown in Figure 13, which provides an interface for a single finger to feel feedback information [Hayward, et al, 1994, and Haptics Laboratory].

FIGURE 12: Phantom [Sensable Technologies].[Picture requires Permission]

FIGURE 13: Pantograph, McGill University [Haptics Laboratory website]. [Picture requires Permission]

Since one of the main goals in providing haptic systems is to be able to create more realistic simulations, one approach has been to design systems that are specifically targeted to provide force feedback for a single type of simulation. The University of Hull Computer Science Department has been developing a surgical simulator called VEKATS - Virtual Environments Knee Arthroscopy Training System, shown in Figure 14a, [Sherman, et al, 2001, and Simulation and Visualization Research Group website]. It is to be used for training surgeons in Arthroscopic knee surgery, a minimally invasive and technically difficult surgical technique, by which a surgeon inserts a miniature camera and surgical tools through small openings that have been cut into the skin. A detailed computerized model of the human knee and a video simulation of the surgery have been developed. The instruments, interfaced with the computerized model, provide an accurate surgical simulator. Specialized instruments, shown in Figure 14b, are used that are designed to look and feel like actual surgical tools. These tools are designed to be as similar to the actual surgical tools as possible so they can provide an accurate simulation for training purposes [Simulation and Visualization Research Group website].

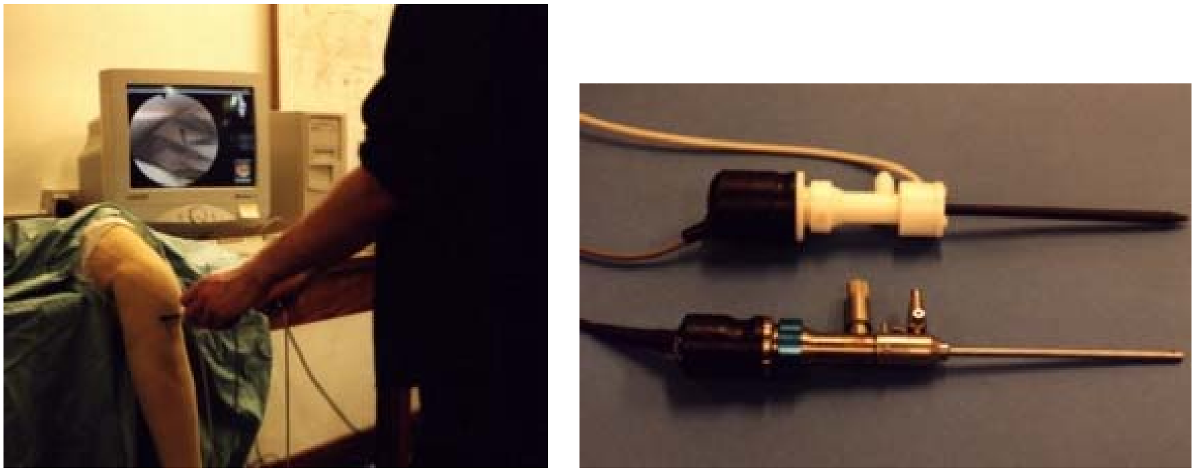


FIGURE 14: (a) Knee Arthroscopy Training System and (b) Mock Arthroscope (top) compared to a real instrument (bottom) [Simulation and Visualization Research Group website]. [Picture requires Permission]

4.3.4 Locomotion Interfaces and Full Body Force Feedback

An interesting application of haptic feedback is in the form of full body Force Feedback called a Locomotion interfaces. Locomotion interfaces are movement of force restriction devices that, in a confined space, simulate unrestrained human mobility such as walking and running for virtual reality. Locomotion interfaces overcome limitations of using joysticks for maneuvering or whole-body motion platforms, in which the user is seated and does not expend energy, and of room environments, where only short distances can be traversed. Their use yields realistic navigation and engagement in modeled worlds and an enhanced sense of spatial layout. The device shown in Figure 15 is the Treadport- a locomotion interface created by Sarcos Inc. [Sarcos website]. The Treadport comprises a treadmill, a mechanical tether, and a CAVE visual display. The Treadport is being applied towards research in perceptual issues involving locomotion interfaces, and control issues regarding the fidelity of Treadport locomotion biomechanics.

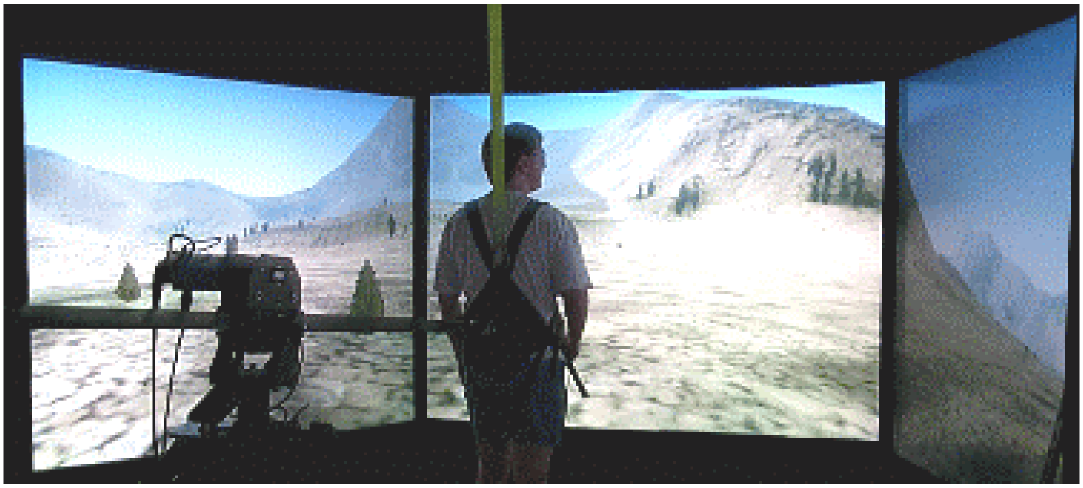


FIGURE 15: Treadport, Sarcos Inc. [Sarcos website]. [Picture requires Permission]

4.3.5 Force Feedback Input Devices

Force feedback input devices are usually, but not exclusively, connected to computer systems and are designed to apply forces to simulate the sensation of weight or resistance in order to provide information to the user. As such, the feedback hardware represents a more sophisticated form of input/output device, complementing others such as keyboards, mice, or trackers. Input from the user is in the form of hand, or other body segment, position or exerted force, whereas feedback from the computer or other device is in the form of force or position.

These devices are translate digital information into physical sensations. For example, when you push on a mouse or joystick, the device pushes back using, for instance, magnetic actuators and sensors built into the device. However, resistance is only one of the sensations that can be delivered. Springs, liquids, textures, vibrations, and many more can be simulated, as long as they can be translated into a mathematical equation. Various types of simple effects can be used individually or together to create a large range of sensations.

Force feedback joysticks, mice, driving wheels, and other devices, some of which are shown in Figure 16, have been developed. This method of conveying force information allows programmers and designers an additional way to interact with and send information to a user.

FIGURE 16: Sidewinder Force feedback Joystick, Microsoft Corp [Microsoft Corp. website] and WingMan Force Feedback Mouse, Logitech [Logitech website].
[Picture requires Permission]

The Logitech WingMan Force Feedback Mouse gives users a tactile, physical response when using the computer mouse input device [Logitech website]. Force feedback software has been added to a variety of popular games. It can also be used as an aid in navigating around the Internet and the computer's operating system. One can feel individual items on the menus as the pointer rolls over them. They feel like rounded speed bumps. When one grabs a small window by the corner and stretches it to fill the screen, it feels like a rubber band, pulling harder as you stretch the box. As the pointer rolls into a scroll bar or input field, one has the sensation of rolling up the lip of a trench, then down into it, and that trench helps to hold the pointer along the bar's narrow track. Some objects feel magnetic while others are repulse.

4.3.6 Tactile Displays

Simulation tasks involving active exploration or delicate manipulation of a virtual environment require the addition of feedback data that presents an object's surface geometry or texture. Such feedback is provided by tactile feedback systems or *tactile displays*. Tactile systems differ from haptic systems in the scale of the forces being generated. While Haptic interfaces will present the shape, weight or compliance of an object, tactile interfaces present the surface properties of an object such as the object's surface texture.

Tactile feedback is applies sensations to the skin, typically in response to contact or other actions in a virtual world. Tactile feedback can also be used to produce a symbol, like Braille, or simply a sensation that indicates some condition or surface texture. For haptic systems tactile feedback interfaces can function as stand-alone systems, or they can be integrated with force feedback systems to enhance the sensation of immersion in a simulated environment.

Tactile display devices stimulate the skin to generate the sensations of contact. The skin responds to several types of physical sensations; such as vibrations, small-scale shape or pressure distribution, and temperature sensations. Systems are being developed that generate many of these sensations. The ability to create these types of surface sensations can be applied in various ways:

- **Vibration:** Information can be relayed about phenomena like surface texture, slippage, impact, and puncture. In many situations, the human sense of touch can only experience vibrations as diffuse and unlocalized sensations, so a single vibrator for each finger or region of skin may be adequate.
- **Small-scale shape or pressure distribution:** This type of force will convey information about the shape and surface texture of an object. One design approach is an array of closely-spaced pins that can be individually raised and lowered against the finger tip to approximate the desired shape. In addition, the display often must be small and light enough to mount on a force- reflecting interface. To convey a range of spatial scales across a fingertip may thus require a number of fast actuators in a small area.
- **Thermal display:** This is a relatively new area of research. Because human fingers are often warmer than the "room temperature" objects in the environment, thermal perceptions are based on a combination of thermal conductivity, thermal capacity, and temperature. This allows people to infer material composition as well as temperature difference. A few thermal display devices have been reported, usually based on Peltier thermoelectric coolers.

- **Other tactile display sensations** have been created by a number of different technologies, including electrorheological devices for conveying compliance, electrocutaneous stimulators, ultrasonic friction displays, and rotating disks for creating slip sensations.

Current research on tactile displays has much in common with previous work on sensory substitution for the disabled. This includes arrays of pins that are used to convey visual information to the blind, and vibrational systems to “display” auditory information for the hearing impaired.

A Shape Display device by the Harvard BioRobotics Lab, seen in Figure 17, consists of 10 individually actuated pins that are raised against the fingerpad [Wellman, et al, 1997, and Biorobotics Laboratory website]. The upper figure shows the top view of the display and a user’s finger. The lower figure shows the side view of the display. Electrical current heats the Shape Memory Alloy (SMA) wires, which undergo a phase transformation and shortens. This forces the pin up against the fingerpad. The pin's position is measured optically.

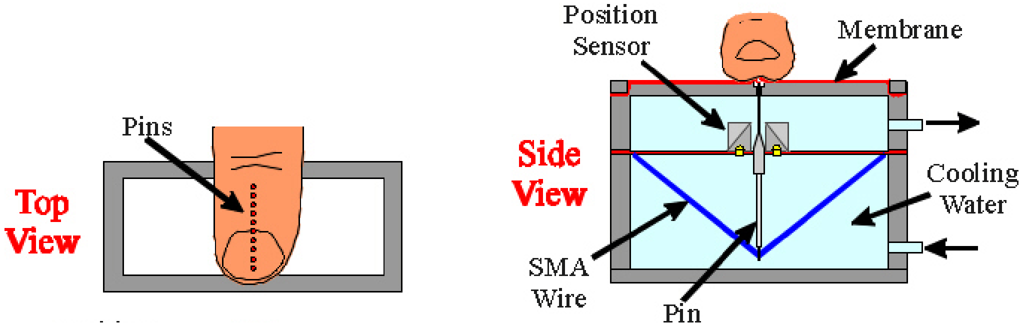


FIGURE 17: Shape Display device by the Harvard BioRobotics Lab [Biorobotics Laboratory website]. [**Picture requires Permission**]

4.4 HAPTIC SYSTEMS USING ELECTRO-RHEOLOGICAL FLUIDS

4.4.1 Electro Rheological Fluids and Haptics

Most of the haptic systems presented above and others that are currently in development use traditional actuator technologies to provide haptic and feedback forces. These systems provide predictable and well-tested technologies for the designers, allowing for the building of robust and useful systems. However, it is important to look for new and better actuator technologies that will allow for the design of smaller and more powerful haptic systems that will bring us closer to realizing the potential of this new field of research. One actuator technology has come from the field of smart materials research, which has provided novel and useful actuator technologies in the past, that is: *Electro-Rheological Fluids* (*ER Fluids* or *ERFs*).

Electro-Rheological Fluids, first described by Winslow in 1949, have the ability to change their viscosity in response to an electric field. This is an ideal capability for haptic systems in which it is important to simulate various different strengths of forces with as few actuators as possible.

ERFs, are comprised of particles that are suspended in an insulating base fluid. When an electric field is applied to the fluid the particles tend to line up in the field, causing the fluid to act more viscous. In Figures 18 and 19, the left-hand pictures show the ER Fluid in its unactuated state, the particles are free to move and the fluid flows as expected when a coils is dipped into it and pulled out. The right-hand pictures show the fluid in its actuated state, the particles are lined up in the electrical field and the fluid has become too viscous to flow from the coil.

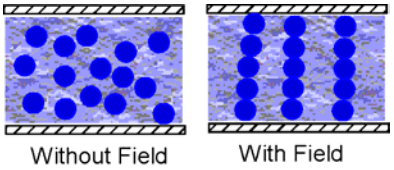


FIGURE 18: Particle Suspension forms chains when an electric field is applied on the ERF.

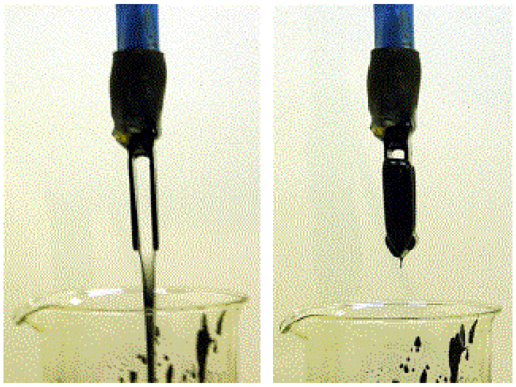


FIGURE 19: Electro-Rheological Fluid at Reference (Left) and Activated States (Right). Courtesy of smart technology limited, England.

Electro-Rheological Fluids will flow once a minimum force, known as the yield stress, is applied to it. Fluids that exhibit this type of behavior are known as Bingham plastics. The most common example of a Bingham plastic is toothpaste, which is a fluid, but will only flow freely if a certain minimum amount of force is applied to it. In designing haptic devices using ERFs the behavior that is exploited is the yield-stress. Since the amount of yield stress required by the fluid to flow changes in response to the strength of the electric field, it is this property that allows the ERF to simulate various different resistances and therefore various different haptic forces.

Since ERFs are actuated by the application of electric fields, which can easily be generated by situation two conducting plates facing each other with a gap in between, they can be incorporated into very small devices. This property along with their high yield stress can result in miniature haptic devices that can potentially fit inside the human palm without creating any obstructions to human motion.

As well, ERFs do not require any transmission elements to produce high forces, so direct drive systems can be produced with less weight and inertia. The ability to easily change the fluid's rheological properties gives designers of ERF-based haptic system the possibility of controlling the system compliance; and hence, the ability to accurately mirror remote or virtual compliance.

Finally, ERFs respond almost instantly, in milliseconds, which can permit very high bandwidth control, which is important for mirroring fast motions.

The only concern that a designer of ERF-based haptic interfaces may have is the need for high voltages to develop the forces and compliance required. This has two consequences: a) it increases the complexity of the electronic system needed to develop the high voltage and b) it raises safety concerns for the human operator. Both issues can easily be solved with modern electronic circuit design techniques. Nowadays, low power and small size circuits can be used to generate the required high voltage using a very low current on the order of micro-amps. Consequently, the required power becomes extremely low, in the order of mWatts, posing no hazard for human operators.

Kenaley and Cutkosky were the first to propose the use of ERFs for tactile sensing in robotic fingers [Kenaley and Cutkosky, 1989]. Based on that work, several researchers proposed the use of ERFs in tactile arrays used to interact with virtual environments [Wood, 1998] and also as assistive devices for the blind to read the Braille system. The first to propose this application of ERFs was Monkman [1992]. Continuing this work, Professor Taylor and his group at the University of Newcastle upon Tyne, UK, developed and tested experimentally programmable surfaces based on ERFs [Taylor et al 1996a; Taylor et al 1996b; and University of Newcastle upon Tyne website], see Figure 20. Professor Furusho and his group at Osaka University in Japan, developed an ERF-based planar force-feedback manipulator system, shown in Figure 21, that interacts with a virtual environment [Sakaguchi & Furusho 1998a; Sakaguchi & Furusho 1998b, Human-Machine Interaction Subarea website]. This system is actuated by low-inertia motors equipped with an ER clutch.

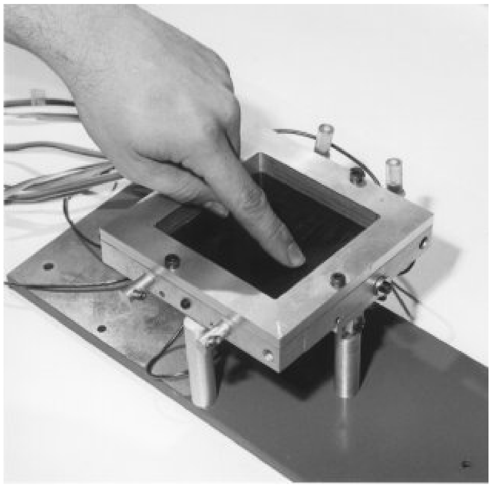


FIGURE 20: Programmable Surfaces Based on Electrorheological Fluids [Intelligent Mechanical and Manufacturing Systems Research website].
[Picture requires Permission]

An ERF-based force-feedback joystick has been developed in Fraunhofer-Institut in Germany. The joystick, shown in Figure 22, consists of a ball and socket joint where ERF has been placed in the space between the ball and the socket. The operator feels a resistive force to his/her motion resulting from the controlled viscosity of the ERF [Böse, et al, 2000].

Finally, researchers at Rutgers University and JPL are developing a family of ERF-based force-feedback devices called MEMICA (MEchanical MIrroring using Controlled stiffness and

Actuators) haptic interfaces [Bar-Cohen et al, 2000a.; Bar-Cohen, et al, 2000b; Bar-Cohen, et al. 2000c; Bar-Cohen, et al 2000d; Mavroidis, et al, 2000a; Mavroidis, et al, 2000b; Mavroidis, et al, 2000c; and Mavroidis, et al, 2001]. In the following section the concept and design considerations for a MEMICA lower limb exoskeleton force-feedback device are presented.

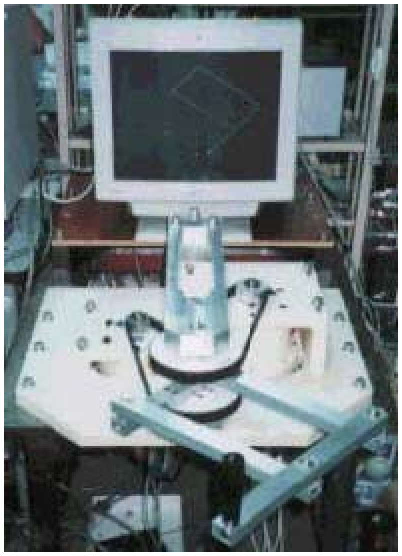


FIGURE 21: Force Display Device Using Electrorheological Fluids [Human-Machine Interaction Subarea website].
[Picture requires Permission]

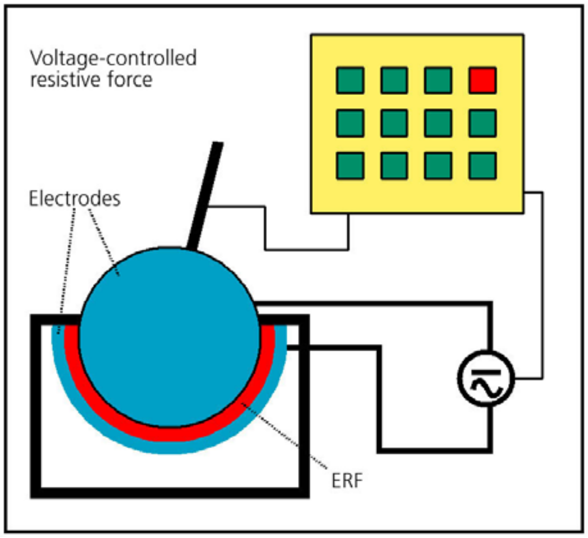


FIGURE 22: Haptic Joystic Using ERFs [Böse, et al, 2000].
[Picture requires Permission]

4.4.2 A MEMICA Exoskeleton with On-Demand Controlled Resistivity and Operability (ExODeCRO) Using ERF-Based Elements

A novel exoskeleton with controlled resistivity and operability that is operational on-demand has been proposed that will use ERF-controlled rotary elements to generate forces. Using rotary elements as a smart clutch that is integrated with rotary motors would be coupled upon activation to provide torques. Linear elements, such as those presented in [Bar-Cohen et al, 2000a.; Bar-Cohen, et al, 2000b; Bar-Cohen, et al. 2000c; Bar-Cohen, et al 2000d; Mavroidis, et al, 2000a; Mavroidis, et al, 2000b; Mavroidis, et al, 2000c; and Mavroidis, et al, 2001], are used to compensate the effect of the movement on the length of the struts. The device can be adjusted to the body size of the user and it consists of struts that are strapped to the user with the aid of belts and Velcro locking. The exoskeleton induces controlled resistivity and operability. This device enables numerous applications both in augmentation and impeding applications. Various rehabilitative applications are available, but the application to a NASA space-related mission is described below.

The use of such an exoskeleton that can provide forces to a user, can effectively simulate the resistive forces of gravity. This system can address the critical need for countermeasures to mitigate the effect of microgravity on bones and muscles. This exoskeleton capability will help assure safe and productive human operation on long-duration missions. Such a countermeasure system will help minimize the risks in readapting to gravity, and help optimize the crew safety, well-being and performance.

As a countermeasure tool the conceived exoskeleton, shown in Figure 23, passively and/or actively counters movements of the human body by providing controlled resistance, forces and torques at high dexterity and rapid response (milliseconds). The passive elements resist body movements that require concentric muscle contraction, whereas the operative elements are actively force movement of the body joints that require eccentric muscle contraction. The operative elements consist of actuators and are used to simulate normal exercises and activity in the 1-g environment. The exoskeleton benefits from the use of ERF allowing it to be commanded by the astronaut users to be either idle, i.e., not resist movements, or electroactive. The exoskeleton design that is shown focuses on the joints of the lower part of the body, but the system can be extended to a full-body configuration.

FIGURE 23: A Graphic View of the MEMICA-Based Exoskeleton for Countermeasures.

The ERF-elements of the exoskeleton consist of linear and rotary Electrically Controlled Stiffness (ECS) elements controlling the resistive forces and torques applied by the exoskeleton. The rotary elements are made to resist, generate and control rotations either normal or along the axes of the connected struts. The operative elements consist of either inchworm linear motors, such as the ones described in [Bar-Cohen et al, 2000a; Bar-Cohen, et al, 2000b; Bar-Cohen, et al. 2000c; Bar-Cohen, et al 2000d; Mavroidis, et al, 2000a; Mavroidis, et al, 2000b; Mavroidis, et al, 2000c; and Mavroidis, et al, 2001] or active-clutch with rotary motors.

4.4.2.1 – Rotary ECS and Actuation Elements

Rotary ECS and actuation elements play an important role in the construction of the exoskeleton. These elements are designed using the basic configuration shown in the top section of Figure 24 and they contain ERF to allow resistivity to rotation forces and torques. Two different configurations of rotary elements are used in order to resist, generate and control rotations where the axis of rotation is either normal or along the axes of the connected struts (bottom section of Figure 24).

The elements consist of multiple electrodes with ERF that fills the thin gap between them. The adjacent electrodes are designed to induce opposing polarity, one set of the electrodes is connected to the axis and the other set to the external section of the element. Even though the current and power that are used to drive the electrodes are very small, the electric field is insulated to protect the user from the potential of an electric shock.

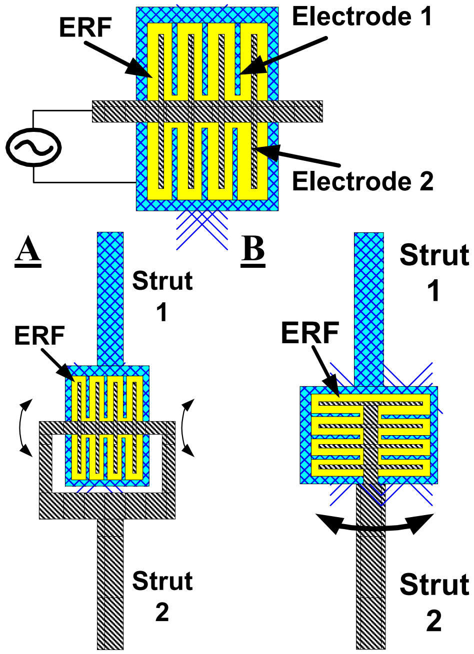


FIGURE 24: Rotary Elements (Top) for Both Horizontal and Vertical Orientations (Bottom).

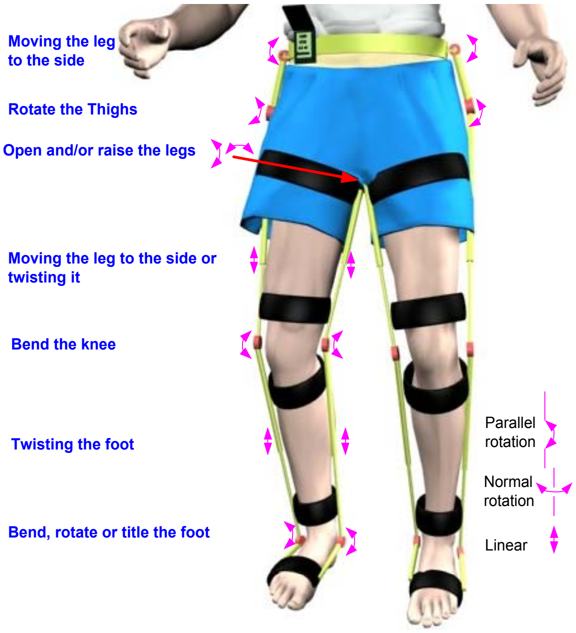
To create maximum resistivity by the individual elements efforts are made to maximize the amount of ERF that is subjected to the electric field with as thin gap as practical. Also, holes are made in the electrodes surface in order to force a flow of ERF through their passage enhancing the resistivity when the electric field is activated. A key issue that guides the design of the elements is the capability to sustain the forces and torques that can be applied by the human operator. This constraint dictates the required size of the specific elements and the thickness of the electrode walls inside the ECS elements. The central axis of the elements is fixed to a strut that is supported by the human body and rotates (Strut 2 in the Figure), whereas the external section of the element is made to rotate (Strut 1).

In order to operate the rotary elements as active devices, rotary motors are mounted on the axis of a strut. When an electric field is applied through the ERF region the viscosity increases mechanically coupling the other strut to the motor forcing it to rotate. This design effectively operates the ECS element as an active clutch mechanism, where higher applied voltage leads to a larger torque transfer from the motor to the coupled strut.

4.4.2.2 - MEMICA Exoskeleton

A schematic description of the exoskeleton is shown in Figure 25. It is designed to be rigid, fracture tolerant and lightweight using struts that are made of graphite/epoxy. Velcro belts are used to allow easy strapping of the exoskeleton to the user's body making it adjustable to different size of users. Moreover, to adjust for different user heights the key longitudinal struts that are adjacent to the thighs and calf are made with a telescopic adjustment that are loosened for adjustment and, once set comfortably to the user's height, a screw is tightened to secure the specific length. The exoskeleton structure is designed to have the smallest dimensions and mass that is capable to counter or augment the user's forces while making it comfortable to operate.

FIGURE 25: The MEMICA Exoskeleton Mounted on a Graphic Simulation of a User.



The various joints of the exoskeleton consist of the resistive and actuation elements that are either linear or rotary. These elements are operated in pairs as shown in Figure 25, where the direction of movement of the elements for the right-hand leg are shown schematically with related arrows. The various elements are equipped with miniature displacement sensors (such as Hall effect sensors) and force sensors (such as strain gauges) to be able to provide feedback to the control system of both forces and displacements. This feedback is necessary to assure that selected safety limits are not exceeded and to track the level of exercises that are performed in order to provide the user with useful information about his/her performance.

Given the fact that a very low level of electric current and power is needed to activate the various elements the exoskeleton is expected to operate using a relative small and lightweight battery. The exoskeleton system electronics include a miniature Pentium PC, D/A and A/D boards, motion controllers, sensor interface boards and a modem card for radio communication with a remote control station. All computers and sensor interface boards can be mounted on a backpack. Control of the exoskeleton is performed intuitively by the user and supported with a sensor system to provide redundancy and robustness. A dual system of sensors is used placed on both the exoskeleton and the human. The sensors placed on the exoskeleton include miniature position sensors placed on the joints and miniature force/touch and myoelectric or myopneumatic sensors are placed on the human to measure the muscle activities (flexion or extension). An algorithm is used that takes into account all sensor signals to infer the human's motion/force and generate an enhancement action if this is needed.

4.4.2.3 - Potential Applications

The presented exoskeleton can also be used as an effective Human Muscle Enhancer (HME) system for the improvement of the physical performance of human operators. Rather than providing resistance to the user, as described above, the exoskeleton can follow the movements of the operator and apply additional forces to the environment in proportion to the forces generated by the operator. HME systems could be used in such applications as medical rehabilitation, sports training, in the heavy lifting industrial sector, in space activities and training of astronauts and by military personnel both as a mechanical assistant device in combat and to maintain fitness for combat while in a restricted environment.

In the military arena, personnel in the field will benefit from the muscle enhancement by having greater load carrying capability with less strain, and ability to ambulate further distances than present conditions allow. The HME system can be applied in the industrial and healthcare industry where many workers who lift heavy materials or equipment experience lower back injuries resulting in work time loss, workmen's compensation insurance premium increases, diminished employee productivity, and a financial burden on the health care industry. As well, with the rising senior population, health care costs are also increasing due to the increased assistance required by the elderly. There are many patients that are suffering of debilitating diseases or being in a rehabilitation phase who can benefit from such HME systems. Patients that may need such systems include those with:

a) *Rheumatoid arthritis* - a chronic inflammatory disease;

b) *Osteoarthritis* - a progressive joint disorder;

c) *Bursitis* - an inflammation of the lubricating sacs surrounding the joint capsule;

d) *Rehabilitation after reconstructive surgery* (hip replacement and knee prostheses; foot surgery)

e) *Rehabilitation after sports related injuries*.

All these patients may need ambulatory aids to sit, to stand, and to walk. Depending on the ability of the patient, the aid can be a human helper with or without the assistance from passive aids such as a cane, crutches, or walker. The use of a Human Muscle Enhancer (HME) can minimize the number of human helpers by providing partial support to the patient.

The ability to augment motion may be used in various applications including police operation or fireman search and rescue action where, if an emergency situation arises requiring high speed running or physical action, the user will be able to run very fast or lift mass that are beyond human capability. It may help patients or other human who need assistance in performing physical functions that may be too difficult without assistance. The resistive aspect of the exoskeleton may be used in exercise machines.

4.5 CONCLUSIONS AND FUTURE WORK

Haptics technologies provide the next important step towards realistically simulated environments that have been envisioned by science fiction authors and futurists alike. The sense of touch is so important to the way in which humans interact with the world that it's absence in simulation technologies of the past has been a major shortcoming. Adding the sense of touch to the sense of hearing and sight currently addressed by simulation technologies is a very exciting development.

The practical applications of such technologies that have been presented show the enormous potential that this technology has for providing realistic simulations for medical and military training resulting in better trained doctors and soldiers. This alone will enhance the lives and security of countless numbers of people. The application to entertainment, although less critical than the medical application, will greatly enhance the enjoyment of artistic and leisurely pleasures as well.

This chapter has provided an overview of the state of the art of haptic technology and research. Much work is being done and great strides seem to be on the horizon to create useful and practical haptic systems. However, Some innovations are still required before the large-scale adoption of haptic technology can occur, such as miniaturization, high-speed devices and communications innovations.

Many of the haptic devices must be miniaturized so that they are lighter, simpler and easier to use. Smaller and better actuation systems are being developed and strides are being made in this area. The introduction of Electro-Rheological Fluid based devices shows one way in which miniaturization of haptic devices can occur.

Accurate and high-speed devices must be perfected in order to create real-world simulations. The simulation of natural phenomenon is an important goal for this technology. Current systems may not be able to generate forces with the speed required to simulate real-world situations. Much work is being done to provide computer and actuation systems that work on such fast speeds and the outlook for improvement in this area is encouraging.

Many of the applications for tele-robotics, whether for medical purposes or space-related purposes, requires that the system be able to simulate remote sensation in real-time. A remote surgical system *must* be able to provide instantly-updated information so that a surgeon can perform his/her work instantaneously. The slightest delay may be the difference between a life or death situation for the patient. One of the stumbling blocks for a real-time system is in the area of communications. A sensation must be read remotely, converted into a digital form, sent by some communications link to the user, converted back to a form that is useable by the actuation system, and the force must be generated for the user based on that information, the users response must then be read and the process must be repeated to send instructions back to the remote site. This system requires high-speed communications links and methods in order to insure that the actions of the remote robot accurately and in a timely fashion mirror the instructions of the operator. Advances must be made in this area in order to be able to implement these haptic technologies in all of the exciting ways that have been imagined.

Although some advances are still needed the fundamental technologies are being developed to provide useful haptic systems. With the advances and leaps that are being made by universities, laboratories and institutions around the world the future of haptic technology is indeed looking (and feeling) very bright.

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