10.2 HAPTIC INTERFACES

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For many years, the robotic community sought to develop robots that can eventually operate autonomously and eliminate the need for human operators. However, there is an increasing realization that there are some tasks that humans can perform significantly better but, due to associated hazards, distance, physical limitations and other causes, only robots can be employed to perform these tasks. Remotely performing these types of tasks requires operating robots as human surrogates. Such a capability has been the goal of many studies and significant success has been reported in recent years. NASA Johnson Space Center is currently developing a robotic astronaut, called Robonaut (see Figures 1 and 2), which is capable of performing various tasks at remote sites. Robonaut was designed such that a human operator who is wearing gloves and/or suit with sensors can control the robot. Unfortunately, due to unavailability of force and tactile feedback capability in the control suit/glove, the operator determines the required action by visual feedback, i.e. looking at the Robonaut action at the remote site. This approach is ineffective and is limiting the potential tasks that Robonaut can perform. As human activity in space increases there is an increasing need for robots to perform dexterous Extra Vehicular Activity (EVA). Existing space robots are inadequate substitutes for an astronaut because they:
(1) require additional special alignment targets and grapple fixtures.
(2) are too large to fit through tight EVA access corridors.
(3) do not possess adequate speed and dexterity to handle small and complex items, soft and flexible materials, as well as most common EVA interfaces.
(4) are controlled by operators that have only visual feedback limiting incredibly their "perception" of the work-environment.

Therefore, there is a great need for dexterous, fast, accurate teleoperated space robots with the operator's ability to "feel" the environment as if she or he is "present" at the robot's operation field. Effective telepresence requires that human operator "feel" the stiffness, temperature, and vibration of the object that is being remotely or virtually manipulated/actuated. The mechanical and thermal characteristics of the remote object needs to be intuitively mirrored including the reaction forces and backward displacements. Such systems need to respond to data by remote sensors or from virtual reality sources at selected points or joints. Providing thermal feedback can be easily conducted by existing technology, whereas the mechanical feedback using miniature elements is critically needed and are being under development. A wide range of remote NDE applications can employ such a technology particularly for applications where it is not safe for direct presence of human operator.

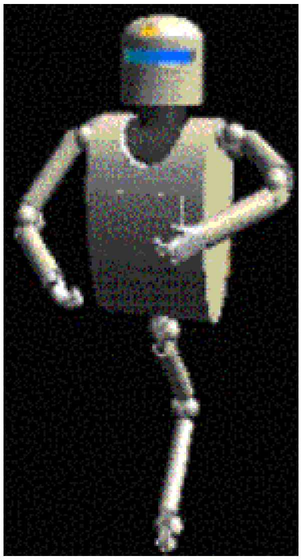


Figure 1: Robonaut - a robotic astronaut under development at NASA-Johnson Space Center.

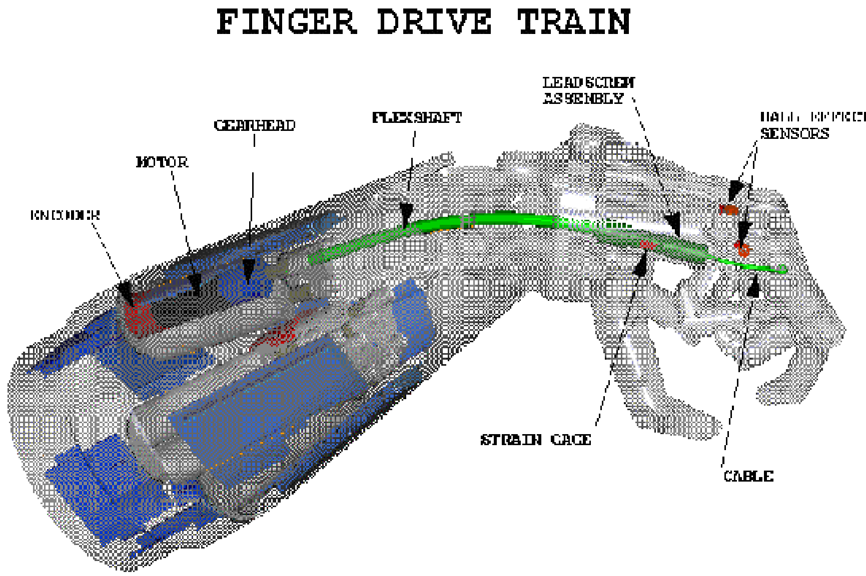


Figure 2: The Robonaut arm and hand are controlled remotely by a human operator. Having a "feeling" of the mechanical condition at the remote site is critical to the effective use of the arm.

10.2.1 ROBOTS AS HUMAN SURROGATES

Telepresence requires that a human operator control the action of a remotely operated robot. In the case of the NASA Robonaut, the human operator must control nearly fifty individual degrees of freedom. The use of three axis hand controllers would present a formidable task for the operator. Because Robonaut is anthropomorphic, the logical method of control is one of a master-slave relationship whereby the operator’s motions are essentially mimicked by the robot. If the user is to interact in a natural way with the robot, the interface must be intuitive, accurate, responsive and transparent. If the user is to control the robot motions in a naturally perceived way, an interface device must be provided which is capable of determining what the user is doing without interfering with their motion or encumbering their body. Furthermore, the operator must be able to extract information about the robot and its environment to effectively control the robot.

To date, there are no effective commercial alternatives to unencumbering haptic feedback devices for the human hand. As a result, intuitive teleoperated control of such robots as the Robonaut is currently being compromised. Tactile feedback devices that provide operator awareness of contact between work space objects and the robot structure is a key technology area for the effective control of dexterous robots. The use of a haptic mechanism internal to a cyber-glove would greatly increase the usability of a cyber-glove while eliminating the bulk and clumsiness associated with an exoskeleton based haptic device.

10.2.2 HAPTIC SYSTEMS

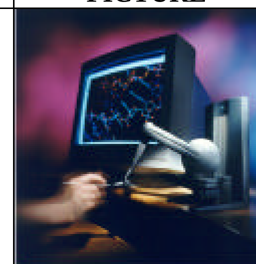
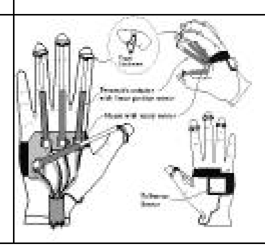
To address the need for surrogate robots that remotely mirror human action and reaction, the engineering community has started developing haptic (tactile and force) feedback systems [Burdea, 1996]. At the present time, haptic feedback is a less developed modality of interacting with remote and virtual worlds compared to visual and auditory feedback. Thus, realism suffers especially when remote and virtual tasks involve dexterous manipulation, or interaction in visually occluded scenes. A very good description of the current state-of-the-art in haptic and force feedback systems can be found in [Burdea, 1996; Brown and Reger, 1998; US Navy, Office of Training Technology, 1999].

Tactile sensing is created by skin excitation that is usually produced by devices also called "tactile displays", [Howe, 1999]. These skin excitations generate the sensation of contact. Tactile feedback is easier to produce than force feedback with present actuator technology, and the interface tends to be light and portable [Burdea, 1996]. Force sensitive resistors, miniature pressure transducers, ultrasonic force sensors, piezolectric sensors, vibrotactile arrays, thermal displays and electro-rheological devices are some of the innovative technologies that have been used to generate the feeling of touch. An example is the tactile feedback suit that was developed by Begej Co. for NASA JSC [Li, 1993]. It consists of arrays of small pneumatic bellows on the arms, chest and abdomen. While tactile feedback was conveyed by the mechanical smoothness and slippage of a remote object, it could not produce rigidity of motion [Burdea and Langrana, 1993]. Thus, tactile feedback alone cannot convey the mechanical compliance, weight or inertia of the virtual object being manipulated [Burdea, 1996].

Force feedback devices are designed to apply forces or moments at specific points on the body of a human operator. The applied force or moment is equal or proportional to a force or moment generated in a remote or virtual environment. Thus, the human operator physically interacts with a computer system that emulates a virtual or remote environment. Usually, the force/moment feedback is applied at the operator's hand or arm. Recently, several force feedback devices have been developed to transfer forces at the human operator's knee and ankle. There are many important applications for force feedback devices. Force-feedback devices are the immediate descendants of the "master-slave" tele-operation systems that started to be developed in the 1940's. Tele-operation is the remote control of robot manipulators that have and are being used in nuclear, underwater and space robotic tasks. Recently, force-feedback systems are being used in conjunction with virtual reality in several other applications such as: a) entertainment and video games where the user realistically interacts with the virtual world using several modalities including force feedback, b) training of specialists in difficult tasks where real prototypes can not be found easily. Examples are the training of medical doctors and surgeons and the training of pilots and astronauts, c) rehabilitation of patients with neuromotor disabilities.

Force feedback devices are distinguished into portable and non-portable interfaces. Several examples for such devices are shown in Table 1. Force feedback joysticks, mice [Cybernet Systems Co., 1995; Immersion Corp., 1999; Haptic Technologies] and small robotic arms such as the Phantom [Massie and Salisbury, 1994; Sensable Technologies, 1999] are non-portable devices which allow users to feel the geometry, hardness and/or weight of virtual objects. These systems are mechanically attached to the ground or to a fixed structure outside the user's body. The main advantage of non-portable force feedback system is that they do not tire the user, since the interface weight is supported by the desk to which it is attached [Burdea, 1996]. However, hand freedom of motion and dexterity are limited since these devices have a much smaller work volume and degrees of freedom than the user's hand. The simplest non-portable haptic systems are force feedback game controller joysticks and force feedback mice that usually offer a low force and inaccurate feedback at low cost. Examples are: the Microsoft Sidewinder (Table 1, System 1), the Impulse Engine (Table 1, System 2), the MouseCAT (Table 1, System 3) and the Feel-IT (Table 1, System 4)

Table 1: Various Haptic Interface Systems

NAME	TECHNOLOGY	PICTURE	NAME	TECHNOLOGY	PICTURE
1) **Sidewinder** force feedback pro [Microsoft, 1999]	DC Motors Low Bandwidth Low Resolution (Game Controller)		**5)** **The Phantom Desktop** System [Sensable Technologies, 1999]	DC Motors (Expanded Workspace)	
2) **Impulse Engine 2000** [Immersion Corp, 1999]	DC motors High Bandwidth Max force output 8.9N		**6)** **PenCAT** [Haptic Technologies, 1999]	DC Motors	
3) **MouseCAT** [Haptic Technologies, 1999]	DC Motors		**7)** **Magnetic Levitation Haptic Interface** [Berkelman, et al., 1996]	Magnetic Levitation	
4) **Feel-IT** mouse [Immersion Corp., 1999]	DC Motors		**8)** **RMII** [Burdea, et al, 1992]	Pneumatic	

One of the non-portable force-feedback systems that really made an impact from the commercialization point of view is the PHANToM (Personal HAptic iNTerface Mechanism, see Table 1, System 5). This is a 6 degree-of-freedom lightweight manipulator composed of a three degree of freedom arm and a three degree of freedom thimble-gimbal. The arm's three joints are powered by DC motor while the gimbal's orientation is passive. The user is able to feel forces at one point at his/her fingertip or at a stylus that will be held by the user. The Phantom has been used in many applications such as medicine, training and tele-operation [Salisbury and Srinivasan, 1996]. The PenCAT (see Table 1, System 6) is a very similar system with the difference that it features only 4 degrees-of-freedom where force feedback is possible on only two of them, and that any motion is in the horizontal plane. Finally, the 6-degree of freedom magnetic interface developed by Carnegie Mellon University provides a high bandwidth, with only one moving part to the palm of the user [Berkelman, et al., 1996] (see Table 1, System 7).

Work towards improved portability with more freedom of motion of non-portable force feedback systems was done by Luecke and his colleagues at Iowa State University [Luecke, 1995]. Their haptic interface consists of an exoskeleton hand master tracked and supported by a robot. Magnetically-levitated finger attachments produce feedback forces at each phalanx without static friction. The system has higher dexterity and a large work envelope, which makes it more suitable for large volume simulations. The use of large currents near the user's hand (required for the magnetic coils in the exoskeleton), and a powerful supporting robot raise safety concerns. Furthermore, magnetic coil overheating prevents prolonged simulations, while robot kinematic singularities may limit the type of motions the user can perform while wearing the device [Burdea, 1996].

Similar work was done at NASA Jet Propulsion Laboratory (JPL) for a telerobotic application. The scientists retrofitted an older JPL Universal Master [Bejczy and Salisbury, 1980] producing wrist force feedback with a 16 degree-of-freedom hand master [Jau, et al, 1994]. The master-structure weighs about 2.5-lb and can move within a 30x30x30-cm cube. The weight of the master may still pose problems, and complexity is a factor to be considered. There is a need for simpler force feedback devices that are both light (so as to avoid user fatigue), dexterous (to allow independent finger interaction) and portable (to maintain the user's freedom of motion). Once such force feedback interfaces are constructed they could be integrated with a large visual display or an HMD.

Portable systems, are force feedback devices that are *grounded* to the human body. They are distinguished into *arm-exoskeletons* if they are applying forces at the human arm and in *hand-masters* if they are applying forces at the human's wrist and/ or palm. An example of an arm exoskeleton is the "Force ArmMaster" produced by EXOS Co. under a NASA SBIR task [Exos Co., 1993]. It uses three DC motors for the shoulder, one for the elbow and one for the forearm. Arm exoskeletons can reproduce, weight feeling, collisions with the environment and other virtual and remote forces that are applied at locations on the human arm besides the hand. However, portable arm-exoskeletons tend to be heavy (the Force ArmMaster weighs 22-lb), producing user fatigue and discomfort in extended simulations.

Portable hand masters are haptic interfaces that apply forces to the human hand while they are attached at the human operator fore-arm. In most of the cases, these systems look like gloves where the actuators are placed at the human fore-arm and the forces are transmitted to the fingers using cables, tendons and pulleys. An example of such a system is the CyberGrasp. The CyberGrasp is a lightweight, force-reflecting exoskeleton system that fits over a CyberGlove (see Figure 3) and adds resistive force feedback to each finger [Virtual Technologies, 1999].

Figure 3: The CyberGlove and the CyberGrasp.

The grasp forces are exerted through a network of tendons that are routed to the fingertips via an exoskeleton. The tendon sheaths are specifically designed for low compressibility and low friction. The actuators are high-quality DC motors located in a small enclosure on the desktop. There are five actuators, one for each finger. The device exerts grasp forces that are roughly perpendicular to the fingertips throughout the range of motion, and forces can be specified individually. Due to the tendon/cable network, the remote reaction forces can be emulated very well, however, it is difficult to reproduce the feeling of “remote stiffness”.

A light force feedback hand master designed to retrofit open-loop sensing gloves was proposed by [Burdea, et al, 1992; Gomez, et al, 1995]. The Rutgers RMII (see Table 1, System 8) has low-friction custom graphite-glass actuators, which output up to 16 N/fingertip with very high dynamic range (300). The large dynamic range and the very low friction, make the RMII a powerful and easy-to-use portable master. Non-contact position sensing within the feedback structure was integrated, thus, the RMII does not need a separate sensing glove. However, the palm can not close completely so that it is not possible to feel remote/virtual objects with small dimensions. In addition, it offers a relatively small bandwidth, and there is a need for many out of body supporting equipment such as air-supply and electro-valves.

Currently, a joint JPL and Rutgers University is underway to determine the potential of using electrorheological fluids [Bar-Cohen, et al, 1999] to produce miniature controlled stiffness elements. To examine the applicability of this Remote MEchanical MIrroring using Controlled stiffness and Actuators (MEMICA) technology, joint efforts are being made to use the NASA Johnson Space Center Robonaut as a testbed.

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