SENSING, PERCEPTION, AND FEEDBACK FOR VR

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Tactile and force feedback are two major components of the "reality" in virtual reality. Without them, the human touch, or "haptic perception", provides no information to verify the existence of objects in the virtual environment. The term "haptic perception" is composed of two parts: tactile perception, or the awareness of stimulation at the skin, and kinesthesis, or the sense of joint positions, movements and torques. EXOS is currently working on three systems that provide kinesthetic and tactile feedback to the human hand and arm. This paper discusses the issues involved in designing haptic feedback devices that match human capabilities. These include determining the critical sensing and actuation requirements based on human capabilities, deciding which of these requirements can be met by the device, and the actual design implementations.

All three EXOS systems have been developed under the Small Business Innovation Research (SBIR) program. In Phase I, the Exoskeleton ArmMaster (EAM) developed a position-sensing device worn on the arm that simultaneously tracked the motions of three degrees-of-freedom of the shoulder and two degrees-of-freedom of the elbow and forearm. EXOS developed an understanding of human arm kinematics and demonstrated that knowledge by building a prototype device which is being used in its current form to provide control signals to robot arms and virtual environments. EXOS' goal in the second phase of this project is to develop and demonstrate a force-feedback EAM capable of controlling robot arms and virtual environments for a variety of tasks in unstructured environments.

The second project's Phase II objective is to develop and demonstrate a multi-fingered sensing and force reflecting exoskeleton (SAFiRE) capable of controlling a virtual hand performing laboratory experiments in a glove box. In Phase I, EXOS demonstrated the feasibility of building an integrated device by building a two degree-of-freedom prototype. This device tracked the motions of the index finger and reflected the interaction forces between the slave and the environment to the finger [Eberman, 1992].

In the third project, the Hand Exoskeleton Haptic Display (HEHD), EXOS is extending the capabilities of SAFiRE by adding tactile feedback for the fingertip in order to create a more complete haptic display.

In order for a feedback device to provide a realistic simulation of virtual environments, the device must match as many of the kinesthetic and tactile capabilities of the human hand and arm as technology will allow. The critical sensing and actuation characteristics required to perform a set of tasks first needs to be quantified. Then engineering criteria can be derived from these human capability descriptions. For example, if a human is incapable of perceiving stiffness gradients above a certain threshold, then the device will have an engineering requirement of keeping stiffness gradients below that threshold. The first section of this paper discusses the construction of a framework for describing human capabilities, both kinesthetic and tactile. The next section discusses the engineering design issues that were translated from the human body capabilities and how they affect the three projects as a whole. The last section discusses engineering design issues specific to each of the three projects.

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sensing capabilities that could be readily translated into design specifications. Experiments were then conducted to estimate human capabilities relevant to the design of haptic interfaces. The following list outlines the experiments performed and data collected [Tan et al, 1993].

- Joint Angle Resolution- Just-noticeable-differences (JNDs) of angle were measured for various joints of the human hand and arm. From the PIP to the shoulder, the joint angle JND decreased from 2.5° at the PIP joint to 2.0° at the wrist and elbow joints, and down to 0.8° at the shoulder joint. Thus, proximal joints were more accurate in sensing joint angles than distal ones.

- Pressure Resolution- Pressure JNDs as a function of contact area was studied for the lower arm. The greater the contact area, the more sensitive the arm was to pressure changes. Overall, pressure JND decreased by a factor of roughly 4 (from 15.6% to 3.7%) when contact area increased by a factor of 16 (from .20 $inch^2$ to 3.14 $inch^2$). The JND appeared to be independent of test sites. It was also observed that force was felt mainly around the smoothed perimeter of the contact cylinders. An explanation of this sensitivity is that the human tactual system is most sensitive to pressure gradients.

- Stiffness- This study was conducted to find out the minimum stiffness required to simulate a rigid object without visual feedback. The stiffness based on the experiments was computed to be 140 lb/in. Fingertip, wrist, and elbow joints were tested, and there seemed to be no significant differences across subjects and joints tested.

- Force Control (Range and Resolution)- The objective of this study was to measure (1) the maximum controllable force humans can produce with joints of the hand and arm; and (2) the precision with which humans can produce the force. The maximum controllable force ranged from 3.72 lb to 23.02 lb and increased from the most distal joint (i.e., PIP) to the most proximal joint (i.e., shoulder). Overall averaged force control resolution standard deviations decreased from 1.96% to 0.87% from PIP to shoulder joints, meaning that the subjects tested had better control over force output with the shoulder joint than the finger joints. From the results, it is hypothesized that humans have better control over bigger forces than smaller ones.

- Fatigue- The experiment was conducted to (1) obtain the weight vs. time curves for various joints of the human hand and arm; and (2) study how weights applied to the elbow affected the dexterity of the corresponding hand. The weight vs. time curves did not indicate a simple method for determining how long an average person can hold a certain weight. It was decided that a study of the dexterity level of the hand while carrying a certain weight would be more useful for this application. These results would give a measure of how long users could carry the devices and still perform tasks to a required degree of dexterity. Subjects were tested using pin-placement tests while weights were applied to their elbows. Test scores decreased by 1 to 2 pins from no weight to a 4 lb 9 oz condition, and by another 1 to 2 pins at a 9 lb 1 oz condition. When 4 lb 9oz was applied to the subjects' elbows, they began complaining about fatigue after roughly 40 minutes. When 9 lb 1 oz was applied to their elbows, subjects started complaining about fatigue after about 15 minutes.

- Force Perception Resolution- From Tan et al., [1992], force JND for the human joints was found to be around 7%, which was independent of the reference forces (2.5 Newtons to 10 Newtons).

In addition to the kinesthetic human capabilities detailed above, knowledge of the tactile capability of humans is also important. The hairless skin on human fingertips is innervated by four types of nervous fibers: the SA I ("slowly adapting Type 1"), SA II ("slowly adapting Type 2"), RA ("rapidly adapting") and PC ("Pacinian"). The highest spatial resolution is exhibited by RA and SA I fibers. These fibers respond differently to stepwise indentation: the SA I and II fibers generate nerve impulses during sustained indentation while the RA and PC fibers only respond to the onset and withdrawal of indentation. These fibers also have different frequency responses to sinusoidal vibration: the SA I and II fibers are sensitive at very low frequencies (order of 10 Hz), the RA fibers are sensitive at 10-100 Hz, and the PC fibers are most sensitive around 250 Hz [Darian-Smith, 1984]. Physiologists have speculated that the SA I system produces an acute representation of the form of an object in contact with the hand, the SA II system codes lateral skin stretch, the PC system represents high frequency vibrations, and the RA system represents transient dynamic events at the object-skin interface such as impending slip [Johnson & Hsiao, 1992]. All these fibers interact to produce a general picture of what the skin is touching and what is happening at the point of contact. This information is then used for the initiation and maintenance of grasp and for fine manipulation.

After determining these force, position, and tactile sensing capabilities, engineering specifications for the haptic feedback devices can be imposed. In trying to meet these engineering specifications during design, issues emerge that are often in direct conflict with each other. The following list discusses the engineering specifications that resulted from the set of human capabilities, and the design issues that appeared in implementation.

- Kinematics- The kinematic setup needs to provide for the human range of motion and also appropriately distribute a number of actuated degrees of freedom to effectively simulate hand-object interaction forces. However, to exactly apply the complete variety of forces and torques would require an impractically large number of actuated degrees-of-freedom. This would increase the complexity and size of the device beyond the size requirements. The task is then to appropriately distribute a limited number of actuated degrees of freedom. In the SAFiRE, we have decided to actuate 3 degrees-of-freedom in each of the thumb and index fingers, and 2 degrees-of-freedom in the middle finger. Passive freedoms have been introduced so that the fingers are not constrained kinematically.

Also, while the device must be able to apply forces to simulate contact with virtual objects, it must also be unencumbering, allowing free motion when virtual objects are not being touched. Thus the system must be light and freely backdrivable, by either active or passive means.

- Transmission/motors- In addition to carrying their own weight, the weight of the operator's arm and that of the device, the motors must generate sufficient torque to display the interaction forces between the slave robot and the environment. This high torque leads to bigger motors and gearheads, which creates greater inertia, friction, weight, and lower backdrivability. Incorporating gear and cable reductions into the design amplifies the torque, thus reducing the torque requirement of the motor. We and others have found that higher quality force application can be achieved by using high-quality, low friction, rare-earth servomotors in combination with custom designed cabled transmission and reductions [Townsend, 1988]. However, cabled reductions also exaggerate the motor brush friction.

The transmission must generate enough force to meet the stiffness requirement but not be affected by the increased friction and inertia resulting from bigger motors. Our choice and design of a cabled transmission and brushed servomotors has come after exploring and prototyping numerous alternative routes including hydrostatic transmissions, and various combinations of friction drives, splined drive shafts, and high precision planetary gearhead reductions as well as having experience with several high performance brushed and brushless servomotors and frameless torque motors.

- Weight- Based on fatigue data, weight limits for the devices were developed. Meeting this specification becomes very difficult if the specifications of force, torque, sizing, and kinematics are to be met. Fatigue or discomfort felt while using the device will detract from the overall perception of the environment therefore the device's performance. The weight of the motors being used is 4.0 oz per motor for SAFiRE and between 4.6 oz and 5.6 oz per motor for EAM. Therefore, increasing the number of actuated degrees-of-freedom increases the weight. For the SAFiRE, a total of 8 degrees-of-freedom has been constructed in the current prototype. Thus, the weight from the motors alone is 2 lbs with conventional motors.

- Comfort- In order to provide a realistic simulation, the devices worn must feel transparent, and whatever body attachments exist must not impinge on the user's motion and comfort. Therefore, the device must fit a wide range of body sizes, and any component that interfaces with the human body must be adjustable. We are designing our devices to fit users in the range of 50 percentile female to 95 percentile male.

In addition to the overall engineering design issues described above, specific issues exist for the three projects that target different parts of the body.

The EAM is being designed to carry the SAFiRE, therefore, its output torque, stiffness, and strength must be increased in order to carry the weight and inertia of SAFiRE. This translates to bigger motors and a bulkier device and thus increases the conflict between size, weight, and torque output. For SAFiRE, in order to meet the weight and size constraints for the lower arm and hand, the motors and other heavier components should be placed away from the fingers, on the body or arm, where they are more easily carried. However, they must still transmit the necessary power to the fingers without a substantial increase in complexity.

In designing the HEHD, the issues focus on tactile perception for the fingers. While many tactile displays have been developed in the past, few take advantage of the full capacity of the human haptic system. Existing tactile displays can be roughly classified into five groups: air or water jet systems, air or water bladder arrays, mechanical tactor arrays, voice coils and electrocutaneous stimulation systems. A few products are commercially available, including the *Optacon* (TeleSensory Inc.), a piezoelectric bimorph reed actuated mechanical vibrator array [Bliss et al, 1970]; the *TouchMaster* (EXOS, Inc.), a single-element vibrotactile display ; the *Teletact* glove (Air Muscle Inc.), an elastic glove lined with 20 air pockets [Free, 1992]; and *Tactools* (Xtensory Inc.), which are shape-memory alloy actuated tactors, available singly or in arrays [Xtensory, 1993]. Most of these systems involve indenting or vibrating the skin; the ability to sense lateral stretch and slip is largely unexploited. Also, many were developed to present visual or audial information by tactile displays, presenting coded tactile signals instead of actually emulating different touch sensations. Finally, most of these devices are large and heavy, and cannot be used as a fingertip display on a hand exoskeleton master. These voids may be filled by a novel tactile display developed specifically for teleoperation systems.

In a robot grasping task, the most important tactile information includes identifying the nature of contact between the gripper and an object, and detecting dynamic events at the gripper-object interface. The nature of the contact is defined by the local curvatures and surface normals (such as whether the gripper has contacted a corner, an edge or a surface, and how the gripper is oriented with respect to an edge) and the surface texture of the object at the point of contact. This information is then used to initiate grasp. Dynamic events between the object and the gripper include vibration, lateral force, and slip. This information is useful for maintaining an optimal grasp force.

EXOS is currently building several benchtop tactile display prototypes, each targeted at presenting a different aspect of this information to the teleoperator. Using these prototypes, experiments will be run to determine how tactile information may be best presented to the user and what forms of information are most pertinent in a grasp task. The results from these experiments will be used to develop a fingertip tactile display that will combine different tactile modalities to present feedback information in a transparent manner.

In designing a device that will simulate human haptic capability, these capabilities must first be determined. By assembling a framework of human capabilities as a base on which to build its engineering criteria for the design of feedback devices, EXOS has come to a better understanding of human perception, the interface on which virtual reality is founded. With this understanding, EXOS is developing devices and exploring the technology and combinations of modalities which can come closest to meeting the capabilities of human operators and thus provide the most realistic experience.

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REFERENCES

Bliss, J.C., Katcher, M.H., Rogers, C.J. & Shepard, R.P. (1970). Optical-to-tactile image conversion for the blind. *IEEE Transactions of Man-Machine Systems*, MMS-11, 58-65, 1970.

Darian-Smith, I. (1984). "The sense of touch: Performance and peripheral neural processes." In *Handbook of Physiology - The Nervous System III*, 739-788. Besthesda, MD: Am. Physiol. Soc.

Eberman, B., An, B. (1992). "EXOS Research on Force Reflecting Controllers." *SPIE Proceedings on Telemanipulator Technology*, Vol.1833, Boston, MA, Novermber 1992.

Free, J. (ed.) (1992). Electronics Newsfront. *Popular Science*, pp. 42, April 1992.

Johnson, K. O., & Hsiao, S. S. (1992). "Neural mechanisms of tactual form and texture perception." *Annual Review of Neuroscience,* Vol.15, pp. 227-250.

Tan, H.Z., Pang, X.D., Durlach, N.I. (1992). "Manual Resolution of Length, Force, and Compliance." *Proceedings of ASME WAM 1992*, DSC Vol.42, pp. 13-18.

Tan, H.Z., Srinivasan, M., Eberman, B., Cheng, B. (1993). "Preliminary Design Specifications for Haptic Interfaces." Presented at the Image Symposium, Tucson, AZ, 1993.

Townsend, W.T. (1988). "The Effect of Transmission Design on Force-Controlled Manipulator Performance." Ph.D.Thesis, Department of Mechanical Engineering, MIT, April 1988.

Xtensory Inc. (1993). Product literature, 1993.