The PHANTOM Haptic Interface: A Device for Probing Virtual Objects

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Abstract

This paper describes the PHANTOM haptic interface - a device which measures a user's finger tip position and exerts a precisely controlled force vector on the finger tip. The device has enabled users to interact with and feel a wide variety of virtual objects and will be used for control of remote manipulators. This paper discusses the design rationale, novel kinematics and mechanics of the PHANTOM. A brief description of the programming of basic shape elements and contact interactions is also given.

Introduction

A dominant focus in robotics research labs has traditionally been the development of autonomous systems - those which operate without human supervision or interaction. However, robotic systems which are under direct human control have begun to enjoy a resurgence of interest in recent years, in part due to advances in robot and human interface technologies. These new interactive systems (telerobotic) promise to expand the abilities of humans, by increasing physical strength, by improving manual dexterity, by augmenting the senses, and most intriguingly, by projecting human users in to remote or abstract environments. In this paper we focus on our work to develop a means for interacting with virtual mechanical objects; this is an important stepping stone toward the development of enhanced remote manipulation systems in which simultaneous interaction with real and virtual objects will be possible.

At the MIT Artificial Intelligence Laboratory, we have been developing haptic interface devices to permit touch interactions between human users and remote virtual and physical environments. The Personal Haptic Interface Mechanism, PHANTOM, has evolved as a result of this research (Massie, 1993). The PHANTOM is a convenient desktop device which provides a force-reflecting interface between a human user and a computer. Users connect to the mechanism by simply inserting their index finger into a thimble. The PHANTOM tracks the motion of the user's finger tip and can actively exert an external force on the finger, creating compelling illusions of interaction with solid physical objects. A stylus can be substituted for the thimble and users can feel the tip of the stylus touch virtual surfaces. By stressing design principals of low mass, low friction, low backlash, high stiffness and good backdrivability we have devised a system capable of presenting convincing sensations of contact, constrained motion, surface compliance, surface friction, texture and other mechanical attributes of virtual objects.

Threee Enabling Observations

Three observations influenced the basic design of the PHANTOM. The first observation established the type of haptic stimulation that the device would provide, the second determined the number of actuators that the device would require and the third established the volume or workspace that the device would possess.

1. *Force and motion are the most important haptic cues*. A significant component of our ability to "visualize," remember and establish cognitive models of the physical structure of our environment stems from haptic interactions with objects in the environment. Kinesthetic, force and cutaneous senses combined with motor capabilities permit us to probe, perceive and rearrange objects in the physical world. Even without detailed cutaneous information (as with a gloved hand or tool), the forces and motions imparted on/by our limbs and fingers contribute significant information about the spatial map of our environment. Information about how an object moves in response to applied force and the forces which arise when we attempt to move objects can provide cues to geometry (shape, locality, identity), attributes (constraint, impedance, friction, texture, etc.) and events (constraint, change, contact, slip) in the environment. Unlike other sensory modalities, haptic interactions permit two-way interaction via work exchange. Controlled work can be performed on dynamic objects in the environment and modulated to accomplish tasks.

2. *Many meaningful haptic interactions involve little or no torque*. Perhaps the most significant design feature of the Phantom is the passive, 3 degree-of-freedom "thimble-gimbal." The decision to use the thimble-gimbal was based on the observation that many finger tip interactions with the environment involve little or no torque about the finger tip. (Tightening a screw with one's fingernail is on of the few clear counter-examples.) Because the three rotations about the center of the finger tip are neither measured nor actuated by the PHANTOM, the user's finger tip can be modeled as a point or frictionless sphere in the virtual environment. The same argument applies for the tip of a stylus - the tip of a sharp pencil or pen touching a surface has virtually no torque exerted on it by the surface. Introducing three passive freedoms with the "thimble-gimbal" greatly simplifies programming as well as mechanism design.

3. *A small wrist-centered workspace is sufficient*. Many meaningful haptic interactions occur within the volume that the finger tip spans when the fore-arm is allowed only limited movement. In order to determine the most suitable workspace for a haptic interface, a wooden mock-up consisting of a 3 degree-of-freedom kinematic chain with a 3 degree-of freedom thimble-gimbal was constructed. Through experience with the mock-up, it was decided that the PHANTOM should be constructed such that a user could move the wrist freely without encountering the edges of the workspace. The size of a mouse pad, a sheet of note-book paper and the computer keyboard are common examples of this scale of haptic workspace.

Three Necessary Criteria for an Effective Interface

The following three criteria are necessary for an effective force-reflecting haptic interface device. Independent psychophysical testing could establish specifications for each of the three criteria, however available actuator, sensor, material and computer technology will ultimately determine the degree to which each of the criteria can be met. Furthermore, the three criteria must be considered simultaneously, as improving the specification for one will necessarily degrade the specifications for the other two. The PHANTOM represents an effort to balance these three criteria to achieve an effective, affordable, force-reflecting haptic interface with existing technologies.

1. *Free space must feel free*. Users must not be encumbered by the device. That is, the device should exert no external forces on a user moving through free virtual space. Translated into engineering requirements, this means that there should be little back-drive friction, low inertia at the human-machine interface and no unbalanced weight. For the PHANTOM, we arrived at values for each of these attributes that were perceivable, yet not distracting. Static back-drive friction for the PHANTOM is less than 0.1 Newton (NT), inertia is such that the user perceives no more than 100 grams of mass at the interface and unbalanced weight is less than .2 Nt for all points within the workspace.

2. *Solid virtual objects must feel stiff*. One metric of a force-reflecting interface is the maximum stiffness of the virtual surfaces that it is capable of representing. Because no structure or control loop is perfectly stiff, each virtual object compliance is not limited by the stiffness of the structure, but rather by the stiffness of stable control that can be achieved. Using the current control algorithm, the PHANTOM can reflect a maximum stiffness of about 35 Nt/cm, We have found that most users can be convinced that a virtual surface with a stiffness of at least 20 Nt/cm represents a solid, immovable wall. The maximum obtainable stiffness depends not only on the natural frequencies of the device but also on the resolution of the sensors and actuators and the servo rate.

3. Virtual constraints must not be easily saturated. There is nothing as disturbing as leaning against a wall and falling through it. In the virtual world, walls should be solid. The maximum exertable force for the human finger is on the order of 40 Nt (Sutter, 1989), but during precise manipulation we find that people rarely exert more than 10 Nt of force, the peak maximum for the PHANTOM. In fact, the time average force exerted during normal operation is on the order of 1 Newton, while the maximum continuous force capability for the PHANTOM is about 1.5 Nt.

PHANTOM Mechanics

In its simplest form, the PHANTOM can be thought of as a transmission between three DC brushed motors with encoders and the human finger. The x, y and z coordinates of the user's finger tip are tracked with the encoders, and the motors control the x, y and z forces exerted upon the user. Torques from the motors are transmitted through pre-tensioned cable reductions to a stiff, lightweight aluminum linkage. At the end of this linkage is a passive, three degrees of freedom gimbal attached to a thimble. Because the three passive rotational axes of the gimbal coincide at a point, there can be no torque about that point, only a pure force. This allows the user's finger tip to assume any comfortable orientation. More importantly, because the user can be represented by a single point of friction-less sphere within the virtual environment, collisions and resulting interaction forces within the virtual environment are easily calculated.

The PHANTOM has been designed so that the transformation matrix between motor rotations and endpoint translations is nearly diagonal. Decoupling the three motors produces desirable results in terms of back-drive friction and inertia. For a haptic interface with perceivable inertia and back-drive friction, it is important that the friction and inertia be nearly constant in all directions to minimize the distraction they create for the user (i.e. well conditioned inertia matrix and small, non-disparate friction components) (Vertut, 1986).

As interesting design feature of the PHANTOM is that two of the three motors move in such a manner as to counterbalance the linkage structure. Because the PHANTOM is statically balanced, there is no need to compromise the dynamic range of the device by actively balancing the structure with biased the motor torques. Conveniently, the first rotational axis of the PHANTOM is located directly above the wrist of the user. This permits aligning the inherently spherical workspace of the mechanism with similarly spherical wrist. The complexity of the cable reduction mechanism is minimized by using a single cable to "mesh" two motor capstans with another pulley. This minimizes mechanism width and tensioning difficulty.

Virtual Worlds

The generation of haptic cues to create virtual objects requires the ability to 1) track motion of the user, 2) detect collision between the user controlled probe (virtual finger tip) and the virtual objects, 3) compute reaction forces in response to contact and motion and, 4) exert forces on the user. Because 1, 2 and 4 are relatively easy with the PHANTOM we have been able to focus on the development of rules or control laws for 3 which generate a wide variety of interaction sensations.

In general we use a one-sided Hooke's law relationship to simulate walls. Walls may be combined in a number of ways to give the sensation of polyhedral objects. To date, the interiors and exteriors of rectangular solids have been created. Because of the unusually low friction in the device these surfaces feel distinctly slippery. Variations in surface stiffness of both of these shapes may be used to give a wide range of "feel" to the objects. Regular, local variations in surface geometry have been used to simulate coarse textures.

It is also possible to give these objects body properties such as mass, permitting objects to be pushed and bounced off the walls of the virtual environment. It has been shown to be relatively easy for users to distinguish between massive and low-mass objects by feel alone. By giving bodies stiffness relative to ground, virtual buttons have also been created which simulate the "fall-away" feeling of real switches.

One of the more subtle effects to simulate is friction. Simply implementing the classic Coulomb or stiction models leads to unstable behavior or flawed sensations due to limitations in resolution and time step size inherent in sampled data systems. A method recently developed in our lab permits stable and convincing friction sensations to be generated even in the face of these limits.

Interestingly, the contact force state can be used to control additional actions. In the case of a virtual painting demonstration the contact force was used to permit intuitive control of the brush width of a virtual paintbrush.

Perceptual Observations

Initially, there was some concern as to how a user would adapt to using his or her finger tip to manipulate a single point in virtual space. The action is quite intuitive, with one exception. When feeling the outside of virtual spheres, some users are disturbed by the "phantom" effect. That is, when using the device, one's hand can physically pass through the volume occupied by a virtual sphere, while only the finger tip is constrained to remain outside of the virtual sphere. Some users are quick to use this phenomena to their advantage and begin probing all sides of virtual objects, unconstrained by the volume of their hands.

In one sense, representing the finger tip as a point within the virtual environment effectively increases haptic resolution beyond that of a finger tip in the real world. Cutaneous receptors aside, when a person manipulates and probes in the real world the effective resolution limited by the finger volume. However, using the PHANTOM, the width of a user’s finger tip in the virtual world can be made as small as data quantization permits. Manipulation remains intuitive, though, because the thimble-gimbal allows the small virtual point to be spatially located within the user's finger tip.

A few common haptic experiences with the PHANTOM seem to evoke strong reactions from users. One such experience is sliding along the top of a virtual block that one cannot see, becoming comfortable with the fact that the invisible block will support one’s finger and then inadvertently sliding off the top of the block. Several users find this falling sensation very powerful. Another experience that users find pleasantly disturbing occurs when one has been probing an invisible virtual environment for several minutes only to have the virtual environment disappear without warning. The feeling is similar to sitting down in a chair only to find that it has been pulled out from beneath you!

Users of the PHANTOM provide evidence that our visual, haptic and auditory senses are closely linked and that all three sensory modes are required for navigation within virtual environments. Even without visual feedback. Many users claim that they can "see a sphere" after touching a virtual sphere with the PHANTOM. Also, users describe the non-linear force characteristics of the virtual buttons they touch as "feeling the buttons click," even when no sound is present.

Even though solid objects within the virtual environment are slightly compliant, users are often willing to accept that the objects are solid. Perhaps users tolerate this amount of compliance because it is on the order of the compliance of the human finger pad. Also, the fact that users can effortlessly slide tangent to the walls seems to re-enforce the illusion of a solid surface.

Conclusions

The development of the PHANTOM device has demonstrated the feasibility of a relatively low-cost system which can provide convincing sensations of interactions with virtual object. The relative ease with which users can learn to use the device and immediately begin perceiving and rearranging virtual objects suggests that we have crossed an important performance threshold. Performance which permits distinct sensations of free space and constrained motion results from a proper balance of mechanism properties such as friction, inertia, force, resolution and bandwidth. It is an important research question as to how this balance scales with the size of the interface workspace. Larger versions of the PHANTOM are under development and will help in determining the appropriate balance of performance qualities needed at new scales.

The PHANTOM is currently in use in several labs at MIT as well as a number of government and industrial research labs. We expect in the near future to see demonstrations of multiple finger interactions and multiple finger interactions and multiple user interactions in shared workspaces with the device. Our own work will focus on the stability and programming issues which arise when two fingers grasp objects to perform assembly tasks as well as use of the device to permit tool interactions such as screwdrivers and pliers.

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References

Brooks, T.L. and A.K. Bejczy, 1985, "Hand Controllers for Teleoperation," Technical Report JPL Publication 85-11, Jet Propulsion Laboratory, Pasadena, CA.

Durlach, N.I. et al, 1992, "Virtual Environment Technology for Training," Virtual Environment and Teleoperator Research Consortium (VERTREC), MIT, BBN Report 7661.

Massie, T.H., 1993, "Design of a Three Degree of Freedom Force-Reflecting Haptic Interface ," SB Thesis, Department of Electrical Engineering and Computer Science, MIT.

McAffee, D.A. and P. Fiorini, 1991, "Hand Controller Design Requirements and Performance Issues in Telerobotics," Proceedings of International Conference on Advanced Robotics (ICAR), Pisa.

Minsky, M., and M. Ouh-young, O. Steele, F.P. Brooks, and M. Behensky, 1990, "Feeling and Seeing: Issues in Force Display," *Computer Graphics*, Vol. 24, pp. 235-243.

SensAble Devices, Inc., 1993 "The PHANTOM," literature from SensAble Devices Inc. 225 Court St., Vanceburg, KY 41179.

Sutter, P.H. J.C. Iatridis and N.V. Thakor, 1989, "Response to Reflected -Force Feedback to Fingers in Teleoperations," *Proc. Of the NASA Conf. On Space Telerobotics, NASA JPL*.

Vertut, J. and P. Coiffet, 1986*, Robot Tehcnology, Teleoperation and Robotics: Evolution and Robotics: Application and Technology*, Vol. 3B, Prentice Hall, Englewood Cliffs, NJ.