Virtual Hand: a 3D tactile interface to virtual environments

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ABSTRACT

We introduce a novel system that allows users to experience the sensation of touch in a computer graphics environment. In this system, the user places his/her hand on an array of pins, which is moved about space on a 6 degree-of-freedom robot arm. The surface of the pins defines a surface in the virtual world. This "**virtual hand**" can move about the virtual world. When the virtual hand encounters an object in the virtual world, the heights of the pins are adjusted so that they represent the object's shape, surface, and texture. A control system integrates pin and robot arm motions to transmit information about objects in the computer graphics world to the user. It also allows the user to edit, change and move the virtual objects, shapes and textures. This system provides a general framework for touching, manipulating, and modifying objects in a 3-D computer graphics environment, which may be useful in a wide range of applications, including computer games, computer aided design systems, and immersive virtual worlds.

Keywords: Haptic display, tactile display, perception, Virtual World, 3-D graphics, 3-D user interfaces, 3-D games

1. INTRODUCTION

Fifty million years of evolution have given the human race superior visually-guided fine motor control. We excel in using our touch sensitivity to discriminate textures, examine shapes and manipulate objects. From an early age, we learn to appreciate our world by interacting with it tactilely, and use touch to communicate, create art, and to express our emotions. Our computer systems, however, have lagged behind. In current state-of-the art 3-D and computer graphics systems, the user interacts with the computer-generated environment visually using standard interfaces, such as a mouse or joy stick. The ability to feel or touch the environment is limited. A data glove can be used to track gross hand positions and provide a graphical representation of it in a 3-D space, but the user cannot feel or touch the environment. Limited touch sensitivity can be added by providing small piezo-electric stimulations to the user's hand (for example the 5DT system [1]) but the usefulness of this interface is limited to collision detection and very coarse graphical object sampling. Recently, haptic interfaces have been introduced which provide touch feedback when probing a virtual object with a single point of contact device (e.g., the SensAble Phantom [2]), and integrating this capability onto a robot arm has provided a greater range for exploration (e.g., the Haption Virtuose [3]). However, in all these systems, the interface to the computer-graphics world is very limited. The user does not have the sense of touching a real object, feeling its texture, judging or modifying its surface, moving or shaping the 3-D object, or responding tactilely to an object that is thrown to him or her. This technology lag is especially acute for the blind who cannot see the shapes, objects, textures and graphs presented by the computer.

There has been significant recent interest in understanding the perceptual requirements of human observers for haptic interfaces [4][5]. Several researchers have demonstrated that the sense of touch can be effectively simulated with artificial, computer-generated interfaces. For example, Klatzky and Lederman have shown that users can reliably distinguish variations in surface texture patterns generated using a force feedback mouse [6]. In addition, it has been shown that observers can classify object shapes based on variations in the force fields applied to their fingertips [7].

The goal of this work is to provide a more complete haptic environment that allows users to have a more realistic appreciation of objects, surfaces and textures. We envision a future where such devices could enhance 3-D computer environments, such as 3-D visualization systems, caves, Virtual Reality, and the 3-D Internet. They could also provide a natural 3-D interface to various applications, such as training in a virtual environment, virtual shopping, computer aided design, data analysis, and on-line games.

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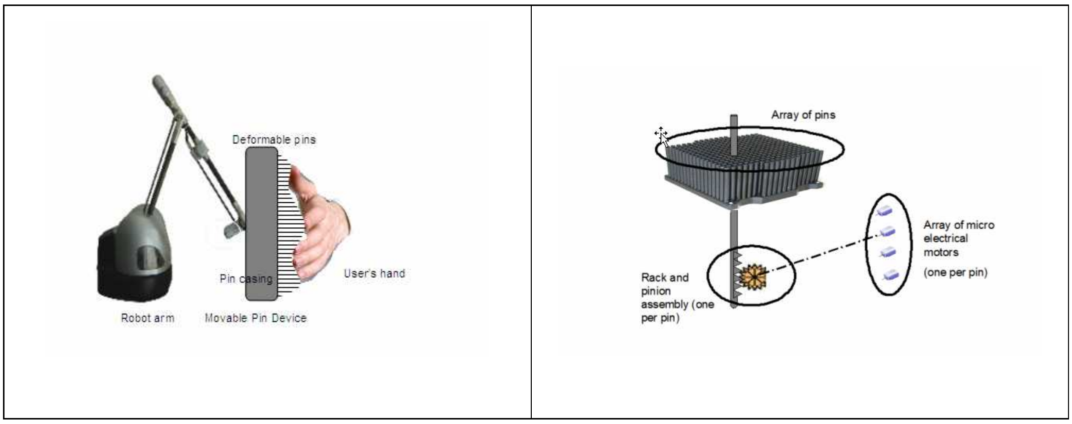
To accomplish this goal, it is necessary to link the virtual computer graphics world with the physical world in which the user lives. That is, it is necessary to create a correspondence between the computer graphics objects that have a defined 3-D geometry and movements and actions in the real world.

This paper presents a 3-D interface and a robotic control system that brings the user's hand into the virtual world, allowing the user to feel, manipulate and modify objects in that virtual space.

2. DESCRIPTION OF THE 3-D HAPTIC DEVICE

Figure 1 shows the physical device designed to transduce shape and texture information to the users' hand and to allow the user to change and edit the shape and texture of objects in the virtual (e.g., computer graphics) environment. The user rests his/her hand on an array of pins which each has a smooth capped surface. The array size is at least 40 x 30 (10 per inch) on a hexagonal grid to ensure uniform distribution through close packing. The impression of the users' hand on the array of pins defines the touching surface of the "**virtual hand**," which is represented using computer graphics in the computer-generated environment. Displacement of the pins in the user's palm and fingers is interpreted as displacement of the palm and fingers of the virtual hand in the virtual world. The pin assembly is attached to a six degree-of-freedom robot arm. The movement of the robot arm is interpreted as movement of the virtual hand in the virtual world. The positions of the robot arm and the virtual hand surface are registered with the geometry of the computer-generated environment, such that movements of the arm and attached array of pins are known relative to the computer-generated environment. Forces exerted by the virtual world on the virtual hand are applied to the users' hand through movements of the robot arm and displacements of the pins. Such forces can occur when the virtual hand "touches" objects and surfaces in the virtual world, when objects in the virtual world are thrown at the virtual hand (e.g., virtual baseball), or when the virtual hand touches another virtual hand located in the same virtual world.



a b

Figure 1. The controller for the virtual hand is an array of pins attached to a robot arm, shown in Panel a. The displacement of the pins represents the shape and texture of the objects in the virtual world. The 6 degree-of-freedom robot arm is based on previous art [3]. Panel b shows how pin displacement is controlled by an array of micro-electrical motors, one per pin, each driven by a rack and pinion assembly. The array of micro actuators acts as an output device, communicating properties of the virtual world to the user through pin displacements. It also serves as an input device, allowing the user to edit and transform the virtual world model by pressing on the pins.

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3. DESCRIPTION OF THE 3-D HAPTIC CONTROL PROCESS

In this system, the displacement of the pins on the pin assembly provides the sense of touch to the user. The robot arm and the control system allow the user to move the virtual hand through the world. They allow the user to feel the shape, texture, and physical properties of the virtual objects, as well as manipulate and move them.

The control algorithm presented in Figure 2 manages the movements of the pins and of the robot arm. It assumes that an endless loop is controlling the pins and the robot. For each pin, the algorithm tests whether the surface of the virtual hand would intersect with the surface of the virtual object. If such an intersection would occur, the control algorithm prevents this intersection by displacing the pins on the pin assembly. The amount of pin displacement represents the magnitude of the object's impact on the virtual hand at that location. The set of pin displacements thus transmits the feel of the object corresponding to its impact on the virtual hand. If the range of pin motion has been exceeded, the algorithm directs the robot motion to change the position of the pin assembly, and thus, the virtual hand.

This control algorithm assumes no specific sequence of actions and therefore handles cases when contact between virtual hand and virtual objects occurs either (a) because the user displaces the pins and/or the pins assembly mounted on the robot, or (b) because virtual objects move in the virtual space.

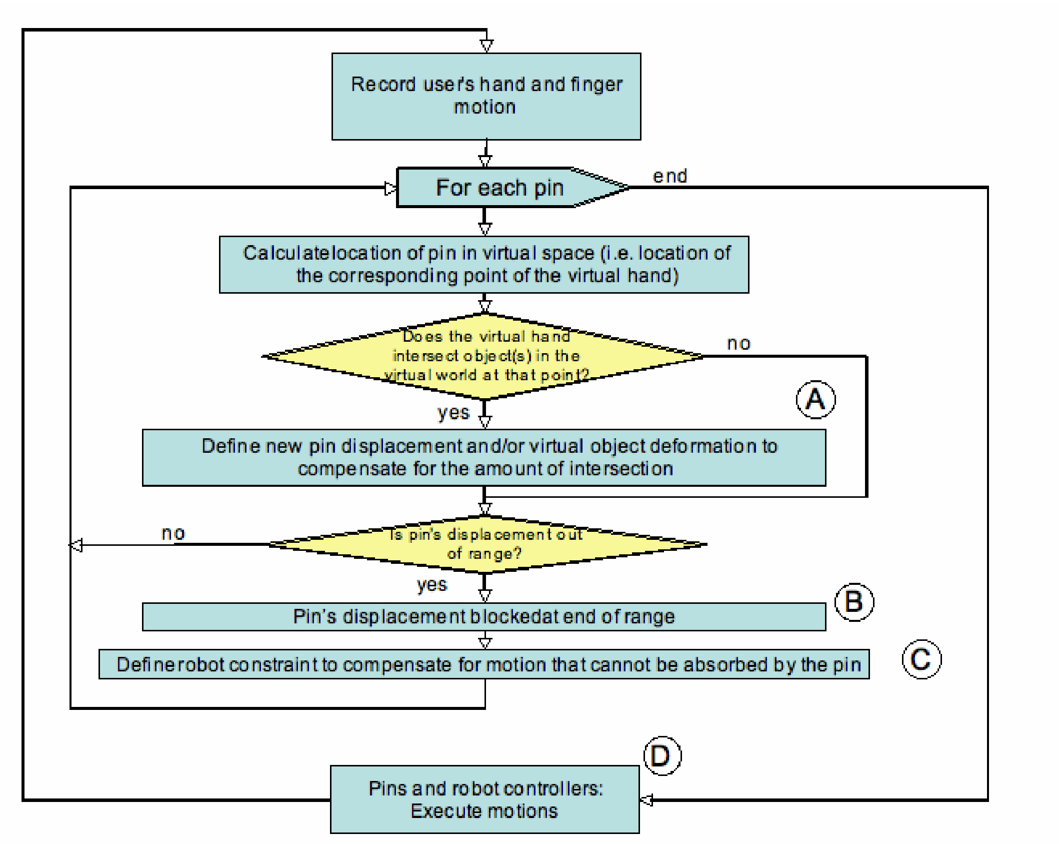

Figure 2. Control program that monitors pin displacement and adjusts the pin and robot controllers to execute appropriate motions to enable the movement of the virtual hand through the virtual space, allowing it to transducer the presence of surfaces and their textures, to edit these surfaces and textures, and to move objects in the space.

The endless outer loop of the algorithm first records the pins' and robot's location. The location and shape of the surface of the virtual hand is derived from this information. For each point of the virtual surface corresponding to each pin, the

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system tests whether there is an intersection between the virtual hand, at that point, and objects in the virtual space. Detecting an intersection results in defining the pin's displacement in such a way that the resulting virtual surface is deformed (Figure 2- Step A). For a hard virtual object, the calculated displacement of the pin is equal to the amount of intersection. For a soft or elastic virtual object, the virtual object also deforms and the displacement is shared between the pin and the virtual object. In both cases, this displacement results in eliminating the intersection between the virtual object and the virtual hand.

Pins have a predefined range of motion, which can either be defined as the maximum extension of the pin or some predefined range that is deemed comfortable for the user. Whenever a pin exceeds this range, the pin is blocked at the end of the range and a constraint of motion is defined for the robot. This constraint will produce a motion of the robot arm that compensates for the displacement that could not be absorbed by the pin (Figure 2 - Steps B and C).

The robot controller (Figure 2 - Step D) accumulates the constraints of motion, described above, and calculates from them a natural motion of the pin assembly. For example, if a single point of the virtual hand is in contact with a virtual object, the robot controller will allow a rotation of the pin assembly around the extremity of the corresponding pin by maintaining this point at a fixed location in space. The robot arm has a given number of degrees of freedom that can be used to accommodate one or more spatial constraints to position the pins in space. A mathematical model allows the robot controller to calculate the displacement of its articulations to maintain the constraints. This type of mathematical formulation can be found in the robotics literature (for example, [8]) and is similar to that of the controller of the Virtuose robot arm.

Examples of the effect of executing the control algorithm in Figure 2 are described in Figure 3 and Figure 4. These figures represent the behavior of the pins and of the pin assembly in the device space (top rows) and the corresponding behavior of the virtual hand and virtual objects in the virtual space (bottom rows).

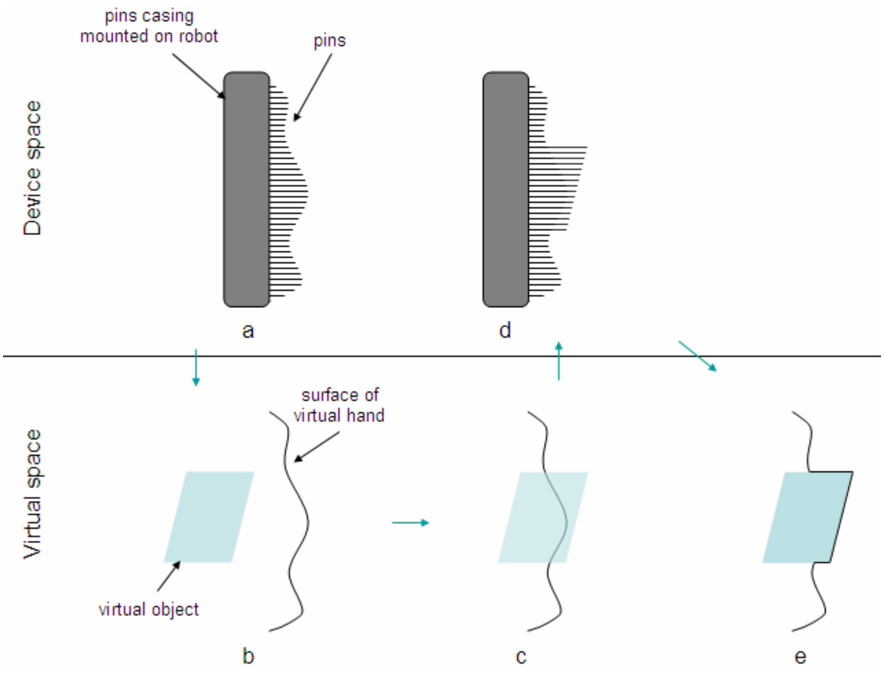

Figure 3. Example of pin displacement to reflect object shape. The surface of the array of pins represents the touching surface of the Virtual Hand. Instead of intersecting with the surface of an object in the virtual world, the virtual hand is deformed to reflect the impact of the object that has been touched. This surface is reflected on the array of pins, thereby communicating the virtual object's shape to the user.

Figure 3 illustrates the part of the algorithm that deforms the surface of the pins, which is in contact with the user's hand, when a virtual object enters in contact with the virtual hand. Figure 3-c shows a relative position of the virtual hand and a virtual object where the virtual object impinges on the virtual hand. Figure 3-d illustrates the effect of displacing the pins in a manner consistent with Figure 2- Step A. The new pin surface represented on Figure 3-d now reflects the location of the impinging virtual object. Since the user can touch the pin surface, he/she now has the illusion that his/her hand is actually "touching" the virtual object. The surface of the virtual hand is also recalculated to reflect the new pin surface on the device (Figure 3-e).

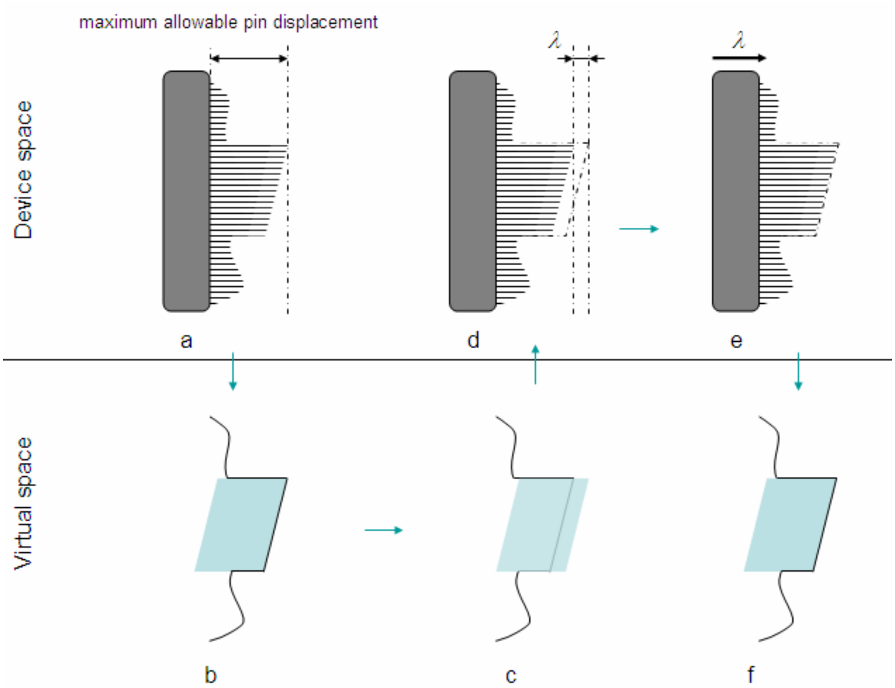

Figure 4. Example of robot motion. When the virtual object creates a displacement greater than can be absorbed by the pin range, the robot arm moves the entire pin assembly. In the case above, the virtual object is moving the hand.

Figure 4 illustrates the part of the algorithm that handles cases when a pin reaches the end its allowable range of motion. Figure 4-a and Figure 4-b illustrate a state where one the pins has reached the end of its allowable range of motion. Since a relative displacement of the virtual hand and the virtual object such as the one depicted on Figure 4-c would result in some of the pins exceeding their allowable range of motion (Figure 4-d), the robot (through a constraint added in Figure 2-Parts c and d) moves the pin assembly in such a way that all pins are within allowable range (Figure 4-e). This in turn results in a new virtual hand surface that does not impinge on the virtual object (Figure 4-f). This same mechanism can be used when the hand is pushing on the object. In this case, when the pin range has been exceeded, the virtual hand moves the virtual object.

4. EXAMPLES OF USAGE SCENARIOS

Sensing the object surface shape and texture. The virtual hand can move over an object to sense its texture (e.g., bumpy, smooth, corrugated) and shape (e.g., convex, concave, spherical), where the pins displace to communicate these physical dimensions.

Moving an object. If the virtual hand is pushing on an object and the motion of the pins goes beyond the allowed range, this motion will be interpreted as exerting a force on the object. This will result either in the object moving, or, if the object is sufficiently massive, the robot will prevent further hand motion (e.g., if trying to move a large boulder).

Sensing or catching a moving object. If an object is moving toward the virtual hand and the pins displace beyond their allowable range of motion, the robot arm will respond by moving backwards to compensate for the object's motion.

Hard vs. soft objects. The displacement of the pins when an object is encountered can be modulated based on the physical characteristics of the virtual object. For example, a very hard object will cause a larger displacement of the pins, while a softer or more elastic object will produce a smaller displacement of the pins. A library of different physical properties and their forces- spongy, could be utilized.

Editing an object, surface or texture. The user applies pressure to the pins, which changes the shape of the virtual hand projected into the virtual space, which can deform the surface of virtual objects in that space.

Mutual Touch. The virtual object can be the virtual hand of another user, thus allowing hand contact mediated by a virtual world. For example, virtual hand wrestling and hand shaking can be enabled.

Beyond Hands. An extension of the above is that the user is not limited to using a hand. For example, the user could place the face onto an array of pins which could drive a virtual face in the virtual world. This virtual face could be touched by another virtual face, or by a virtual hand.

Applications for these usage scenarios include a virtual masseuse avatar, virtual pottery, virtual sports, tactile skill learning, training, Computer Aided Design, etc.

5. DISCUSSION AND CONCLUSION

This paper introduces a 3-D system in which a user can move a virtual hand through a computer graphics environment, feel the textures, surfaces and objects in the environment, and to actively deform and shape these surfaces. This work is currently in the design stage, and many questions remain to be answered. User experiments will be needed to evaluate the right parameters for this system, including the resolution of the pin array, the temporal response function of the system, and the stiffness of the feedback mechanism. This system also assumes interaction with a computer graphics environment. There is a wide range of such environments, including stereoscopic systems with head-mounted displays, immersive walls and caves, and many 3-D computer graphics applications shown on 2-D displays, such as many on-line games, 3-D internet, and computer-aided design. Because there is a wide range of applications, and a wide range of usage scenarios, significant research will be required to understand the user interface requirements for 3-D haptic systems.

If successful, this technology could open the door for new applications which could capitalize on the sense of touch. Training applications could be significantly improved, especially for tasks that require visually-guided manipulations, such as parts assembly. Computer games could allow users to feel a baseball or the fur of a werewolf. Giving users a “feel” for what they are learning could be especially helpful in on-line training for physical or rehabilitation therapists, and an instructor could even use a virtual hand to shape the virtual hand of a trainee. Collaboration on physical projects, such as product design, could be supported by multiple users each using a virtual hand. The ability to manipulate the computer model through a haptic interface opens the door to fanciful ideas, such as virtual pottery or sculpture. And, although the spatial resolution of this technology is not sufficiently high to allow the user to feel the difference between silk and satin, it would enable shoppers to feel different object shapes and textures, providing a new interface for on-line shopping.

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Perhaps the most promising application is the use of rich haptic interfaces for users with visual impairments. These users are currently very limited in their ability to appreciate even simple line drawings, and the idea of providing haptic interfaces for data visualization, 3-D graphics, and virtual environments is very exciting.

Although this work is still in its early stages, the design of the haptic device, the robot arm, and the control system demonstrate a path toward creating an interactive system that allows users to touch, feel, and interact with data. This could lead to a new generation of applications that take advantage of fifty million years of evolution.

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