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Paper:

Virtual Force Feedback
Lessons, Challenges, Future Applications

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Virtual force feedback prototypes have been developed in the last couple of years. Their number of degrees of freedom and range of motion are limited by present (bulky) actuator technology. Lessons from these first prototypes point to possible solutions in the future. Several applications of virtual reality with force feedback are then described.

Keywords: Force feeddback, Virtual reality, Dextrous master, Human factors

1. Introduction

There seems to be a strong relationship between the fields of telerobotics and Virtual Reality. Many researchers who's earlier work was in telerobotics are now eagerly investigating the newer virtual (or alternate) reality. They either use older telerobotic masters as input devices to the computer simulation (Brooks, 1990), or newer instrumented gloves (VPL, 1987) and exoskeletons (Marcus, 1988). Conversely, such dedicated VR hardware as the Dataglove, has been successfully used in telerobotics (Clarck et. al., 1989). System aspects such as master-slave interaction, distributed system architecture, time delay and human factors are just a few of the common problems that are presently being investigated.

Both teleoperation (of a real or simulated robot) (Bejczy, 1990) and virtual reality can produce a sense of immersion. In Virtual Reality this immersion is due to the operator wearing a head-mounted display, gloves, and other input/output devices and interacting with a computer that responds to body motion and to voice commands by generating images, sounds, forces etc..

At the present time the graphics are primitive (despite what is perceived through the media and Hollywood hype), primarily due to the real-time requirement of the graphics interaction. Relative to the complexity of the problem present computing hardware seems slow. Fortunately, the overlapping of several sensing modalities such as vision and sound seems to help in the operator's realistic immersion sensation (Chapin and Foster, 1992). Can this observation be extended to other sensing modalities, such as touch or force feedback? The answer seems to be yes, especially when there is a simulated interaction with virtual objects.

The literature often mixes the terms "touch feedback" and "force feedback". This confusion is probably due to the authors' concern with the human factors only and not with the hardware aspects. In our view force feedback to the grasping action opposes the human finger motion actively and can stop it (for large feedback forces). Touch feedback can provide "touch/no touch" cues to fingers, but cannot stop them from moving further and thus possibly destroying remotely grasped objects. Therefore "touch feedback" should be distinguished from "force feedback".

2. Current Developments

2.1. Portable Masters

An example of a dextrous master with touch feedback is the Teletact System produced in UK (Stone, 1991) shown in **Fig.1**. This master has a number of air bellows which are distributed on hand fingers and the palm. The pressure in the bellows is controlled by proportional regulators, enclosed in a separate interface. A (remote) second individual having another glove with Force Sensitive Resistors (FSR) grasps a real object, applying a certain force. This force is then used to drive the pressure in the air bellows so that the Teletact wearer can have a "reading" of the object grasped by the (remote) second individual.

An example of a dextrous master with force feedback is the MIRAGE System developed at Rutgers University and shown in **Fig.2** (Burdea et.al., 1992-a). The master has three pneumatic micro-actuators mounted on a small "L"-shaped platform attached to the palm of the Dataglvoe. The

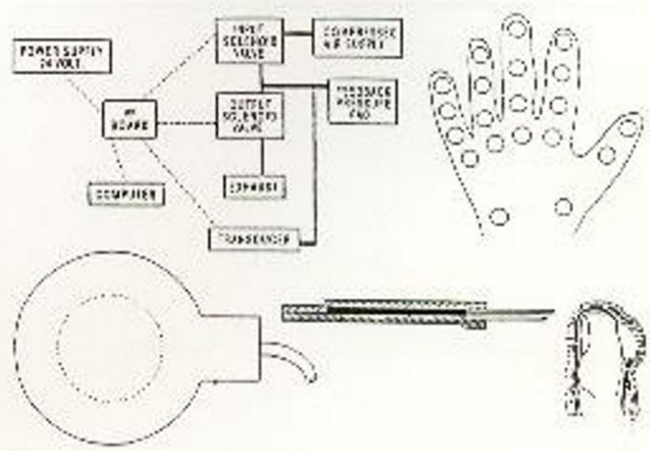

Fig.1. The teletact master (courtesy of A.R.R.L.).

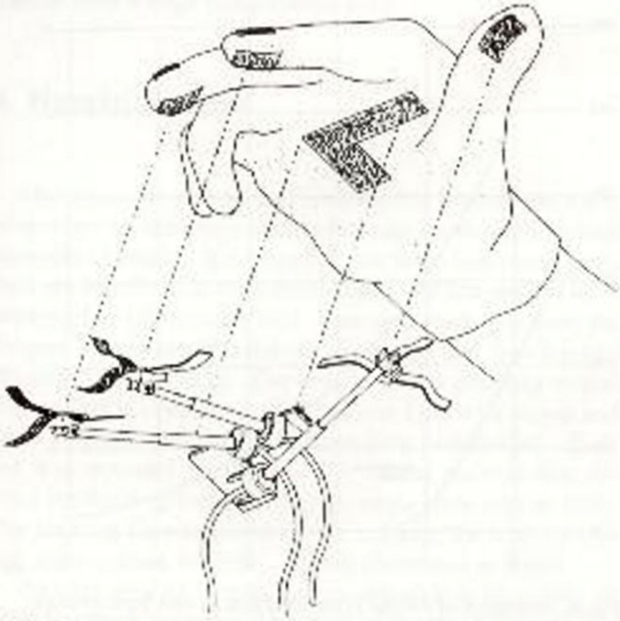

Fig.2. Rutgers dextrous hand master with force Feedback (Burdea et.al., 1992-a).

cylinders are mounted coaxially with three sphere joints, thus allowing for direct connection to air tubes passing through the sphere joints. The actuator conic work envelope allows both adduction-abduction and anteposition-retroposition finger motions. Each cylinder shaft is attached to the glove finger tips through cylindrical joints that allow movement in a plane normal to the fingertips. The attachment of the feedback structure to the glove is done with Velcro TM strips mounted in the palm and on the fingers.

The master is integrated with a Dataglove that reads the hand and finger positions. The force applied on the wearer fingertip is proportional to forces applied by a virtual hand on several types of virtual objects (spring, ball and soda can). The feedback forces produced by the master are controlled according to elastic (spring and ball) and plastic (soda can) deformation laws (Burdea et. al., 1992-b). The advantage of the Rutgers system is that it provides simulated force sensation to the person wearing it, while being compact, light (about 50 grams), clean, silent (due to exhaust mufflers) and safe.

Portable masters need to be light and compact. This requirement is dictated by the hand geometry and the need to reduce operator fatigue. The requirement for compactness limits the use of cable and pulleys to transmit motion from remotely placed actuators. Ideally, actuators need to be placed in the palm where the forces are to be sensed. This in turn determines the number of feedback actuators and therefore the hand degrees of freedom provided with force feedback. Key questions such as how many actuators are needed and how much force is needed, are still being investigated.

The grasping motion using a portable master can be classified as "power" or "precision" grasping. During power grasping the whole palm and fingers make contact with the grasped virtual object. The grasped surface encreases and dexterity decreases as only the wrist degrees of freedom are available for hand motion. Precision grasping of virtual objects differs from power grasping in that only the finger tips are use.d If the simulation involves light virtual objects

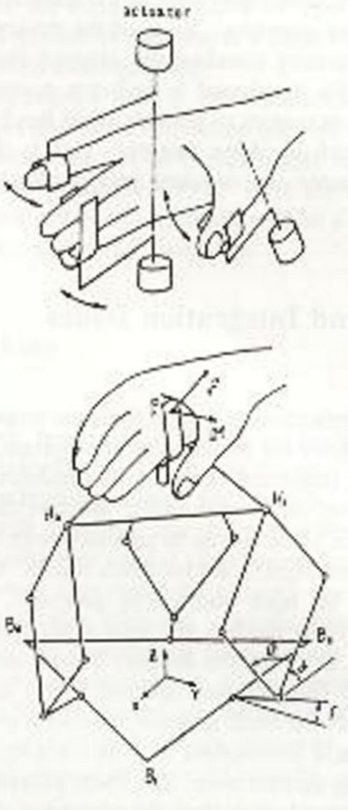

Fig.3. Master manipulator (Iwata, 1990).

then gravity effects are small and only forces at the finger tips appear. In this case a reduced number of actuators are sufficient in order to produce force feedback at the user's finger tips. Simple precision grasps require three fingers, therefore three actuators are needed. With four fingers (and four actuators) most precision grasps can be simulated.

New actuator technology will allow more actuators to be placed in the palm and on the wrist. The ESPRIT Glove (Stone, 1992) project, for example, will use micro-actuators and kevlar tendons to transmit force feedback. Other actuator technology being investigated for portable masters includes Shape Memory Metals (Gharaybeh, 1992), rheologic fluids or polymer memory foams (Monkman and Taylor, 1991). All have problems, either due to poor dynamic response and large volume, therefore new microactuators are needed for VR masters.

2.2. Joysticks

Both the Teletact and the Rutgers Master are portable. Freedom of motion in a large volume is an important aspect of the "immersion" requirement of Virtual Reality. In this respect portable masters differ from other input devices such as joysticks (Minsky, et. al. 1990), and (Schmult, 1990). Force or touch feedback joysticks limit the hand motion to a very small volume. In return they provide force feedback to both hand and arm, while today's portable masters provide feedback to the hand only. Joysticks have their weight supported by the desk, and therefore can use large motors and actuators with very high bandwidth. This bandwidth in turn allows the simulation of texture, not just touch contact, which is another advantage over the portable masters described above.

Certain applications may require the simulation of gravity effects during grasping. None of the devices described so-far can adequately simulate the grasped object weight. Iwata (1990) has developed a desk-top master that uses small electrical actuators to provide wrist feedback as well as force feedback on three fingers. This is illustrated in **Fig.3**. This master can simulate gravity effects on virtual objects.

3. Design and Integration Issues

Weight, compactness and good dynamic response are not the only criteria for the selection of appropriate micro-actuators. Another important factor is the min/maximum force capability. For now, pneumatic micro-cylinders have proved adequate, since air can be provided with high enough pressure to obtain significant feedback forces. Ideally these forces should be high enough to produce "rigidity of motion", that is to prevent the user from further closing his/her grasp. Tests for the Rutgers Master and its predecessor PDMFF (Burdea and Speeter, 1989) have demonstrated up to 4N for each actuator (almost a pound force). This force would correspond to 2.66-1.6N/cm^2 on a 1.5-2.5cm^2 fingertip surface area. The force generated is therefore 8 to 14 times higher than the minimum sensitivity of the human hand force receptors of 0.19N/cm^2. The master total force output (for three actuators) was about 13N. This is compared to the average male/female maximum tip pinching force of 13-16N (An et. al., 1980). Thus the force feedback level was large enough to simulate a solid object in the grasp.

Touch feedback actuators need not have large force capability but their compactness is critical. Many actuators need to be placed on the finger tips and other areas of the palm and fingers. Micro-pins have been proposed, similar to the braille readers (Steele et. al., 1988), but this older technology is not light or compact enough to be portable. Shape Memory actuators may be a light and compact solution. Recently a tactile enhancement of the Data-glove has been demonstrated using five Shape Memory actuators placed one on each fingertip (Cutt, 1992).

A key design parameter is the number of touch feedback actuators that need to be placed on each fingertip and in the palm. Even one actuator per finger proved useful (Cutt, 1992). Therefore good touch sensation should not require a one-to-one relationship between actuators and tactile receptors in the fingertip skin. Stimuli at less than about 2.5mm apart are perceived as one (Sherrick and Craig, 1982). Typically there is "cross talk" between tactile receptors, so several may respond to the same signal. Another argument for a smaller number of touch feedback actuators is related to data refresh rates. If the touch sensation needs to be transmitted remotely on serial lines, then the time required to transmit the data grows with the number of actuators used by the master. A large number of actuators will then result in considerable time delays.

The amount of position, tactile and force feedback data depends also on the data refresh rate. There are wide differences in literature on what constitutes "adequate" touch and force feedback rates. High bandwidth (such as those in telerobotic systems) cannot be attained presently due to relatively slow graphics hardware.

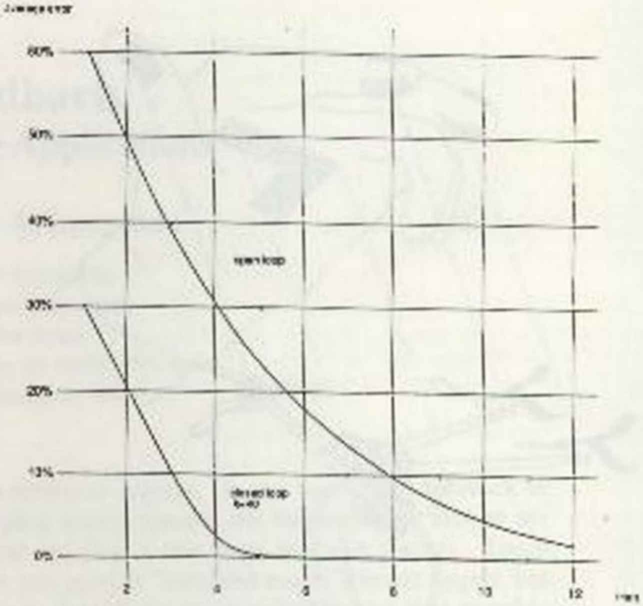

Fig.4. Influence of virtual force feedback in task performance and task learning (Richard et. al., 1993).

The immersion in Virtual Reality uses several senses, such as sight, hearing and kinesthesis. For sight we know that the lowest refresh rate to ovoid image flicker and discontinuity is 16Hz. The question is how frequently need forces be updated? Is 16Hz the minimum rate? The low-level (spine) sensing loop has much higher bandwidth of 100-300Hz (Kokjer, 1987) for the tactile receptors. Touch sensations are then used as input in the high-level loop. Hogan (1989) estimates that the human high-level(cortex) force compliance control loop has a very low bandwidth of about 1-2Hz. It is this control loop that is important as the Virtual Simulation loop is closed by the user in a position feed-forward force feedback loop.

The position feed-forward loop measured by input devices such as the Dataglove provides a maximum refresh rate of about 30Hz. This rate drops to 15Hz when two position trackers are used. The proportional air controllers used by the Rutgers Portable Force Feedback Master have a bandwidth of 10-15Hz. Overall the force feedback loop has less than 10Hz bandwidth. Even this low bandwidth improved task performance as discussed in the "human factors" section.

Data refresh rate for other types of virtual interaction is much higher. For example, general texture sensing needs about 500 to 1000Hz (Minsky et.al., 1990), while virtual music playing may need as much as 800Hz (Cadoz, 1992). These applications are using desk-top input devices, thus avoiding the use of a sensing glove. Freedom of motion is subsequently sacrificed.

A non-anthropomorphic master with a reduced number of actuators, such as the ones previously described, requires kinematic transformations in order to determine the actual feedback forces from the calculated virtual forces. These transformations need to be done in real-time and represent an additional burden on the computing resources. As more objects share the same Virtual Environment and as the simulation becomes more realistic (with second order mechanics), the computational load may become critical. This motivates the need for distributed systems (Appino et al., 1992), (Grimsdale, 1991) (Burdea et al., 1993) which can handle such a large computation load.

4. Human Factors

One area of human factors research has become the study of operator's interaction with virtual objects through various sensorial channels. It is intuitive that force and touch feedback are beneficial in such interactions, but few studies have attempted to substantiate this. One such study has used the Rutgers Master on 10 subjects (five male and five female) (Richard et. al., 1993). The tests involved grasping virtual objects first in open-loop, then in close-loop with vision and force feedback and finally in close-loop blindfolded. Each test was repeated 12 times. The results showed that the force feedback reduced the task average error rate by 50%. The learning time required by the subjects for a given task was also reduced by 50%. This is illustrated in **Fig.4**.

Another area of human factors research is the safety of force feedback masters. The level of feedback forces need not be large enough to produce accidental hand injury. The approach taken at Rutgers was to have a fail-safe system, in that the actuator's maximum travel did stop at a location corresponding to a fully extended hand. In this way the user's fingers could not be pushed backwards past this position, and thus produce injury. The drawback is a reduction in the master range of motion.

Safety issues will become more complicated as the feedback masters are extended from the user wrist to the elbow and shoulder. In such a configuration the force feedback devices should provide a safety button, similar to that used with many present robots. If both arms wear master "sleeves", then the safety button may become a safety pedal. If full-body feedback is provided (some time in the future!), then voice commands should be used to "freeze/unfreeze" the feedback suit.

5. Applications

Force and touch feedback opens the door for new applications of virtual reality in medicine, entertainment and the military. As digital models of the human body are developed, it should become feasible to explore such models in Virtual Reality. These body explorations may become very powerful tools for both students and for experienced practitioners. One medical application can be in surgical planning and training, in order to reduce the potential errors and increase practice period (Satava, 1992).

Another medical application of virtual force feedback is diagnostic and rehabilitation for different hand impairments. In the future it may be possible to eliminate the need to develop different grips or fixtures for different tests. Instead we should use the simulated environment to introduce different grips to evaluate the patient's performance. By monitoring the finger feedback forces a patient recovery history from hand injury may be realized and the treatment customized (Burdea, 1992-c).

Force and touch feedback extend Virtual Reality in other areas such as entertainment. While home based systems are still in the future, commercial video-arcade products such as the "Virtuality" system have recently emerged (Waldern, 1992). One of the enhancements of the system are pneumatic bellows placed in the player's hand, which inflate when virtual objects are grasped.

Another application area is the simulation of military missions. Flight and battle simulation are well known, however less known is the use of virtual reality to train troops in mine disposal (Rousseau, 1992). Here the future ability to produce force and touch feedback will be a definite plus in the simulator, and could save lives.

6. Conclusions

Virtual force feedback is still in its beginnings, with many new developments expected in the next years. Present actuator technology allows for portable, compact and safe systems with relatively few degrees of freedom. New, more compact actuators should allow more degrees of force feedback, but may also make the systems more costly and more computationally intensive. Applications of virtual force feedback are expected to revolutionize many areas such as medicine, entertainment, teleconferencing, or the military. More human studies are needed to determine performance tests and develop design standards. These new standards should appear as the field matures.

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