Jacob Jurmain
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Overview of Haptics Science and Technology with Applications to Telemanipulation

Jacob Jurmain
Dartmouth College
ENGS 5

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Abstract

Telepresence robotics is the concept of using remotely-operated robots to perform tasks which are judged too dangerous for a human to perform, but which nevertheless require a human's judgement and intelligence. The objective of telepresence robotics is to permit humans to use robots effectively as a second body, perfectly sharing all the robot's senses, and commanding the robot as intuitively as we command our own bodies. Current telepresence robots adequately share their senses of vision, hearing, and smell (i.e. chemical detection) with their human operator. However, most commercial and government robots in use do not share the sense of touch. Extensive research and development on this function has been done at the academic level, but industry has not yet widely applied it. Touch can provide useful information to remote operators regarding their manipulation of target objects. This ability is particularly important in delicate precision tasks such as surgery and explosive ordnance disposal. Technologies facilitating the exchange of touch information between humans and machines are grouped under the label "haptics".

An overview on state-of-the-art of haptics technology, as relevant to teleoperation and telepresence robotics, will be given. Basic concepts of haptic systems will be introduced. Principles of haptic system design, including human factors, force feedback, and features and benefits, will be reviewed. Current problems, limitations, and issues in haptics will be discussed. Finally, representative examples of haptics as applied to teleoperation will be reviewed.

I. Haptic Systems – Function and Classification

A. Top-Level Classification – Real- and Virtual-World Systems

Haptic systems can be classified according to whether their slave component exists in a real or virtual environment. These are referred to as real-world and virtual-world systems, respectively.

In the case of virtual-world systems, this environment exists as a computer simulation, with all dynamics modeled by a software engine. Haptic feedback is determined by rendering algorithms. [1] Virtual-world systems are useful for realistically simulating physical activities which cannot be readily performed in reality. The most prominent example of a virtual-world system is a laparoscopic surgery training simulator. One such simulator is discussed in [2].

Real-world systems have a physically real operating environment. Dynamics in the environment are observed and recorded by the system, rather than modeled. Feedback forces to be rendered are calculated from these direct observations. Real-world interfaces are most relevant to remote manipulation applications, such as actual laparoscopic surgery, hazardous materials handling, and explosive ordnance disposal. It is these real-world interface systems that are the focus of this paper. See Figure 1 for a simplified map these systems.

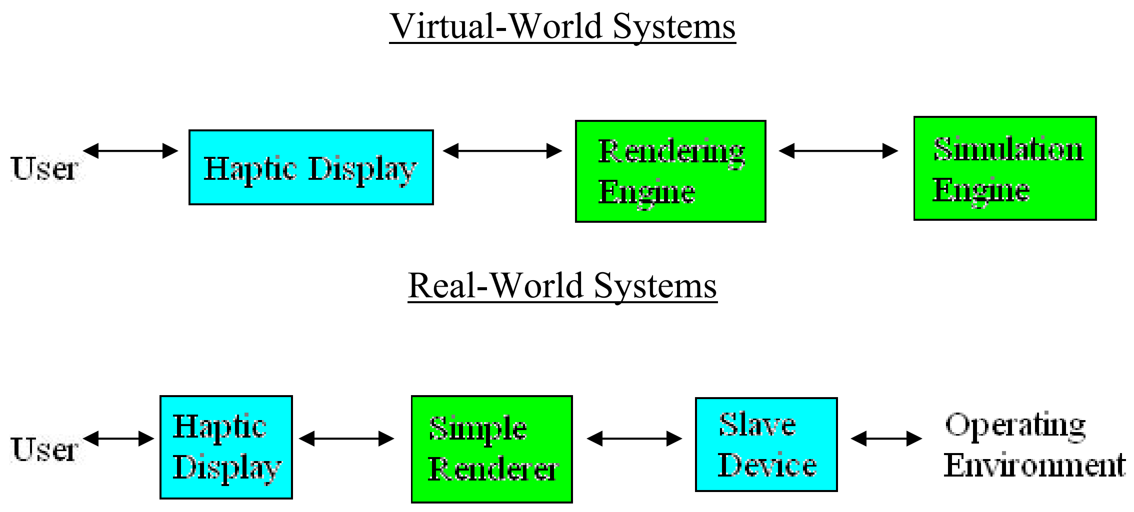


Fig. 1) Simplified map of virtual- and real-world haptic systems. Blue indicates a physical device, green a computational device.

B. Control Method Classification – Impedance and Admittance

There are two methods of haptic control: impedance and admittance. In impedance control, the user provides a motion input, and the display returns a reaction force as a function of that input or the operating environment. This is commonly referred to as "force feedback". In admittance control, the user applies a force to the display, and the system drives the output device to a proportional position or at a proportional velocity. Impedance control is less expensive and simpler, and is more widely used. [1]

Impedance control provides active feedback, facilitating exploration of and reaction to the operating environment. Therefore impedance control is useful for operating in unknown environments, such as the interior of a patient's body, or on unknown objects, such as a suspected improvised explosive device.

Admittance control does not provide force feedback. Therefore admittance control is poorly suited to operating in unknown environments. However, it is well suited to precisely controlling large forces in known environments, such as assembly tasks. The advantages of admittance control are that it can be damped to produce smooth motion, and that it can command over a wide range of motion. Damping is not possible with impedance devices, since it interferes with the user's ability to perceive feedback forces. [3]

Impedance and admittance control have in the past been referred to as "isotonic" and "isometric" control conditions, respectively. [4] These terms are not in wide use today.

The majority of practical haptics applications require the investigation of unknown environments and objects. Therefore, further research and development of impedance control will probably yield the best returns.

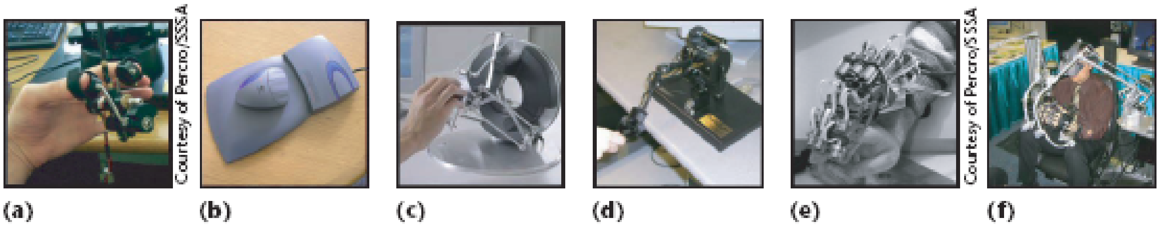
C. Types of Haptic Displays

A haptic display is a device which simultaneously reads and writes touch input to and from a user, by exchange of mechanical energy [1]. It is this bi-directionality that distinguishes haptic displays from uni-directional control devices, such as a standard mouse or joystick. Note that haptic displays need not be technologically advanced to meet this definition. The earliest haptic devices were devised over 50 years ago for remote manipulation of hazardous materials, and used mechanical control and feedback methods. Today, however, devices commonly accepted to be haptic displays use analog or digital control. [4]

Haptic displays can exhibit an enormous variety of form and function. Refer to figure 2 for examples of haptic displays. Such a wide variety makes meaningful comparison and classification difficult at best. Two top-level aspects of haptics have been defined which facilitate classification.

First is the number of degrees-of-freedom (DOF) offered by the system. The maximum number of DOFs a single joint can have is six (up/down, fore/back, side/side, pitch, yaw, roll); the number of DOFs of a complex haptic system is the sum of the DOFs of each joint of the system. The DOF number is commonly written as *n*-DOF. For example, a simple vibratory force-feedback mouse would be described as 2-DOF. In theory, a sophisticated exoskeleton suit could have as many DOFs as the human body itself. See Figure 2 for representative examples of haptic devices across the range of complexity.

A second method of haptic display classification is display grounding. A device's grounding refers to its absolute reference point. Effectively the display's anchor in its virtual space. A joystick's grounding might be the table it rests on. An exoskeleton for a hand and wrist might consider the forearm to be its grounding. The fact that the forearm itself moves is irrelevant to the display's function. [1]



2 Sample of increasingly more complex haptic devices: (a) force-reflecting gripper, (b) Logitech Wingman force-feedback mouse, (c) ForceDimension's Omega haptic device, (d) SensAble's Phantom haptic device, (e) the Hand Force Feedback exoskeleton, and (f) Immersion's Haptic Workstation.

Fig. 2 – Taken from [1].

II. Principles of Haptic System Design

A. Deriving Guidelines from Human Biology

Guidelines for haptic system design can be drawn from human neurology and psychophysics. The touch sensitivities and resolutions of relevant parts of the body are potentially limiting factors to the utility of a haptic device, so an understanding of these factors is necessary to haptic design. The mind's methods and capabilities of processing information should be understood for the same reason. In [5], Kelly Hale and Kay Stanney consolidate information on a wide range of human psychophysiology, and from it derive detailed design guidelines for haptic system parameters. Refer to [5] for these guidelines and a thorough explanation of their origin.

B. Feedback Methods – Features and Benefits

Haptic feedback is the physical information which the display writes to the user. It can be tactile or kinesthetic, or a combination of the two.

1. Force feedback.

Force feedback is a combination of tactile and kinesthetic feedback. The operator initially detects the feedback forces as tactile pressure, and measures them kinesthetically as strain on the muscles.

Force feedback is thoroughly demonstrated to reduce undesirably high forces in precision teleoperation tasks. Many years of field use and numerous scientific studies confirm this. [6] and [7] are prime examples of such studies. Force feedback gives operators awareness and control of the forces they exert in the course of their tasks. This is important in delicate tasks such as laparoscopic surgery, where high forces can damage tissue unnecessarily. [6]

In [7], Christopher Wagner and Robert Howe describe another benefit of force feedback. They discovered that in addition to giving the operator conscious control of their applied forces, force feedback actively restrains unwanted incursions to a significant degree, and does so faster than the operator is consciously capable of. However, this author hypothesizes that this benefit is only present when the slave device moves its probe from a region of low resistance to one of comparatively high resistance (the circumstances of Wagner and Howe's experiment). When moving from high resistance to low, the reverse effect would be expected, with excessive force increased. Fortunately, the former condition is more frequently encountered than the latter, so this would still be a net benefit for force feedback, but it is important to remember that force feedback may be a two-edged sword in this aspect.

Experimental testing of the above hypothesis is desirable.

2. Partial force feedback.

It is not always necessary for a haptic system to provide force feedback for each of its degrees of freedom. In [8], Semere, Kitagawa, and Okamura tested the performance of operators of a 3-DOF remote manipulator. Some of the operators performed their tasks with force feedback along all three degrees of freedom, and some along only two. The tasks involved motion in all three degrees of freedom. The data show that the removal of the third degree of feedback did not significantly reduce performance, as compared with performance with full force feedback.

The implication of this study is that it may be possible to reduce the cost of a haptic display by providing only partial force feedback. In some situations this could result in significant savings in exchange for only a small performance loss. Partial force feedback could thus be an attractive option to commercial endeavours. This author suspects that clever ways could be found to minimize the performance loss associated with the use of partial force feedback.

3. Sensory substitution.

Sensory substitution displays haptic information through other senses. The most common form of sensory substitution is visual force feedback, which takes the form of a bar indicator of force on a display screen. In [9], Tavakoli, Patel, and Moallem tested the effectiveness of this form of sensory substitution. They compared the operator's force precision at telemanipulated suturing using various combinations of regular (physical) force feedback and visual force feedback. Their conclusion was that visual force feedback is a tradeoff, improving force precision at the expense of task duration. Therefore its appropriateness will depend on the particulars of the situation. However, visual force feedback should be coupled with physical force feedback for maximum effectiveness.

C. Other Features and Benefits of Haptic Teleoperation

Haptic teleoperation can facilitate controlled alteration of the user's commands. Computers can detect high-frequency user hand tremor and smooth the slave device's motion. The user's motion can be scaled up or down, for appropriate operation in large- or small-scale environments. [8]

III. Current Problems in Haptics

A. Performance Evaluation and Comparison

A difficulty in haptics is that of comparing performance indices of different devices:

> "For any robotic mechanical system, such as a hand controller, there are several essential criteria for describing the system, e.g. inertia, friction, weight and backlash. However, the duality of [controllers] to drive and to be driven causes discrepancies as to from where these measures should be taken. For example, is inertia measured as seen from the actuators, or from the output device itself?" – [4], p. 3

Evaluation and comparison of haptic devices is a lengthy subject, and will not be discussed here further. Refer to [4] for a detailed, if somewhat dated, exploration of this problem.

B. Transparency vs. Stability

A major goal in haptics is to make systems both transparent and stable. A system is transparent to the extent that its dynamics do not affect the information it displays. The operator should feel only the dynamics of the task being performed. A system is stable to the extent that it performs the ordered tasks without deviation. The system should not overshoot or undershoot the operator's commands. System transparency and stability are frequently trade-offs of each other. [11]

C. Physical Design

High-DOF haptic systems, such as exoskeleton suits, are currently big, cumbersome, expensive, complex, and heavy. The eternal problems of engineering. New scientific developments are the best hope for improvements.

IV. Examples of Haptics in Teleoperation

A. Laparoscopic Surgery

Laparoscopic surgery is a long-standing application of haptics, and by far the most common. It is the only application of haptics to be commercially widely implemented. Force feedback teleoperation systems are used to give surgeons greater awareness and control of the forces they exert through the surgical instruments. This reduces unnecessary tissue damage. [6] It also reduces the cognitive load on the surgeon, speeding operations. [7]

Refer to [2], [12], and [13] for more information on laparoscopic surgery.

B. Explosive Ordnance Disposal (EOD) Teleoperated Robots

Explosive ordnance disposal is a complex task for robots. It requires that the platform be fully mobile, and that at least one manipulator arm be available. An EOD robot may have upwards of nine degrees of freedom in total, each of which must be controlled by the operator. A system this complicated requires a very intuitive control system to be usable. Haptic control has been shown to meet that requirement. EOD robot ROBHAZ-DT2, described in [14], [15], and [16], has been successfully used as a platform for testing several types of high-DOF haptic control devices. Another article, [17], lays out a plan for an EOD bimanual telepresence robot controlled with two off-the-shelf haptic displays.

C. Robonaut: Haptics in Space

NASA's Robonaut system is a humanoid telepresence robot designed for EVA work. In [18], Glassmire et al. controlled Robonaut in a manipulation task with and without force feedback and measured the forces applied in the course of the task. Just as in laparoscopic surgery, the use of force feedback significantly reduced peak forces. This is a desirable effect because high forces are more likely to cause damage to objects being manipulated.

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