Preliminary Report on a Haptic Feedback Technique for Basic Interactions with a Virtual Control Panel

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Abstract. This paper discusses haptic feedback for interactions with sliders and buttons on a virtual control panel. We present a haptic technique that uses both feedback from a portable force-feedback glove and feedback from direct contact with a real panel. An evaluation comparing this combined approach to each individual approach is presented. The combination of two approaches is shown to result in improved user performance and improved subjective ratings when compared to the use of only a force-feedback glove, and it is shown to improve subjective ratings when compared to the use of only a static panel.

1 Introduction

There is a growing interest in developing haptic displays for virtual environments and in understanding their effects on user performance and perception. In this paper, we present a haptic feedback technique that can improve interactions with a virtual control panel for training, design, or other applications.

1.1 Active Feedback Devices

Most research into haptics for virtual environments involves devices with computer-controlled actuators that provide force or tactile feedback. Examples include joysticks with force feedback, pin arrays for tactile feedback, vibrotactile devices using Piezo elements or small motors, thermal displays using Peltier modules, and pen-based force displays such as the PHANTOM. We refer to such devices as *active* devices.

Some devices, such as pen-based displays, perform well for specific styles of interaction but do not provide a general solution to haptic feedback. To support a natural range of interactions with a virtual control panel, a different approach is needed. Glove-mounted devices offer a more general solution by providing direct feedback independently to multiple fingers and allowing a wide range of hand motions, but the more difficult nature of the general problem presents challenges that have so far limited the success of force-feedback gloves. Although force-feedback gloves have been shown to improve performance for some grasping tasks (e.g., maintaining constant compression of a deformable grasped object being moved to target positions [1]), their usefulness for a virtual control panel is limited due to limitations described in Section 2.2. Our approach augments a glove-based system with a technique known as passive haptics to produce a more effective haptic display.

1.2 Passive Haptics

The term *passive haptics* has been used to refer to the use of passive objects such as low-fidelity mockups of walls or other obstacles [2]. These can produce a sense of touch with minimal cost and without complex mechanical devices. Other terms, including *static haptics, tactile augmentation*, and *instrumented objects*, have been used to refer to recent approaches using rigid objects in the real world to provide a sense of touch to users interacting with virtual environments, e.g., [2-5].

The use of a static panel has been shown to improve performance for a selection task with similarities to button presses [4]. This is not surprising, since a panel can help a user control hand motion and provide feedback about contact with its virtual counterpart. However, this approach offers limited flexibility and does not provide feedback for all components of our virtual control panel. Our approach provides additional sensations using a force-feedback glove.

1.3 Our Approach

As indicated in the preceding sections, our approach combines passive haptics with an active force-feedback glove to provide haptic feedback for a virtual control panel. For this paper, we refer to this as the *mixed* or *combined* approach. Figure 1 shows the virtual visual environment including the virtual control panel with sliders, buttons, and LED readouts.

Figure 2 shows an external view of a user interacting with the control panel (the specific interactions are not exactly those seen in Figure 1). The user wears a stereoscopic head-mounted display and a Rutgers Master (RM) force-feedback glove. The surface of the real panel is spatially registered with the virtual panel in the visual display. Contact with the real panel provides sensations of contact for the virtual panel surface, and a force-feedback glove provides sensations of contact with dynamic slider handles and short force pulses to indicate button reactions. The table surface is also registered with the table surface in the visual display.

The goals of our work are as follows:

1. Develop effective haptic feedback for basic interactions with a virtual control panel by combining strengths of existing techniques.
2. Identify and solve technological challenges to producing the combined system.
3. Compare the approach to the individual contributing approaches in terms of both objective performance measures and subjective evaluation.
4. Take a first step towards a mixed reality display that allows users to haptically interact with both real and virtual elements.

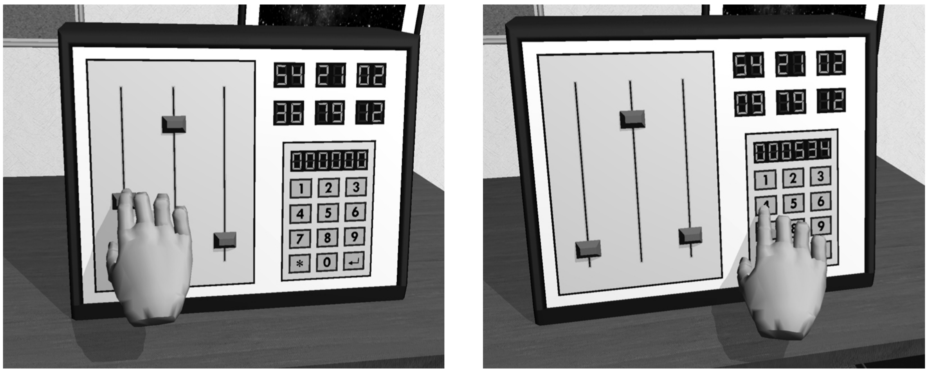

Fig. 1. Virtual visual environment from a user's point of view.

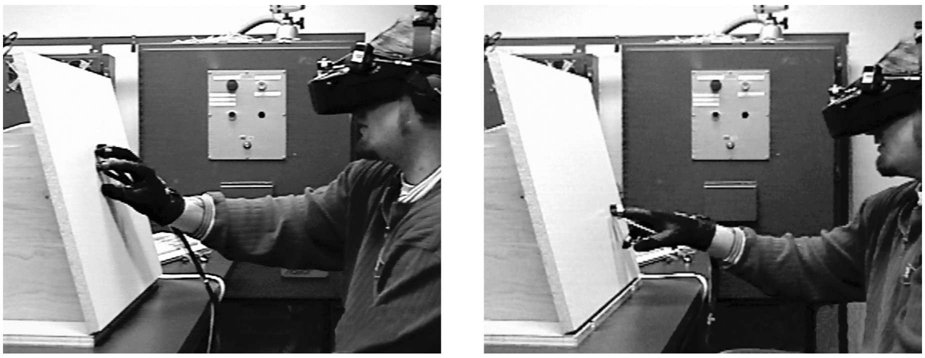

Fig. 2. External view showing the force-feedback glove and the static panel in the real world.

1.4 Relation to Mixed Reality

Mixed reality research is currently focused on combining real and virtual elements in visual displays. Development of haptic versions of mixed reality has been minimal.

Some researchers recognize the use of passive haptics with a virtual visual environment as a form of mixed reality, since a real object is experienced haptically while a virtual object is experienced visually. For example, Hoffman uses the phrase "mixed reality object" in discussing his approach [3], and Lindeman et al. use the phrase "haptic augmented reality" in discussing the HARP system [4]. In Milgram's taxonomy of mixed reality [6], these systems are perhaps best described as augmented virtuality systems, since the experience is still primarily virtual. The taxonomy does not provide a distinction between visually mixed displays and displays that are not visually mixed but instead mixed by a haptic component, nor is it clear how to categorize mixes involving haptics. An extension of the taxonomy into higher dimensions to account for different modes of feedback can provide insight into this problem, but is beyond the scope of this paper.

In our approach, the haptic display in itself is a form of mixed reality display, since users can interact with both haptically real and haptically virtual components. We refer to such approaches as *haptic mixed reality* displays, even when they are not used with visual mixed reality displays.

Iwata describes a haptic mixed reality display with a pen-based haptic device that can be used to feel forces from both real and virtual objects [7]. The system evaluation shows that haptic feedback improves the accuracy with which users position a virtual box next to a real box, but the evaluated task does not require contact with the real box, so the haptic mixed reality aspect is not fully considered.

1.5 Applications of Our Approach

A mixed haptic feedback approach is useful in a variety of applications. For example, during ergonomic design of dashboards, real dashboard components could provide feedback for completed design portions while a haptic glove simulates contact with portions that only exist virtually. During engine maintenance training or practice runs, a force glove could provide internal forces of grasping for a virtual tool or part while real objects realistically constrain arm motion. A mixed approach could also be used to provide a sense of touch for a configurable cockpit that allows the user to select from various arrangements of virtual panel components. In such a configurable cockpit, the panel itself could consist of a visual display.

2 System Design and Technological Challenges

2.1 System Overview

Our system provides active feedback with a Rutgers Master (RM) force-feedback system [8]. The RM glove uses four pneumatic pistons for feedback to the thumb and index, middle, and ring fingers. For each piston, there are sensors to measure piston displacement, piston flexion (inward bend), and piston abduction (lateral motion). A haptic control interface performs low-level pressure control and interfaces with a host PC using serial communication. Tracking of the piston base in the palm is performed using a small magnetic tracking sensor from an Ascension MiniBird system.

The haptic panel consists of shelving material with a Melamine laminate surface and is held in place by two heavy plywood supports. The virtual panel and the front portion of the virtual table are spatially registered with their real-world counterparts.

Visual rendering is performed with OpenGL. Stereoscopic rendering and projective shadows provide important depth cues that help users determine the relative positions of the hand and the panel surface. A Virtual Research V8 head-mounted display (HMD) is used for viewing. It provides a wider field of view than most current HMDs, but this results in a very small number of pixels available per arc. For this reason, we find it essential to include anti-aliasing, which our system performs using polygon smoothing. An Intersense IS-600 M2 Plus system is used for HMD tracking.

The main application runs on a dual-processor PC using two main execution threads, which will be referred to as the graphics thread and the haptics thread. The graphics thread contains the graphical rendering loop and performs related operations such as managing head tracking measures. This loop also checks for keyboard input that is used to toggle rendering options or control other program functions. It iterates at the graphical update rate, which depends largely on the complexity of the currently viewed scene.

The haptics thread implements force rendering and related operations. These include hand kinematics and tracking operations needed to compute fingertip positions, object dynamics to compute object positions, and a module for recording sessions for offline analysis. The haptics loop is synchronized with the RM serial communication driver to provide updated force commands with minimal latency.

2.2 Limitations of Force-Feedback Gloves

A primary goal of our approach is to overcome limitations of an existing force-feedback device with minimal added complexity. A main limitation of current force-feedback gloves is that they provide limited degrees of freedom for feedback. Typically, one degree of freedom is available per finger, with force available only along an actuator's "line of action" and in only one direction. This limits the manner in which objects can be contacted for realistic feedback and does not support feedback to other parts of the hand. Tangential forces of friction are not available, although they are important for constraining fingers on objects and producing the feeling of weight. Also, additional feedback is needed to produce tactile sensations distributed across fingertips that are important for detecting surface features such as edges and corners.

Portable force-feedback gloves are grounded on the hand to provide a large workspace and freedom of motion. As a result, they cannot prevent the hand from moving through a virtual wall, and gravitational forces felt in the wrist or arm cannot be simulated. Similarly, simulations of grounded objects can be awkward. Virtual Technologies has recently developed the CyberForce armature to ground its CyberGrasp system on a desk, but such devices limit mobility and can feel cumbersome for the user, in addition to increasing cost and complexity.

Glove-mounted actuators or exoskeletons can restrict motion or collide with other objects. This is particularly relevant to the mixed haptics approach due to collisions with the real objects. The RM glove used in our system prevents users from grasping real objects. In contrast, the CyberGrasp system allows users to pick up real objects but not to reach into a cavity. Such differences can be the deciding factor for suitability of a glove to a particular mixed reality application.

Due to these limitations, force-feedback gloves are best suited for circular grasps of lightweight virtual objects that are held in the hand and not grounded elsewhere. The size and apparent stiffness of objects is also restricted, particularly for the RM actuators that have a low mechanical bandwidth and restrict finger motion range.

We believe careful use of force-feedback gloves can nonetheless provide useful sensations for various tasks. For example, our experiences suggest that short force pulses are useful for simulating button clicks or the initial moment of contact with a virtual wall. Also, good visual feedback may overcome device limitations by enhancing the perception of haptic information [9].

2.3 Technological Challenges

The successful combination of real and virtual components requires accurate spatial registration between them. For the control panel environment, a virtual panel must be accurately registered with a real panel and the virtual fingertip positions must accurately reflect the positions of the real fingertips. Otherwise, distracting sensations can result when visual feedback does not match haptic feedback or when the feedback from the glove seems to occur in the wrong position relative to sensations from the real panel. The accuracy of finger positions depends on the accuracy of glove sensor readings, hand modeling, and hand tracking.

The control panel environment also requires higher performance in terms of force feedback quality than other environments for which the RM system has been used successfully. The slider handles being simulated are rigid rather than compliant and are grounded on a panel rather than held in the hand. For reasons discussed in the previous section, this complicates feedback. The problem of simulating rigid objects is also complicated by a low communication rate in the RM version used.

Although mechanical limitations of the RM glove remain, the needed spatial accuracy and haptic quality are achieved by the technological developments described in [10] and [11]. They are summarized in the following list:

1. Piston sensor calibration using piecewise cubic curves.
2. Improved hand joint model with accurate kinematics system.
3. A tracker calibration scheme to correct for field warp in hand tracking.
4. A new serial communication scheme using data compression and synchronization with the haptics thread to improve update rate and latency.
5. Low-level pressure control loop modifications to produce finer changes at a cost of reduced maximum force.
6. Differences in force rendering to improve force at rigid object boundaries.

3 Evaluation

This section presents an evaluation of our approach. Some details are omitted due to space constraints. Tables of raw performance data, questionnaires with all responses, demographics, data plots, and additional information are found in [11].

3.1 Experiment Overview

We use between-subjects experiments to evaluate our approach. Subjects are randomly assigned to one of the three following groups:

M: Mixed – the subject feels both the real panel and glove forces.
P: Panel – the subject contacts the panel but does not feel glove forces.
G: Glove – the subject feels glove forces but does not feel the panel.

There are 16 subjects per group, for a total of 48 subjects, recruited primarily using flyers posted throughout a university campus. Subjects are compensated for participation. Median subject age is 22 years, with a median of 10 years experience with computers and a median of 2 hours of video game play per week. One subject in the G group is female and all others are male, presumably due to an advertised hand size requirement necessitated by a large device size.

Three experiments are performed and are presented to subjects as three sessions of one experiment. Each subject performs all three experiments in one visit. Experiment 1 is a basic comparison in which subjects perform a task repeatedly. In Experiment 2, the subjects repeat the task with degraded visual feedback (keeping the same group assignment). In Experiment 3, subjects again repeat the task, but all subjects receive mixed feedback consisting of both panel and glove sensations.

Dependent variables include both objective performance measures and subjective questionnaire responses. Task times are evaluated for Experiment 1 and Experiment 2, and are divided into *slider time* (time spent manipulating sliders) and *button time* (time spent manipulating buttons). Task errors are also considered for Experiment 2 and consist of *slider error* (sum of differences between actual and desired positions) and *button error* (a measure of difference between the actual and desired digit string displayed in an LED readout above the buttons). For all experiments, questionnaire responses are also evaluated. Each question is answered on a 7-point scale.

3.2 Task Description

During each experiment, the subject performs eight trials of the following task:

1. The subject presses the panel's asterisk button to begin the trial. A set of predetermined target values appears in the top row of LED readouts as a result.
2. The subject moves the sliders to the specified target values (the second row of LEDs indicates current slider positions).
3. Using the buttons, the subject enters the six digits seen in the top row of LEDs.
4. The subject presses the enter (↵) button to end the trial.

The particular sequence of target values is the same for each subject and for each experiment.

3.3 Statistical Methods

We report p-values for two-tailed statistical tests. Between-group differences are first tested with the appropriate omnibus test (ANOVA or Kruskal-Wallis, depending on the nature of the data). When this test detects a difference, follow-up testing is performed using a protected least significant difference approach. Specifically, two pairwise comparisons are used to compare the M group to the P and G groups, and results are not interpreted as significant if the omnibus test has not first detected significant difference. Pairwise comparisons following ANOVA are T-tests, and those following a Kruskal-Wallis test are Mann-Whitney tests.

We use a p-value threshold of 0.05 to determine demonstrated *significant* effects. Due to limited experiment power resulting from a small sample size, we also use a p-value threshold of 0.1 to identify other potentially interesting results and refer to them as *near significant*. The sample size of 16 subjects per group results in limited power (based on Cohen's conventions [12], less than a 30% chance of detecting an existing medium effect with a p-value threshold of 0.05). Therefore, failure to show significance should not be interpreted to suggest the absence of a meaningful effect.

The statistical tests are univariate (as is typical in similar studies), so the reported p-values control the per-variable likelihood of error and do not control the overall probability of error across all experiments and tests.

3.4 Objective Performance Measures

Analysis of objective performance measures for Experiment 1 and Experiment 2 is based on summed performance measures for trials 6, 7, and 8. Trials 1 and 2 are practice runs – scripted verbal instructions are given during Trial 1 and some subjects request additional instructions during Trial 2. Trials 3 through 8 are grouped into two composite tasks based on the experiment design. Specifically, the sequence of target values used for the last three trials is identical to the sequence of target values for the previous three trials. The two composite tasks are denoted by (3,4,5) and (6,7,8), corresponding to two sets of three trials each. Each of these two sets uses the sequence of target values ((34, 84, 43), (90, 63, 32), (44, 22, 07)).

No p-values below 0.1 result from the analysis of composite task (3,4,5), due in part to outliers and large variances as discussed in [11]. The remaining composite task, (6,7,8), is detailed here.

3.4.1 Experiment 1

Experiment 1 is the basic experiment for comparison between groups. At the beginning of Experiment 1, each subject has signed an informed consent document, provided a page of basic background information, and reviewed a written description of the task to be performed. Scripted verbal instructions are given during the first trial.

Table 1 shows task times for Experiment 1 (defined in Section 3.1), and Table 2 shows p-values for the corresponding statistical analysis.

Compared to the use of only glove forces, the mixed approach is shown to result in significantly improved button time toward the end of the Experiment 1 ($p < 0.05$). Additionally, the reduced slider time of the M group is near significant ($p < 0.1$).

Table 1. Experiment 1 task times for composite task (6,7,8)

		Slider Time			Button Time		
		Mean	σ	Median	Mean	σ	Median
Task (6,7,8)	M	90.7	27.9	92.3	37.6	13.3	37.9
	P	91.6	25.3	84.6	45.3	12.3	42.3
	G	121.3	57.8	104.4	53.1	22.9	48.2

Table 2. Statistical test results (p-values) for Experiment 1 task time data

	Slider Time (6,7,8)	Button Time (6,7,8)
ANOVA	0.057	0.042
M vs. P	0.950	0.201
M vs. G	0.035	0.012

3.4.2 Experiment 2

Prior to Experiment 2, the subject has answered an Experiment 1 questionnaire. The subject returns to the environment for Experiment 2 and repeats the same task sequence, but light levels in the virtual room are lowered progressively. Ambient and diffuse light intensities are approximately halved for each trial and set to zero for the final trial. Panel LEDs remain luminous and buttons remain slightly luminous. Most users become unable to use normal visual cues during the sixth or seventh trial, so composite task (6,7,8) is carried out with severely degraded visual feedback.

Table 3 summarizes resulting task times and task errors, and Table 4 shows p-values for the corresponding statistical tests.

Table 3. Experiment 2 task times and task errors for the composite task (6,7,8)

		Slider			Button		
		Mean	**σ**	**Median**	**Mean**	**σ**	**Median**
Task Time (6,7,8)	**M**	308.8	160.6	293.3	73.2	43.1	62.3
	P	377.6	159.3	336.9	91.2	64.9	70.3
	G	474.5	196.2	480.1	107.8	60.5	84.9
Task Error (6,7,8)	**M**	24.7	52.0	0.0	0.7	1.7	0.0
	P	63.3	133.7	0.0	0.8	1.7	0.0
	G	81.1	94.0	39.5	3.0	2.9	2.5

Table 4. Statistical test results (p-values) for Experiment 2 task time and task error data

	Slider Time	Button Time
ANOVA	0.032	0.239
M vs. P	0.267	-
M vs. G	0.009	-

	Slider Error	Button Error
Kruskal-Wallis	0.169	0.005
M vs. P	-	0.715
M vs. G	-	0.006

For interactions during heavily degraded visual feedback, the mixed approach is shown to produce significantly improved performance for both slider and button interactions when compared to the use of only glove forces. For slider interactions, this appears in the form of significant task time reduction ($p < 0.05$). For button interactions, this appears in the form of significantly reduced errors ($p < 0.05$). Task times suggest slider interactions with a darkened display are difficult for all groups.

3.5 Questionnaire Responses

A written questionnaire follows each experiment. Responses to questions are on seven-point scales with semantic anchors at the ends. Due to space constraints, the presentation of results is heavily abbreviated here. Table 5 shows statistical test results for all questions mentioned by the following subsections. Questions are different for each experiment, so identical numbers do not imply identical questions.

Table 5. Statistical test results (p-values) for all questions mentioned in Section 3.5

	Experiment 1		Experiment 2			Experiment 3		
	Q12	Q14	Q1a	Q2a	Q2b	Q2a	Q2b	Q3
Kruskal-W.	0.020	0.019	0.030	0.028	0.076	0.001	0.000	0.007
M vs. P	0.799	0.059	0.047	0.019	0.907	0.007	0.047	0.077
M vs. G	0.017	0.009	0.016	0.024	0.036	0.001	0.000	0.003

3.5.1 Experiment 1

The Experiment 1 questionnaire begins with a page of ten general presence questions in the style of Witmer and Singer [13]. Analysis of presence subscale scores does not detect any significant differences between groups; however, the sensitivity of such questions is questionable [14].

A second page contains three questions asking for ratings of object solidity (such as those found in [3]) and one question about the overall sense of touch. The tabletop is rated as significantly more solid by the M group than the G group (Q12, $p < 0.05$). The direct question about overall haptic quality (Q14) results in significantly higher ratings from the M group than the G group ($p < 0.05$) and higher ratings than the P group are found to be near significant ($p < 0.1$).

3.5.2 Experiment 2

The Experiment 2 questionnaire consists of six items asking subjects to rate their ability to perform interactions when the display is darkened – three for sliders and three for buttons. Q1a asks subjects to rate their ability to “perform the interactions” with sliders when the display is darkened, and Q2a asks “how natural” the slider interactions seem. For both items, ratings from the M group are significantly higher than those from both the P group and the G group ($p < 0.05$). Additionally, near significance ($p < 0.1$) is found for higher ratings of button interaction naturalness from group M than from group G (Q2b). Since buttons are slightly luminous, the darkening of the virtual room may not affect button interactions as much as slider interactions.

3.5.3 Experiment 3

For Experiment 3, subjects repeat the task sequence of Experiment 1, but all subjects receive mixed feedback. This experiment is intended to allow subjective comparison of the experience to that in Experiment 1. The questionnaire contains four items asking for this comparison in terms of visual display, sense of touch for sliders (Q2a), sense of touch for buttons (Q2b), and overall quality of experience (Q3). Responses are on a scale of 1 to 7, with a value of 4 indicating no perceived difference.

No between-group difference is detected for the question about visual quality (note visual quality is identical for all groups). For both of the questions about haptic quality (Q2a and Q2b), groups P and G report improvement that is significantly larger than that reported by group M ($p < 0.05$; note the M group experiences no change from Experiment 1). A similar difference is seen between the M and G groups for overall quality (Q3, $p < 0.05$), and higher values reported by the P group are near significant (Q3, $p < 0.1$).

3.5.4 Free-Form Question Responses

After Experiment 3, subjects are also given three questions allowing free-form response. In response to a question about the most beneficial system aspects, subjects commonly indicate haptics in one form or another. When subjects identify a specific haptic component, the one mentioned most frequently is the active force feedback for sliders. Some subjects from the P group identify the addition of glove forces in Experiment 3 as the most beneficial system aspect.

The second question asks subjects to identify the system aspect needing the most improvement. The sliders are mentioned most often, with several comments referring to “sensitivity” of sliders or lack of “resistance.” Often, a subject spends substantial time trying to make small adjustments to an almost-correct slider position. A coarser resolution for LED readouts indicating slider position may solve this. Several comments also reflect mechanical limitations of the glove. Subjects mention that their sense of touch is limited and that properties such as “texture” are not felt. Three subjects mention the glove’s limited finger motion range, and other comments about grasping appear related to the limited motion range or difficulty grasping sliders that results from the lack of tangential forces of friction needed to anchor the fingers.

Finally, subjects are asked to provide any additional comments they may have. Responses typically echo comments from the other questions or speak positively of the overall experience, describing the system as natural, realistic, and user-friendly. One subject writes, “I was able to tell when I was interacting with [objects] without looking directly at them,” suggesting that the haptic feedback can enhance interactions performed outside of the field of view.

3.6 Summary

Although the power to detect effects is limited by a small sample size, some meaningful effects are detected. Where significant performance differences are detected between feedback approaches based on objective measures, they consistently favor the mixed approach over the use of only glove feedback. In comparing the mixed approach to the use of only the passive panel, analysis of objective measures is inconclusive (no significant effects are identified, but power is low). Subjective evaluations favor the mixed approach to each of the individual approaches and indicate that glove forces remain useful for improving perceived haptic quality.

4 Conclusion

An approach to combining passive haptics with an active haptic device has been presented and evaluated. It provides an improved sense of touch for virtual environments by combining strengths of passive haptics and an active force-feedback approach, and it results in a haptic mixed reality system for future integration with visual mixed reality displays.

References

1. Fabiani, L. and G. Burdea. *Human Performance Using the Rutgers Master II Force Feedback Interface*. in *IEEE Virtual Reality Annual International Symposium*. 1996. Santa Clara, CA: IEEE Computer Society Press.
2. Insko, B., et al., *Passive Haptics Significantly Enhances Virtual Environments* (Computer Science Technical Report 01-010). 2001, University of North Carolina: Chapel Hill.
3. Hoffman, H.G. *Physically Touching Virtual Objects Using Tactile Augmentation Enhances the Realism of Virtual Environments*. in *IEEE Virtual Reality Annual International Symposium*. 1998. Atlanta.
4. Lindeman, R.W., J.L. Sibert, and J.K. Hahn. *Hand-Held Windows: Towards Effective 2D Interaction in Immersive Virtual Environments*. in *IEEE Virtual Reality 1999*. Houston, TX.
5. Boud, A.C., C. Baber, and S.J. Steiner, *Virtual Reality: A Tool for Assembly?* Presence: Teleoperators and Virtual Environments, 2000. 9(5): p. 486-496.
6. Milgram, P. and H. Colquhoun, *A Taxonomy of Real and Virtual World Display Integration*, in *Mixed Reality: Merging Real and Virtual Worlds*, Y. Ohta and H. Tamura, Editors. 1999, Ohmsha, Ltd.: Tokyo. p. 5-30.
7. Iwata, H., *Feel-Through: Augmented Reality with Force Feedback*, in *Mixed Reality - Merging Real and Virtual Worlds*, Y. Ohta and H. Tamura, Editors. 1999, Ohmsha, Ltd.: Tokyo. p. 215-227.
8. Bouzit, M., et al., *The Rutgers Master II-New Design Force-Feedback Glove.* IEEE/ASME Transactions on Mechatronics, 2002. 7(2): p. 256-263.
9. Biocca, F., J. Kim, and Y. Choi, *Visual Touch in Virtual Environments: An Exploratory Study of Presence, Multimodal Interfaces, and Cross-Modal Sensory Illusions.* Presence: Teleoperators and Virtual Environments, 2001. 10(3): p. 247-265.
10. Borst, C.W. and R.A. Volz. *Observations on and Modifications to the Rutgers Master to Support a Mixture of Passive Haptics and Active Force Feedback*. in *Eleventh Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. 2003. Los Angeles.
11. Borst, C.W., *Haptic Feedback for Virtual or Mixed Reality Environments using a Combination of Passive Haptics and Active Force Feedback*. PhD dissertation. Department of Computer Science, Texas A&M University. 2002.
12. Cohen, J., *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. 1988, New York, NY: Academic Press.

13. Witmer, B.G. and M.J. Singer, *Measuring Presence in Virtual Environments: A Presence Questionnaire.* Presence: Teleoperators and Virtual Environments, 1998. **7**(3): p. 225-240.
14. Usoh, M., et al., *Using Presence Questionnaires in Reality.* Presence: Teleoperators and Virtual Environments, 2000. 9(5): p. 497-503.