Augmented Haptics for Low-Cost Teleoperation

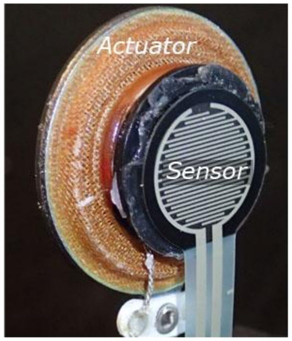

Figure 1: FS/VA Prototype


Figure 2: FS/VA Mouse


Figure 3: FS/VA Phantom

Philip Feldman
UMBC
1000 Hilltop Circle
Baltimore, MD 21250 USA
feld1@umbc.edu

Ravi Kuber
UMBC
1000 Hilltop Circle
Baltimore, MD 21250 USA
rkuber@umbc.edu

Abstract
This paper describes an approach to enhance a conventional haptic interface through the development of a low-cost module that measures force and provides vibrotactile feedback. The aim is to support semi-structured 'picking and placing' tasks, with the long term goal of assisting skilled and semi-skilled workers to perform tasks via teleoperation. We created a generic force sensing/vibrotactile actuator (FS/VA) module (Figure 1) and integrated this with a range of prototypes, including a mouse (Figure 2) and an enhanced Phantom Omni (Figure 3). Initial results from a pilot study to determine the efficacy of the solution indicate that using such augmentation is effective, and allows users to reduce errors and potentially improve performance when compared to open-loop systems (e.g. gesture tracking).

Author Keywords
Haptic; Tactile; Teleoperation; Vibrotactile

ACM Classification Keywords
H.5.2. User Interfaces: Haptic I/O.

Introduction
While teleoperation has most commonly been used to support medical, space and defense initiatives, it can also be applied to tasks where skilled or semi-skilled labor is needed (e.g. remote factory work). This would assist organizations who may experience difficulties recruiting due to their location or skills shortage.

Because of the intricacies of performing tasks where fine motor skills are needed (e.g. assembling a product), haptic technologies would offer considerable potential to assist the user with their tasks.

This paper describes a first step towards determining ways to use touch to support manual tasks, through the development of low-cost modules that measure force and provide feedback. Prototypes developed have been used to perform a task similar to one that may be used in a work environment ('picking and placing'). The long term goal of the research is to use a similar solution to support teleoperation.

Related Work

In recent years, lower-cost technologies such as the Phantom Omni and Novint Falcon have been released to support haptic interaction. However, to lower the price, the degrees of freedom (DOF) are reduced to the point that a user is only able to manipulate a single point in 3D space. Extending a low-cost platform such as the Phantom Omni to accommodate more sophisticated interactions has been tried several times. Examples include a 3 DOF grasping interface developed by Barbagli et al. [1], who added additional force-feedback components and a multi-channel vibrotactile display. The display was composed of a cylindrical handle with four embedded vibrating elements driven by piezoelectric beams developed by Debus et al. [2].

Vibrotactile feedback has long been associated with teleoperation and virtual environments, and is known to be a particularly cost-effective way to provide multimodal feedback to support interface interaction. Vibrotactile systems range in sophistication from the unbalanced motors in phones and game controllers to systems that convey sophisticated contact and surface characteristics[3]. Multiple studies have examined the interaction of vibrotactile systems with visual, haptic and audio to determine optimal multimodal configurations[3][4]. It is not always the case that more equals better. If the feedback is poorly designed, it can lead to cognitive loading that can interfere with efficient task completion[3][5].

Studies of user interaction with multidimensional devices and tasks such as grasping, rotating and assembling tend to focus around measures of overall task time[4][6][7], errors[3][6] and workload[5]. Additional measurements that are more specific to the type of feedback being applied such as over/under grip[9], excessive force[8] and subjective measures[3] have also been used. Studies using Fitts' Law have been used in this context, though they tend to be "problematic", given that Fitts' Law provides the greatest benefit when studying highly repetitive tasks, where source and target do not vary [10]. Manufacturing are more ad hoc, tasks, such as loading a set of tools from a bin into the magazine of a flexible manufacturing system (FMS).

In this paper, we focus on a way to augment low cost haptic systems to perform high-complexity tasks such as those found in manufacturing.

Device Configuration

We created a generic force sensing/vibrotactile actuator (FS/VA) module. The prototype version consists of a force sensor on a voice coil vibrotactile actuator (the FS/VA unit in Figure 1). In this implementation, the user applies pressure to the sensor, which causes a proportional action in a virtual or telepresence

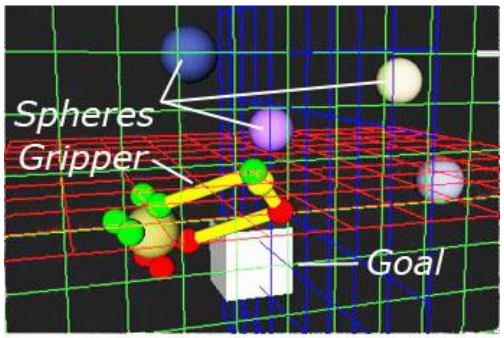

Figure 4: Virtual Environment

environment, such as closing or releasing a gripper element. If the gripper element contacts an item within a virtual environment, a signal is sent to the vibrotactile element, presenting proportional vibrotactile feedback to the user. This feedback can vary by waveform and amplitude.

Study Design

The study was conducted to determine whether FS/VA could assist in reducing errors and/or increasing performance when performing grasping tasks similar to those found in light manufacturing.

Design of the Testbed

The prototype was developed using the Phantom Omni and FS/VA elements(Figure 3). Two FS/VA components are mounted to either side of the Omni's handle. Rather than gripping the handle, the user interacts with the Phantom by gripping the system at the force sensors. Mounted directly under the sensors are vibrotactile actuators that are associated with the sensor. Using a Phidgets 8/8/8 interface kit and the Microsoft XAudio2 API, up to eight sensors and their associated vibrotactile elements can be operated simultaneously. Due to the mounting constraints of the Phantom, we decided only to use two FS/VA elements.

Participants

10 participants were recruited for the study (8 male, 2 female, ages 21 to 54). All participants were information workers and comfortable with technology. None had experience with tactile or haptic systems other than videogame and phone-based vibration systems.

Experimental design and procedure

To determine the efficacy of the FS/VA concept, a randomized grasping and placing task was developed. We aimed to identify whether grasping tasks could be performed with greater levels of accuracy when different modalities were presented via the interface. These included:

- OPEN_LOOP (no feedback)
- HAPTIC (force reflection output only)
- TACTOR (vibrotactile output only)
- HAPTIC_TACTOR (force reflection and vibrotactile output)

A transfer (picking and placing) task was selected, as it better represented the type of work performed within a factory environment. The user was presented with a 3D virtual environment rendered using OpenGL. Viewpoint angle and position could be controlled by the mouse.

The design of the experiment crossed Feedback Type x Errors and Feedback Type X (Errors/Task Completion Time) as independent within subjects designs. Order bias was counterbalanced by randomly determining the Feedback Type sequence for each participant. Each of the 12 tasks (3 tasks of each modality) were randomized across participants.

Cutkosky[11] created a taxonomy of single-hand grips used for light machining. The grips that are possible in this study are Prismatic Precision grasps where the thumb and opposed index finger are used. The task consists of moving 5 randomly positioned spheres to a "goal box" at the center of the environment (Figure 4). Each sphere emits a vibrotactile frequency (100-500hz in 100hz increments) whose amplitude was in proportion to the simulated contact force between the sphere and the a gripper element, in accordance with Murray's findings on proportional vibrotactile feedback[9].

The task of grasping and placing balls in the goal was designed to be completed by user with a minimum of training, in a timespan of between 30 seconds to a minute per task, resulting in a test session of approximately 20 minutes. The environment was explicitly set up without constraints on the sphere's range so that errors in manipulation could occur.

Participants were introduced to the system, and given as much time as they liked to become comfortable with the task. All participants were instructed to complete the task as quickly as possible. Time for each task was calculated from the moment that the Start/Next button or the space bar was pressed to the time that the last sphere was placed in the goal. If the participant was unable to place all the spheres in the goal, the timer stopped when the space bar was pressed and the next setup started.

Preliminary Results and Discussion

The goal of this effort was to determine if the hardware (haptic base with FS/VA components attached) could be used to augment haptic interaction. To determine this, we need to address errors and task efficiency.

Errors

A total of 7 participants committed a total of 44 errors in 32 tasks. Most errors occurred in the first session (37 vs. 7). The type of feedback greatly affected the error rate, with the greatest number of errors made under the vibrotactile only output condition (TACTOR condition) and fewest when multimodal feedback was presented (HAPTIC_TACTOR condition):

- TACTOR (vibrotactile output only) 19
- OPEN_LOOP (no feedback) 14
- HAPTIC (force reflection output only) 7
- HAPTIC_TACTOR (force reflection and vibrotactile output) 3

Modality	Estimate Std.	Error	t value	Pr(>|t|)
HAPTIC TACTOR vs. HAPTIC	-0.3333	0.3123	-1.067	0.7110
OPEN LOOP vs. HAPTIC	0.5833	0.3123	1.868	0.2565
TACTOR vs. HAPTIC	1.0000	0.3123	3.202	0.0130*
OPEN LOOP vs. HAPTIC TACTOR	0.9167	0.3123	2.935	0.0262*
TACTOR vs. HAPTIC TACTOR	1.3333	0.3123	4.269	<0.001***
TACTOR vs. OPEN LOOP	0.4167	0.3123	1.334	0.55

Table 1. Significance by condition

Table 1 shows the results of a one-way ANOVA. A means plot of these values is shown in the figure below.

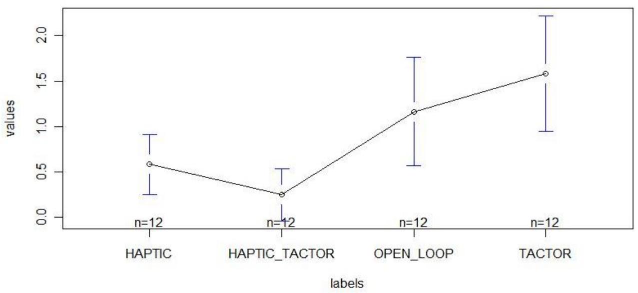

Figure 5. Distribution of results by condition

Looking at the chart (Figure 5), it seems apparent that results for the HAPTIC and HAPTIC_TACTOR conditions belong to one cluster and that results for the

OPEN_LOOP and TACTOR conditions belong to another. Further, there is a significant difference ($p < 0.001$) between HAPTIC_TACTOR vs. TACTOR. This suggests that vibrotactile interaction alone is not sufficient to reduce errors, but combined with the information from the haptic component, it may act as an alarm that enhances interaction. This is in line with the study by Ng and Chan [7] that showed that reaction times were fastest for the vibrotactile enhanced condition, and slowest for visual.

Performance

The percentage of time to complete the tasks was calculated and used to compare the task completion using a normalized baseline. Thus, within each session, the fastest time took 0% of the baseline and the slowest time took 100% of the baseline. Although the population tested was small (5 individuals), there is enough difference in the results to get a significant result and some hints as to where additional data may lead.

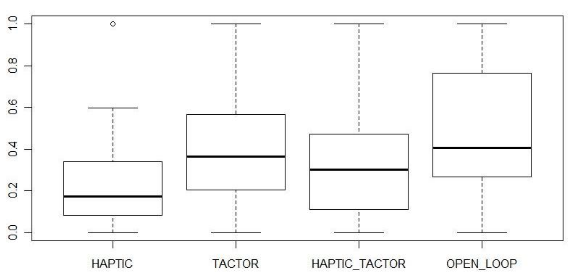

Figure 6. Box plot of time taken by condition

Figure 6 shows that the fastest times are associated with the HAPTIC modality alone (Avg. 31.35 sec), and that the times are most tightly clustered here. Even though the average of the HAPTIC_TACTOR is not too distant (Avg. 33.85 sec), the values are considerably more scattered. Results of a one-way ANOVA indicate possible significance between HAPTIC, and OPEN_LOOP (Avg. 32.46 sec), $p=0.0117$. Because of the low sample size of this pilot study, further work would need to be done to gain a conclusive result.

The findings are somewhat counterintuitive. We would expect results for the HAPTIC_TACTOR condition to be faster, as there were fewest errors experienced under this condition. Instead, participants were able to perform tasks using the HAPTIC alone condition faster, though not conclusively. Further work with a larger sample size will help to determine if these results are valid.

Discussion

In this study, we found that FS/VA modules could be effectively be integrated with a force feedback base. Users were able to grasp and place targets with the augmented Phantom Omni. To do these same tasks with a standard model would be challenging, due to low DOF limitations of the hardware. Based on the error data, the potential of adding FS/VA components to other, non haptic devices may be worth pursuing, for example in the case around a smartphone or a videogame controller. We have begun examining this with a variety of other form factors, such as the mouse pictured in Figure 2.

The vibrotactile response in this study was minimal, consisting of sine waves at given frequencies and varying amplitudes. This interaction can also be made far richer, by mimicking the waveforms produced by contacting different materials[3], the sensations that can be produced when moving over a variety of textured surfaces[12], as well as the resonant qualities of objects[13]. It may be that such improvements in the vibrotactile channel will improve results when compared to the current, simple vibration patterns.

Conclusions and Future Work

Findings from our study have revealed the benefits of using a combination of force reflection and vibrotactile output (HAPTIC_TACTOR) in reducing errors, and that force reflection output alone (HAPTIC) potentially provides the highest performance in completing the task after becoming familiar with the system and the task. In terms of future work, we intend to configure another Phantom Omni with the same FS/VA platform and work on connecting them to a manufacturing robot such as Baxter[13]. Further studies will then focus on effectively mapping real-world interaction to augmented haptics for teleoperative manufacturing-style tasks.

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