Multichannel vibrotactile display for sensory substitution during teleoperation

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ABSTRACT

This paper presents the design and testing of a multi-channel vibrotactile display composed of cylindrical handle with four embedded vibrating elements driven by piezoelectric beams. The experimental goal of the paper is to analyze the performance of the device during a teleoperated force controlled task. As a test bed, a teleoperator system composed of two PHANToM™ haptic devices is used to trace a rectangular path while the operator attempts to maintain a constant force at the remote manipulator's tip. Four sensory modalities are compared. The first is visual feedback alone. Then, visual feedback is combined with vibration, force feedback, and force feedback plus vibration. Comparisons among these four modes are presented in terms of mean force error. Results show that force feedback combined with vibration provide the best feedback for the task. They also indicate that the vibrotactile device provides a clear benefit in the intended application, by reducing the mean force errors by 35 percent when compared to visual feedback alone.

Keywords: vibrotactile, piezoelectric beams, teleoperation, force feedback, sensory substitution.

1. INTRODUCTION

Augmenting perception in man-machine systems consists of two parts. First, machine sensor data must be interpreted in a way appropriate to the task. Second, the task-specific information must be communicated to the operator in a way that addresses the limitations of human sensory information processing. This paper presents a comparison of force feedback and vibrotactile display for performing constant-force contact motions during teleoperation. Even without teleoperation, it is difficult for humans to maintain constant contact forces. This is largely a sensing limitation as opposed to one of motor control. Thus there is potential to augment human performance in this task by presenting changes in force magnitude in a format amenable to human sensory interpretation. A vibrotactile display is promising for such applications due to its modest cost. In addition, it may be preferred to visual and auditory displays, which might distract the operator from existing inputs on those sensory channels.

In the next section, a brief review of prior work on vibrotactile displays is presented. The following section describes the mechanical and electrical design of a multichannel vibrotactile display for sensory substitution during teleoperation. The subsequent section describes an experimental evaluation of the device. A teleoperated force controlled task is performed using a system composed of two PHANToM™ haptic devices, and performance of the vibrotactile device are compared with other sensory substitution modalities. Conclusions are presented in the final section of the paper.

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2. BACKGROUND

Force substitution via vibrotactile display is not a new concept. It has been an ongoing research topic for the past forty years. During this period, many vibrotactile systems have been designed, utilizing a broad range of actuators and spanning a wide range of applications, from undersea teleoperation[3] to aiding the blind[1].

These devices can be roughly grouped according to the number of vibrating elements and, if more than one, whether the elements are widely separated or placed in a closely packed array. The latter case is exemplified by Bliss[1] et al. in which a series of 0.1mm-diameter pins are arranged in a matrix configuration with six rows of 24 vibrating pins. Driven by piezoelectric crystals, the device is used to convert optical signals to vibrotactile information. Called Optacon™, it is used by blind people to feel the image viewed by an associated handheld camera. In Wellman[7] et al., a shape display consisting of a regular array of 10 pins actuated using SMA wire was used to convey tactile information. The device had a -3dB point of 40 Hz and detectable output that could still be felt at frequencies approaching 150 Hz. The device was used to transmit information about the texture and contact state. The shape display was fast enough to keep up with finger speed when scanning over small object features; however, it was much more complex and expensive that traditional vibration displays that use piezoelectric crystals or small motors.

Devices exemplifying widely spaced vibrating elements include those described in Tan and Rabinowitz[6], and Massimino[5]. In Tan and Rabinowitz[6], a system composed of three contact point actuators was designed. Each actuator used a disk-drive head positioning motor controlled via a digital angular position feedback controller to produce vibrations at a frequency range from DC to above 300Hz. The system was attached to the thumb, index, and middle finger and was used for a variety of tactual perceptual studies. In Massimino[5], an experimental study of the use of auditory and vibrotactile display as sensory substitution for force feedback was conducted. Specifically, a vibrotactile display consisting of vibrating voice coils placed at the fingertips and palm of the dominant hand was used to perform a peg-in-hole task. Each vibrator had a resonant frequency of 250 Hz, with intensity proportional to the magnitude of the associated force measured using force sensing resistors. Results showed that the vibrotactile or auditory displays did not speed up the task in the case of clear visual feedback. However, they did help in the cases of an obstructed view or time delay.

Few vibrotactile devices are used in real industrial tasks. One notable exception can be found in Dennerlein[3] et al., where a vibrotactile system designed for the harsh condition of undersea hydraulic connector mating was presented. First a sensor using piezoelectric contact sensor was built and packed to fit into the manipulator gripper. Second, a simple voice coil motor mounted on an aluminum base was clamped on the unmodified master controller and was used as the vibrotactile display. The preliminary result showed that the device consistently eased the undersea connecting task.

Finally, some commercial systems have also been developed. One is The Cybertouch™ from Immersion. This device is composed of six vibrotactile displays attached to the palm and fingertips of the Cyberglove®, a fully instrumented glove that provides up to 22 joint-angle measurements. Each actuator provides sustain vibrations at a frequency ranging form 0 to 125Hz, with a 1.2N peak to peak amplitude at 125Hz. The system is used primary to interact with virtual environments.

3. DISPLAY DESIGN

The motivating design premise was that the best approach for teleoperation would be to mount vibrotactile modules in the handle or stylus of the master device. The goal was to provide the most straightforward mapping between vibrations on the hand and coordinate directions on the master and remote manipulators.

For ease of construction, it was decided to equally space four vibrotactile modules around the circumference of a cylindrical handle. As shown in Figure 1, the four resonators can be used to represent positive and negative forces (or torques) with respect to two directions in the tool frame.

The vibrotactile modules were designed according to the following goals:

- They should not interfere with the natural grip of the handle.
- They should permit a variety of grasp locations on the handle.
- The vibration amplitude should be uniform over the surface of each module.
- The vibration amplitude should be independent of the grasp force.
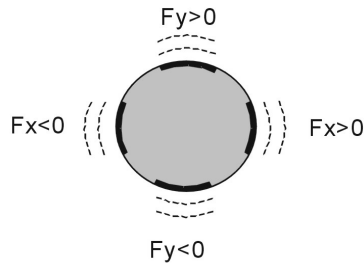

Figure 1: View along cylinder axis showing vibration conditions of four resonators.

These goals led to a design in which the vibrotactile modules were embedded flush with the cylindrical handle. Figure 2 shows the device with one module disassembled. The module is about 1" by 2" allowing for a variety of grasps and finger sizes. To achieve a uniform level of vibration over the module's surface independent of grasp force, each module consists of a piezoelectric bimorph beam which sits freely in a cavity under 11 rows of 4 pins, spaced 0.1 inch apart. Vibrations are transmitted to the hand through the pins, which pass through holes in the module's cover. The pins in each row vary in length so that they conform to the radius of the module's cover plate.

By allowing free-free motion of the beam within the cavity, nodes of vibration (dead spots) are precluded such that the vibrotactile response is perceived to be uniform over the surface of the module. Furthermore, the depth of the cavity is such that the beam can still vibrate freely under the pins regardless of grasp force. While a large grasp force does affect hand impedance and thus energy transfer from the pins to the hand, the beam and pins continue to vibrate against the skin.

Figure 2: Disassembled Vibrotactile display revealing piezoelectric beam, cavity in which it vibrates and floating array of pins.

The circuit driving the four modules is capable of delivering a variety of input voltages to the resonators (up to $\pm$ 80V; 50-600 Hz; sinusoidal, triangular or square waves). The input voltage to each resonator is amplitude modulated at a frequency of ~300 Hz, which is the most sensitive frequency of human fingers[2] and is also the resonant frequency of the piezoelectric beams. As currently designed, the two input channel voltages *(x,y)* are mapped to four outputs by dividing them into their positive and negative parts (x^+, x^-, y^+, y^-), each of which is used as the input to a resonator circuit. Assuming a force input, the output is as shown in Figure 1.

The final device, as shown in Figure 2, is a 4-inch long cylinder of outside diameter 1 1/4 inch and inside diameter 3/8 inch. The device has a total mass of 130 grams. While initially intended for mounting on the master handle, the final size of the device made it appropriate to hold in a power grasp (e.g., like holding a hammer). As shown in Figure 3 the palm, thumbs, index and middle finger are in contact with one or more vibrotactile modules during this grasp. It was found in preliminary experiments that operators had more success gripping the master with a dextrous grasp (e.g., like holding a pen). When given the choice, operators preferred a direct and dextrous grasp of the master with the dominant hand while power grasping the vibrotactile device in the other hand.
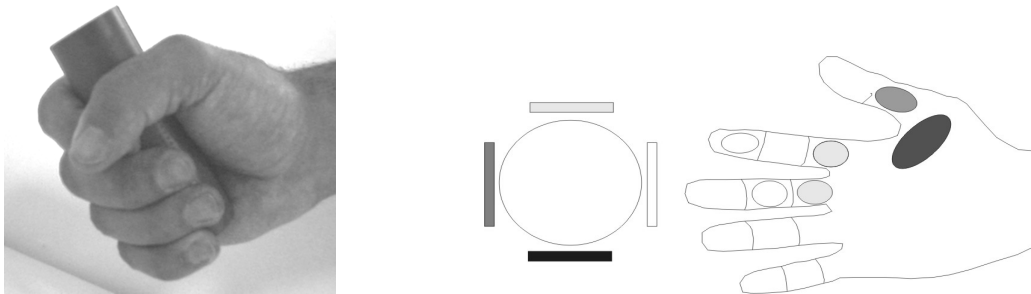

Figure.3: (a) Power Grasp of the device, (b) Contact locations between the hand and a top view representation of the four resonators.

4. EXPERIMENT

4.1. Application

A teleoperated force controlled task was chosen to assess and compare the performance of the vibrotactile device with other sensory substitutions. The experiment is designed to find the best sensory device that can be used to follow a preset contact path while maintaining a constant contact force at the tip of the remote robot. Such an experiment can find its motivation in many minimally invasive surgical applications, (i.e., blunt dissection) where force control can be used to improve accuracy, decrease execution time as well as decrease the risk of damaging surrounding tissue. For these teleoperated surgical tasks, where force feedback is currently unavailable, vibration could provide a cheap and risk free way of providing force information to the surgeon. In the following, the performance of the vibrotactile device is compared with force feedback and a combination of force feedback and vibration.

4.2. Apparatus

A tabletop teleoperator system, composed of two PHANToM® haptic devices (Model 1.5, Sensable Technologies, Cambridge, Mass., USA) is used to perform the task (figure 4a). The master manipulator is a six degree of freedom manipulator. The operator controls the master by manipulating a stylus attached through a passive spherical wrist. The remote robot is identical. A force/torque sensor (Model mini40, ATI Industrial Automation, Apex, NC, USA) is attached to the end effector of the robot, and a stylus with a ball bearing tip is then attached to the other side of the sensor (figure 4b).

At each sample time, the forward kinematics is computed such that the position and orientation of the end effector with respect to the base frame is known. The workspace is roughly a box of dimension 19.5 cm $\times$ 27 cm $\times$ 37.5 cm. Each device can exert a continuous tip force of 1.7 N, and a maximum force of 8.5 N can be achieved.

As shown in equation (1), the controller uses a symmetric proportional control scheme based on position and velocity error between the master and remote manipulators. Here, $X_i, \dot{X}_i, F_i$ are the ith components of the Cartesian position, velocity and force.

The controller gains are adjusted experimentally to achieve stability and haptic realism. Earlier tests [4], showed that forces ranging from .2N and 8.5N could be felt using this bilateral force control scheme. The controller output is taken as an estimate of the force acting on the robot's tip. The control loop rate is approximately 1 kHz. Note that forward position control without force feedback can be easily enabled by setting the master forces to zero.

$$F_i^{remote} = K_{pi}\left(X_i^{master} - X_i^{remote}\right) + K_{vi}\left(\dot{X}_i^{master} - \dot{X}_i^{remote}\right)$$
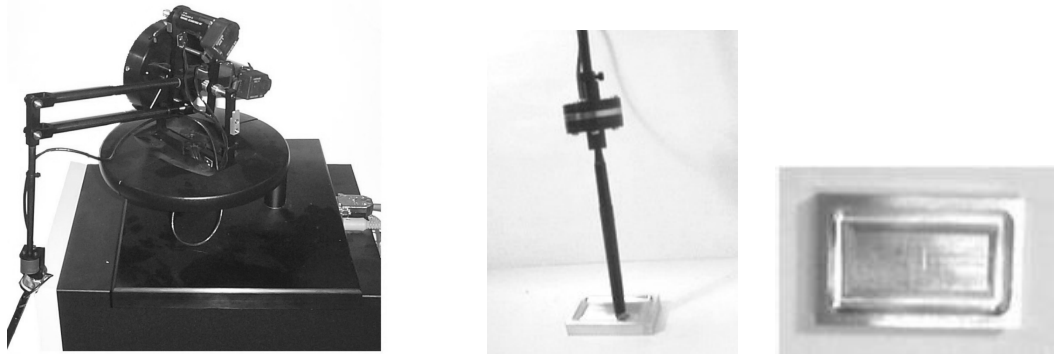$$F_i^{master} = -F_i^{remote}, \quad i = \{x, y, z\} \tag{1}$$

Figure 4: (a) PHANToM arm. (b) Tip of the PHANToM remote robot with attached force sensor and (c) grooved track.

4.3. Force control task

The path that the operator must follow is a rectangle groove machined in an aluminum block. The rectangle is 2.25'' long and 1.25'' wide. The rectangular shape was chosen for two reasons. First it is simple enough so that operator can focus solely on maintaining a constant normal force while following the path. Second the corners of the rectangle act as a disturbance to which the user must adapt in order to maintain a constant normal force. Note that lateral contact forces are not conveyed to the operator in any mode.

The experiment is conducted as follows: First, the operator positions the remote robot tip at the start position in the grooved track and is asked to achieve a *-1N* normal force by viewing the numerical force level displayed on a video screen. The operator is asked to maintain this force (without moving in the track) for 10 seconds while looking at the displayed force. The visual display is then turned off and the operator is asked to trace out one circuit of the track while maintaining the desired contact force. Four teleoperation modalities are employed, in turn, by the operator:
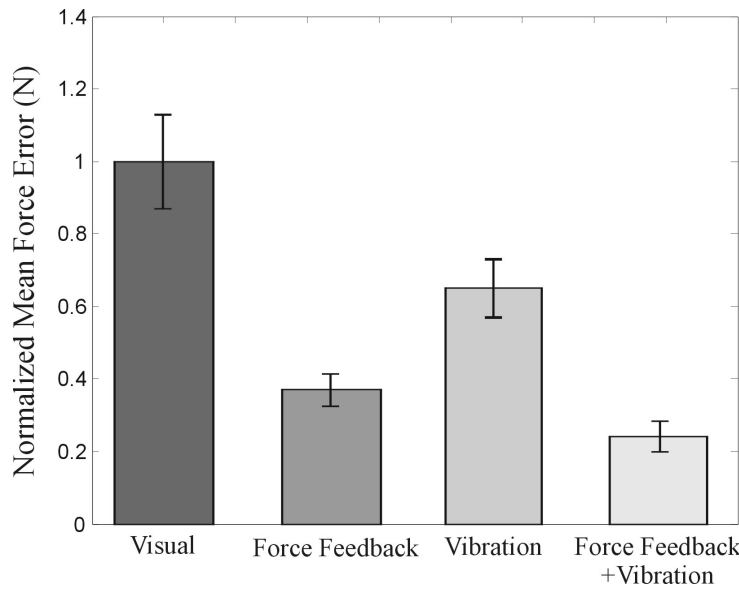
1) Visual Feedback alone: teleoperation is carried out using only forward position control (i.e., no force feedback). The operator uses visual feedback alone to maintain a constant contact force.
2) Force Feedback: the bilateral force control scheme is used to drive the system. In addition to visual feedback, the operator can feel the normal forces that he/she applies.
3) Vibration Feedback: forward position control is used to control the teleoperation system. Normal force information is conveyed to the operator using the vibrotactile display. Visual feedback is also available.
4) Force Feedback combined with vibration: modes 1,2 and 3 are combined.

In modes 3 and 4, only two channels of the vibrotactile device are used to convey normal force information using a 0.1 N dead band about the desired force value. One side of the display vibrates if too much force is applied and its opposite side vibrates if too little force is exerted. The intensity of the vibrations is proportional to the magnitude of the force.

Before collecting any data, the users are trained until they become fully accustomed to the system, and to the four system modalities. Once fully trained, each operator completes three consecutive trials using each mode. A total of five subjects, naïve to the purpose of the experiment, voluntarily participated in the experiment (4 males, 1 female, all with engineering backgrounds, ages 19-25). In the end, each subject performed a total of 12 trials.

4   RESULTS AND DISCUSSION

The results are summarized in Table 1. Four feedback conditions were tested and compared: 1) Visual feedback alone, 2) force feedback, 3) vibration, and 4) force feedback combined with vibration. In all the cases, clear visual feedback was available. Figure 5 summarizes the magnitude of mean normal force error for the four different modes. These results are normalized using visual feedback as a baseline. Compared to visual feedback alone, mean force error magnitude is reduced by 65%, 35%, and 75% using force feedback, vibration, and force feedback plus vibration, respectively.

For statistical analysis, a Kruskal-Wallis test was done to check if the results associated with each feedback modality were statistically different. This test was chosen because of the relatively small number of samples used in the study. The results are summarized in the p-value matrix (2). All the results are statistically different at a level $\alpha < 5\%$ except for the comparison between force feedback and force feedback combined with vibration. For this case, it cannot be concluded with high confidence that the difference between these two modalities is statistically different. Repetition of the experiment with more subjects is needed and will be part of our future work.

Figure 5: Normalized mean force error in for the four different modes.

	Mean	Std Error
Visual	0.963	0.126
Force	0.357	0.061
Vibration	0.623	0.095
Force + Vibration	0.232	0.056

Table 1: Mean force error and associated standard error for the four different modes

$$p = \begin{bmatrix} 1 & 0.0002 & 0.0437 & 0.0001 \\ 0.0002 & 1 & 0.0228 & 0.1529 \\ 0.0437 & 0.0228 & 1 & 0.0014 \\ 0.0001 & 0.1529 & 0.0014 & 1 \end{bmatrix} \begin{matrix} VF \\ FF \\ Vib \\ FF+Vib \end{matrix} \qquad (2)$$

with column headers $VF \quad FF \quad Vib \quad FF+Vib$

Figure 6 shows normal force error for the four different modes during a typical trial. The zero dashed line corresponds to the desired force target. Note that for this trial, time to completion varies among the different modes. However, no evidence was found that a particular feedback mode was speeding or slowing task execution. Thus, this trial cannot be viewed as typical with respect to execution time.

As shown in figures 5 and 6, vibration combined with force feedback produces the best results compared to the other feedback modes. In this mode, the user was able to maintain normal force close to the desired value throughout the task. This combination of sensory inputs appears to increase human sensitivity to changes in force more effectively than either force or vibration alone. While more data is needed for statistical justification of this result, a possible explanation can be made by analogy with stochastic resonance. Vibrations can be viewed as a noise that enhances force feedback. In effect, vibrations warn the operator of a problem, recapturing his/her attention, and directing the user to refocus on the force feedback. In other words, it can be used to overcome desensitization to a continuous stream of information. Moreover, the two-channel design of the vibrotactile device communicated the appropriate corrective action by indicating the direction of motion necessary to decrease the vibration and reach the desired force.

As expected, force feedback did decrease the mean force error significantly, in this case by 65%. As seen in Figure 6, however, operators tended to apply more force than necessary using this mode. This can be expected as well since the operator was not allowed to brace their hand during the motion. As an example, consider writing with a pen, but without resting your hand on the table. The lack of support makes fine motion control, as well as force control, difficult at the tip. The situation is only exacerbated when both the bracing force and the contact force are removed from the hand as in modality 1. Adding force feedback to the unbraced hand in modes 2 and 4 helps by preloading the closed kinematic chain formed by the human arm and the master manipulator. The effect of force feedback is, of course, inferior to the direct force feedback experienced holding a pen against a table since the closed-loop stiffness of the teleoperated system is limited by mechanical and stability considerations.

By reducing mean force error by 35 percent, the vibrotactile display demonstrated a clear benefit over visual feedback alone. In the absence of force feedback, the vibrotactile display can thus be effectively used as a simple force substitution device. From the force plot (figure 6), it can be seen that the display is used as a reactive device. Although, it does not help the user to maintain constant force; it is efficient at bounding the force error within $\pm 0.5\,N$. This result suggests that the operator is interpreting vibrations on the device's two channels as binary signals and is unable to utilize the vibration amplitude modulation as implemented. Further supporting this hypothesis, initial experiments showed that the user's reaction was bang-bang in nature, creating a chattering effect until a dead band of sufficient size was implemented. Based on Figure 6, one might assume that the dead band was $\pm 0.5\,N$ and not $\pm 0.1\,N$. The larger errors can be attributed to the sharp corners of the path. The corners induce large and sudden changes in force that take time to compensate for using the vibrotactile device.
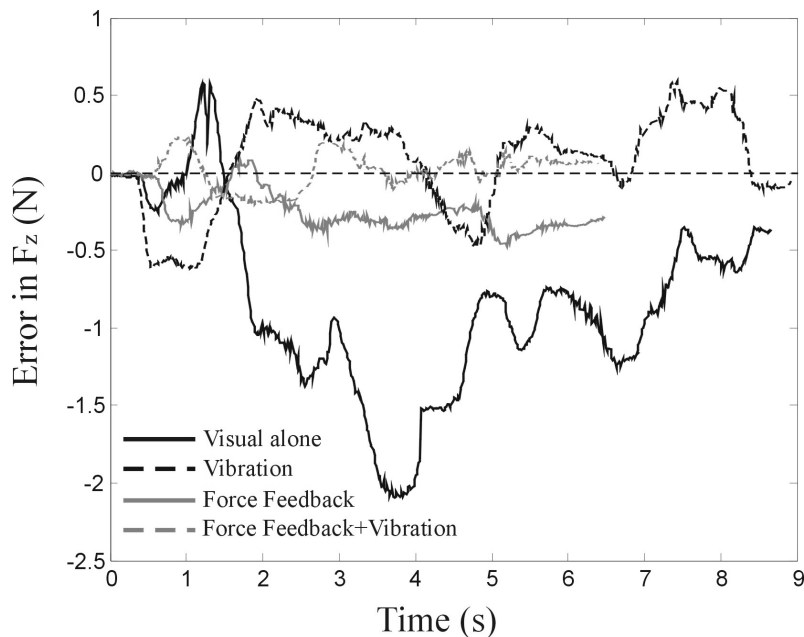

Figure 6: Typical trial showing normal force error function of the four different feedbacks.

5   CONCLUSIONS

These results demonstrate that vibrations used as force substitution can significantly improve a teleoperated force controlled task. Moreover, added to force feedback, vibration is an easy way of enhancing teleoperation performance. The proposed design presents a low cost and flexible device that can be use in a wide range of applications. Associated with a teleoperation system the device can be used without interfering with normal task execution and without significant modifications to the existing manipulator. Consequently, if the system fails; it has no impact on the manipulator's capabilities, so operations can continue as with the original manipulator system.

Further work is needed to investigate all the capabilities of the device. Specifically, the four channels need to be tested simultaneously using different frequencies and input waveforms. For example, by combining the different phases and frequencies available, one could use the device to map torque as well as force information.

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