Extending Human Proprioception to Cyber-physical Systems

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ABSTRACT

Despite advances in computational cognition, there are many cyber-physical systems where human supervision and control is desirable. One pertinent example is the control of a robot arm, which can be found in both humanoid and commercial ground robots. Current control mechanisms require the user to look at several screens of varying perspective on the robot, then give commands through a joystick-like mechanism. This control paradigm fails to provide the human operator with an intuitive state feedback, resulting in awkward and slow behavior and underutilization of the robot's physical capabilities. To overcome this bottleneck, we introduce a new human-machine interface that extends the operator's proprioception by exploiting sensory substitution. Humans have a proprioceptive sense that provides us information on how our bodies are configured in space without having to directly observe our appendages. We constructed a wearable device with vibrating actuators on the forearm, where frequency of vibration corresponds to the spatial configuration of a robotic arm. The goal of this interface is to provide a means to communicate proprioceptive information to the teleoperator. Ultimately we will measure the change in performance (time taken to complete the task) achieved by the use of this interface.

Keywords: haptic, sensory substitution, proprioception, human-machine interface, robotic control, human-computer interaction, funneling illusion

1. INTRODUCTION

This work describes the possibility of using the human proprioceptive sense to augment visual information during robotic teleoperation. Using the phenomenon of sensory substitution, the human's proprioceptive sphere can be expanded to develop an intuitive understanding of the state of the robot based on vibro-haptic feedback. The current state of the art in robotic control relies on visual information for teleoperated function. This control paradigm leads to underutilization of the machines, resulting in awkward and slow control. An absence of proprioception in the human body can provide useful analogs to robotic control without proprioception. Proprioceptive damage has been studied after strokes and in Parkinson's patients[1]. Stroke patients often have a difficult time describing the location and position of their limbs in space. Current teleoperated robotic control can be compared to a stroke patient's limb movement.

For specific cases such as bomb disposal robots, quick and fluid motion is critical for successful task completion, and could lead to human death if not performed in an optimal manner. In the case of a bomb disposal robot, various cameras provide partial information about the spatial state of the robot to an operator. These views encompass the joint positions and end effector positions. The operator then individually moves the joints to position the end effector in the desired space to complete the task[2]. This is a suboptimal solution as it requires the operator to process multiple visual signals during the control process. It also lacks depth information which is critical to properly move the end-effector. A more intuitive control paradigm would allow increased functionality from the systems.

The robotic systems currently available are capable of rapid, smooth motion in planned and repeatable situations. Welding, pick-and-place, and various other industrial operations consisting of a repeated sequence of planned motions are not an issue. These operations can be planned and taught to allow full use of the system. The issue of intuitive control arises during unplanned and unique situations such as bomb disposal, surgery, search and rescue, or military applications. A human operator is required to guide the robot during unplanned situations. Since the response time of a human operator to changes in visual information is on the order of hundreds of milliseconds this total delay compounds and causes significant slowdowns during operation[3]. This work shows the preliminary results of using vibro-haptic feedback to extend the operators proprioceptive sense to decrease the time required to complete a task.

Research has been done into extending human proprioception and other human senses via the phenomenon of sensory substitution. The human brain has proven to be a flexible organ able to accept non-standard sensory input and understand it as part of the body's standard senses[4–6]. Prior work has been done on using kinematic vibrotactile feedback to simulate and control a simulated prosthetic arm or hand with mixed success[7,8]. Instead of human arm simulations, our work focuses on extending human proprioception to non-anthropomorphic arm configurations to allow more extensible robot configurations.

In our work, we simulated a non-anthropomorphic robotic arm and provided limited visual information to the operator during the simulation. The operator was tasked with moving the end effector to a location within the arm's workspace to complete a task. During the operation, the user was provided with vibro-haptic feedback which encoded joint state information as a change in frequency of haptic actuators. The user was tested on their ability to assimilate the feedback into control information.

For our vibro-haptic feedback, we developed a wearable where each stream of data to be encoded, such as joint angle or velocity, requires one pair of tactors which are placed on an athletic compression sleeve on opposite sides of the arm horizontally. By using this method, the system is easy to expand to a variety of robotic systems. The operating principle of the sleeve utilizes tactile illusions which theoretically causes each pair of tactors to have high resolution for communicating data[9–12].

In this work, we first give background information in Section 2 on what psychophysical laws guided the design of our wearable, the different motor types we considered for the design, and what form the wearable would take based on the vibration sensitivity of the human body at different locations. Next, in Section 3, we present the robot simulation, vibro-haptic wearable, and experimental procedure that we developed. Finally, in Section 4 and Section 5, we respectively speak about the results of our experiment and what conclusions can be drawn from them.

2. BACKGROUND

In this section, we first explain different types of mechanoreceptors in detail, psychophysical laws regarding human perception of amplitude from tactile stimulations, and explain how these guided our design process. Next, we present two tactile illusions which can allow humans to perceive tactile stimulations with higher accuracy while using a smaller number of actuators than perceived. Afterwards, three different motor types are explored for usage in a vibro-haptic wearable. Finally, we explain how the location of a vibro-haptic wearable affects the accuracy of data which is perceived by the user.

2.1 Mechanoreceptors and psychophysical laws

The human body perceives vibrations above 10 Hz via three separate receptors: Pacinian Corpuscles (PC), Meissner Corpuscles (MC), and Hair Follicle Afferent (HFA) fibers[13]. Pacinian corpuscles dominate the human frequency response at high frequencies up to 1000 Hz, and peaks between approximately 200-350 Hz[13–17]. Other than hair cells in the cochlea, they have the smallest detection threshold of all mechanoreceptors. As a result of this low threshold, they have a broad receptive field and low spatial resolution (2 cm)[16,18]. PCs are concentrated in subcutaneous tissue around bones and joints. Meissner Corpuscles on the other hand dominate the frequency response between 10-50 Hz[16]. They have high spatial resolution (2-5 mm) but a small receptive field[18]. However, these mechanoreceptors are only located in glabrous (smooth and hairless) skin which only makes up a small part of our skin including palms, lips, and soles of feet. The sensor which handles low frequency response up to 80 Hz in hairy skin is the HFA fiber. Based on the results of Mahns et al[16], both detection thresholds and frequency discrimination are worse for HFAs than MCs by as much as a factor of 5 at their resonant frequencies. However, once the PCs start to dominate the response at higher frequencies the detection threshold and frequency discrimination of hairy skin improves by as much as 2.5 times compared to HFA[16]. Since the motors of the size and scale we are interested have an approximate bandwidth of 0 to 250 Hz, we are most interested in the response of the PCs since they dominate the response of the brain for much of the bandwidth.

In general, humans have a limit to what they can sense as an increase in amplitude from a previous sensation. This is called the just-noticeable difference (JND) and the physical measurement of increase is the difference-limen (DL)[19]. The main difference between the JND and DL is that the JND is a linear mapping of the DL. The JND tends to follow the Steven's Power-law, seen in Equation (1)

$$\varphi = k\phi^{a} \quad (1)$$

where φ is the linearized measure of the perception amplitude, ϕ is the stimulus amplitude, k is the log-y intercept of the function on a log-log scale, and a is a constant which changes for each sense. Steven's published values for the constant a for sensing the amplitude of both a 60 and 250 Hz vibration on the finger and found them to be 0.95 and 0.6, respectively[19]. At 250 Hz, since the PCs are dominating the amplitude response for both hairy and glabrous skin, this value should be applicable to hairy skin as well.

2.2 Utilizing tactile illusions

There are two main proprioceptive illusions which have been explored in the field of vibro-haptic HCI's: the funneling illusion and the cutaneous rabbit (or saltation) illusion. When short vibratory signals are applied at two or more locations on the skin, one perceives that the vibration actually occurred at a point somewhere between the real input locations. This is the funneling illusion. The cutaneous rabbit illusion can be thought of as a kinetic form of the funneling illusion. The setup is similar, except that the vibrations are only applied in short bursts at one location at a time. This imparts the sensation that the vibration is traveling between the two locations away from the location where the vibration was first applied[17]. Work has been done to study the brain while inducing tactile illusions. It was found that the brain perceived illusions as a memory and recognition task. This provides insight into potential limitations on the number of illusionary points which can be displayed due to limitations in working memory – the part of short-term memory concerned with immediate conscious perceptual processing[20]. Despite this potential issue, the advantages these illusions can provide in perceived resolution of an array of tactors outweigh the negatives.

The use of the funneling illusion for vibro-haptic interfaces has been explored extensively. In work by Barghout et al[10], they studied the ability of subjects to localize a virtual point on a 12x1 array using only a 4x1 array of cell phone vibrators with 80 mm spacing, located between the elbow and wrist. They ran this experiment for both static and moving points. The spacing was chosen because the ideal distance between tactors to induce the funneling illusion was found to be 40-80 mm[11]. Even though in other works the funneling illusion is said to only occur with stimuli length on the order of 5ms, the device in this work was turned on for 1s at a time. Regardless of this, the subjects were usually able to localize both moving and static points within 1 point of the true array value. The most accurate localization occurred near the ends of the array. This is thought to be for a variety of reasons. One is that there aren't as many possible locations at the end of the array. Another is that we have more mechanoreceptors near our joints than in the middle of our forearm. This work shows promise in using this technique to display higher resolution data than your individual tactors would allow[10].
Another study, by Borst et al[9], investigated the adaptation of graphics processing techniques for inciting the funneling illusion on the palm of the hand to display points along a virtual line on a 5x6 tactor array. In this study, they focused on controlling the intensity levels of each tactor in the array by adapting four rendering methods commonly used in graphics processing – two anti-aliasing and two bi-level. They found the best technique to be the Interpolated-Midpoint Method, where only one tactor per column could be activated, and the intensity of tactors was interpolated based on the ratio of distance between the two closest active tactors[9]. This method would be useful to implement if an array of tactors is desired for higher degree of freedom systems.

2.3 Motor considerations

Several types of motors have been considered for this research based on previous work in the field. The three main motors types of interest are Eccentric Rotating Mass (ERM), Linear Resonant Actuator (LRA), and Piezoelectric. Eccentric Rotating Mass motors are DC motors which have an off-center mass attached to their shaft. When the motor is powered, the mass pulls the motor around with it causing it to vibrate. ERM motors are very common in the cell phone industry for tactile feedback which makes them very cheap and readily available. In addition, they are easy to drive and the amplitude can be controlled by a PWM interface through a microcontroller[18]. ERM motors, which vibrate parallel to the skin, could be preferable to some other types because vibrations tend to propagate along the skin to remote mechanoreceptors worse with motors which vibrate perpendicular to the skin[21]. However, ERM motors have some disadvantages. One is that the amplitude and frequency are coupled, making it difficult to target a single type of mechanoreceptor which could be beneficial. Another is that they have very slow response times and can take on the order of a hundred ms to start and stop[18].

LRAs work by a principle similar to acoustic speakers. However, instead of the electromagnetic field controlling cone which pushes air, the field moves a mass which is attached to a spring. This mass-spring system has a natural frequency associated with it, usually on the order of 200-300 Hz for a cell phone style vibrator. One advantage to this system is the frequency and amplitude of vibration are uncoupled, allowing for the targeting of a single mechanoreceptor. Generally, LRA's vibrate perpendicular to the skin, but there are ones available which can vibrate parallel to the skin, similar to ERMs. This mitigates the potential disadvantage of propagating vibrations through the skin to remote mechanoreceptors[21]. Another advantage is that LRA's are much more efficient than ERMs and have low voltage and current requirements. LRA's are about as inexpensive as ERMs, since they are also used by the cell phone industry in the mainstream. However, one disadvantage is complexity[18]. LRA's must be controlled using a sine wave at the resonant frequency, therefore DC powered systems need to use special haptic IC's, such as the TI DRV2605L, to drive the LRAs.

The third motors of interest are piezoelectric. These work based on the piezoelectric effect, which is an electro-mechanical coupling some materials have such that when you apply a voltage to them they deflect, and vice versa. Piezoelectrics have a lot of interesting features. One is that they have an extremely high bandwidth, some with resonant frequencies around 8 kHz[18]. However, since the human body can only sense vibrations up to around 1 kHz, much of this bandwidth would be wasted[16]. They are low power and efficient, but require high voltages between 30-200 V. This makes them potentially dangerous to use around humans if not properly protected. Lastly, they require an AC input, are complex to drive, and are costly compared to other solutions[18].

2.4 Location for human computer interface (HCI)

There are many factors which must be considered when determining where to place a wearable human computer interface (HCI) on the skin. Some examples include: common acceptance within society as a location for hardware, sensitivity of the region, comfort of the area, and a place where you can easily adapt an interface to people with different body shapes. Research has been done on many different areas of the body, including the roof of the mouth, back, palm, soles of the feet, and others[4,5,22–24]. While many of these body parts are extremely sensitive, such as the glabrous skin on the palm, devices placed there could get in the way of normal usage of that body part. One area that is accessible and has been commonly used for hardware, such as smart watches, is the forearm. This is a convenient and socially acceptable place to put a vibro-haptic device. However, there are some potential issues with using it. Multiple studies have found that the forearm does not have the sensitivity needed for communication of complex information[14,22,23]. In a study by Cholewiak et al[23], they found that at a 2.5 cm spacing of a 7x1 array of tactors on the forearm, the subjects only correctly determined the location of the vibrating tactor 46% of the time. At 5 cm, this jumped to 66% of the time. However, near the joints, they found that the subjects had 80% localization. This makes sense as there is a concentration of Pacinian Corpuscles near joints[23]. Another important design consideration, found by Piateski and Jones[22], was that vibration patterns tend to be perceived better across the forearm than along it. They found that with a 3x3 array on the forearm displaying simple patterns, subjects correctly determined the pattern 96% of the time across the forearm, and only 80% of the time along it. They also used a back array with the same test and found that subjects had perfect localization scores, with which they concluded that the forearm is a poor spot for a vibro-haptic array[22]. Even though the forearm has low resolution, this can be turned to an advantage. Areas on the body with low spatial resolution are more susceptible to tactile illusions which, as explained previously, can be used to increase the perceived resolution of a small tactor array.

3. PROCEDURE

It was postulated that if vibrations encoding robotic joint state were presented to a human operator, the human sensory substitution for the proprioceptive sense would manifest itself providing the human with a more intuitive understanding of the robot. This would result in quicker, more intuitive control of a cyber-physical system. This experiment was designed to test this idea by determining if the use of a vibro-haptic wearable device would improve tele-operated robotic performance of a designated task. To test the efficacy of the vibro-haptic wearable to extend the subject's proprioception, we developed a simulated robotic arm for the user to operate while wearing the device and tested the time taken to complete a search activity in a simulated space after training designed to encourage sensory substitution

The robot (see Figure 1) was simulated and controlled using Robot Operating System, the Gazebo simulation tool, and Pygame (a 2D game development module for Python). The simulated robot consisted of three links with four degrees of freedom. The base joint allowed Z and X rotation, while the remaining joints were constrained to X rotation. We constrained the workspace to a positive Z axis to allow a single hemisphere of potential motion. Figure 1 shows a model of the simulated robot with applied degrees of freedom. The positive Z limit resembles the constraints of potential real-world applications. No rotation limit constraints were placed on the joints (allowing +360 degree rotation) except for the positive Z requirement.

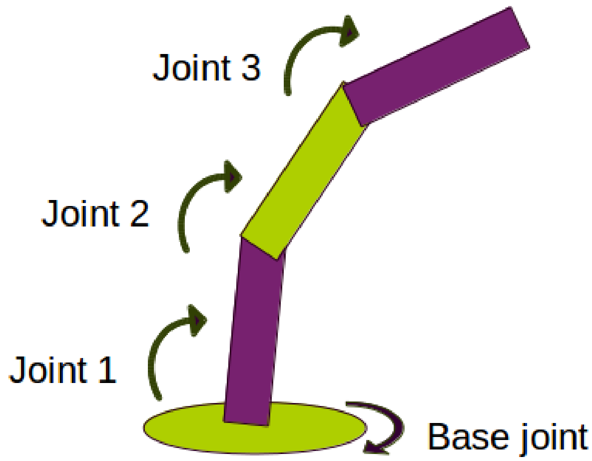


Figure 1. Model of the simulated robot

Each degree of freedom on the robot was represented by a pair of vibrating actuators placed on the subjects forearm and separated by two inches. We chose this placement so that we could utilize the funneling illusion to relay joint information during operation as presented in Section 2.2. Each side of a pair would pulse at different relative intensities, creating an illusion of vibration at a point along the chord between the two actuators. The position of the illusory point corresponded to joint rotation angle. Figure 2 shows the physical sleeve worn during the test with the virtual points illustrated. The pairs of vibrators were used in a cascade manner to avoid overwhelming the subject with vibration information. In the cascade manner, the actuator pairs were pulsed in sequence (pair A, then pair B, etc.) to reduce sensory overload. If all four pairs are pulsed in parallel the operator's ability to discriminate the sensory input is reduced.

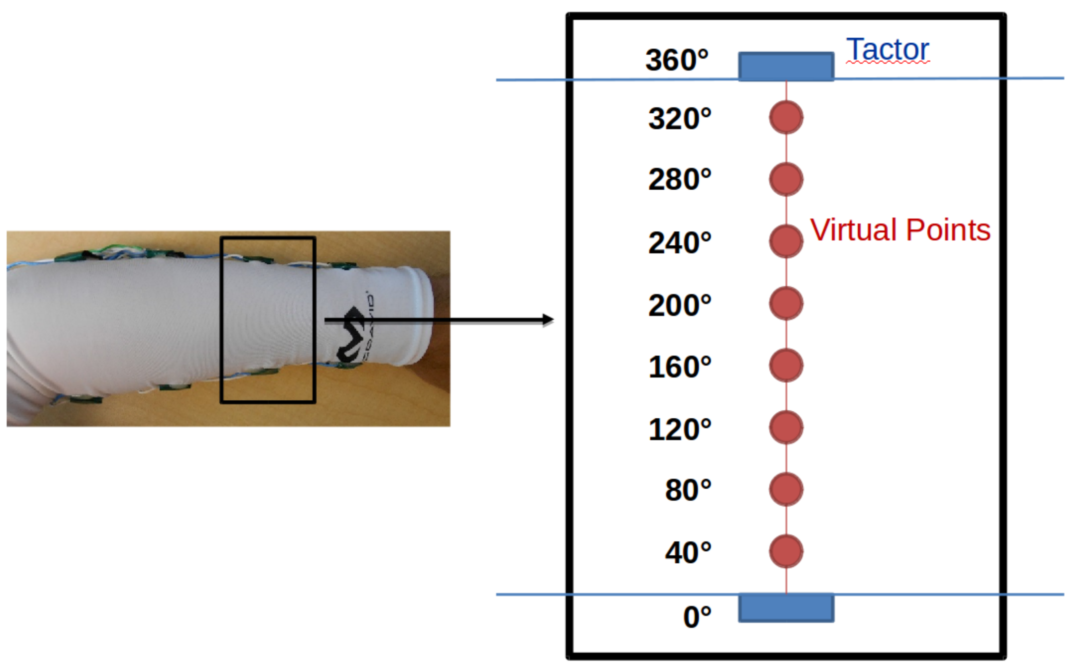


Figure 2. Sleeve worn during the test and virtual points created using a funneling illusion

During the experiment, the subject wore the vibro-haptic sleeve and operated the simulated robot using four rotational knobs Powermate ® USB manufactured by Griffin Technology, Nashville TN. Each knob in Figure 3 corresponded to a degree of freedom present on the simulated robot. Like the simulated rotational joints, the knobs had no rotational limits during use. In the case of the base joint, if the user over-spun the knob the arm would hit the ground and stay there. In the case of the other joints, the arm would simply wrap around with no constraints.

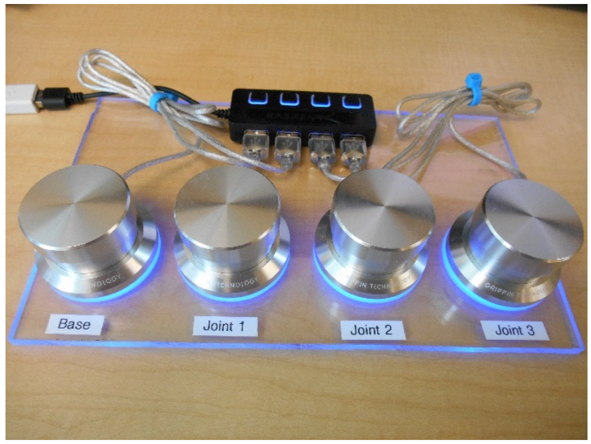
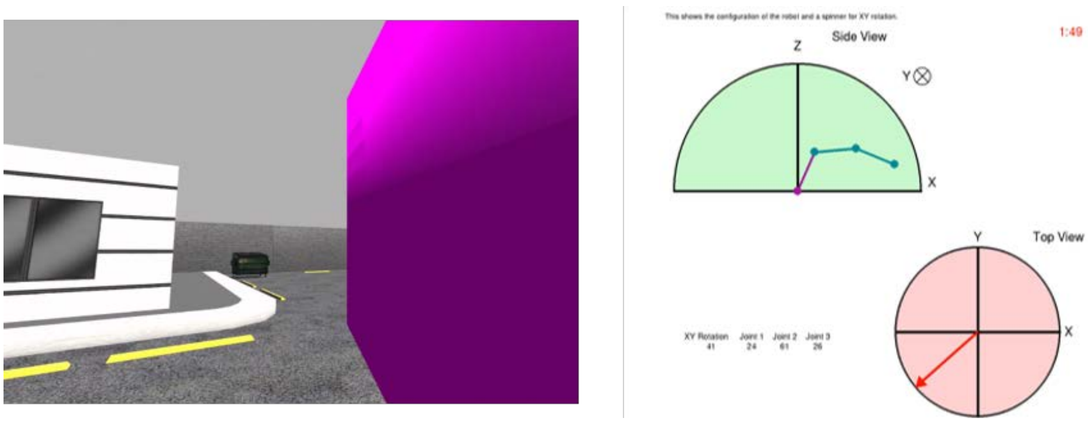


Figure 3. Knobs used to control the simulation

During the experiment the subject had access to two possible views. Shown in Figure 4-a, the first view was a camera, *camera view*, mounted 10 cm from the end of the end effector of the robot showing the simulated world. Figure 4-b shows the second possible view, *robot configuration view*, which allowed the user to quickly see the configuration of the robotic limbs as well as the numeric joint values. Two monitors were provided with one view on each screen, but during the actual testing phase the subject was only able to view one view at a time with the other going black. They could switch between the *camera view* and the *robot configuration view* by pushing down on the Powermate ® control knobs. This limitation on visual information was designed to allow the subject to rely on the information from the wearable device.



(a) (b)

Figure 4. Camera mounted close to the end effector (a) and robot configuration view (b)

The experiment was conducted at the Bradbury Science Museum in Los Alamos, New Mexico, with subjects volunteering from the visitors at the museum. Each trail was twenty minutes long and consisted of two training and two testing modules. In the first training module, passive training, the subject wore the sleeve and the simulation ran through a preconfigured routine with each joint rotating through its full range of motion in a clockwise and counterclockwise direction to acclimate the user to the system. The operator watched both views while feeling the vibrations on their arm. The next stage was five minutes of active training where the operator was allowed to control the simulated arm using the knobs and was restricted to only one view at a time. After the training phase, the subject started the testing phase and was given the task of moving the arm to a specific target location (a neon green cube) in space. Upon completion of the task, the screen would flash a success message and the subject would press space to end that test. Due to the somewhat imprecise movements of the simulated arm, the success message reduced uncertainty for the subject about the required location of end effector in the experiment.

In the testing phase, the subject was randomly assigned two locations (from three possible locations A,B,C). For the first location the initial stimulus was randomized between haptic or non-haptic, but for the second location we ensured it would be the reverse of the first. We did this to reduce effects of learning the game as time passed and improving performance from practice. We also alternated between locations to reduce short-term memory of target location. An example testing module would be Location 1 Non-Haptic, Location 2 Haptic, Location 1 Haptic, and Location 2 Non-Haptic.

4. ANALYSIS

Performance was determined by time taken to achieve the task without the haptic feedback less time taken with the haptic feedback. This metric indicated whether the vibro-haptic device would significantly decrease time taken to complete a task, in this case capturing a target. A second performance metric was number of times the user had to switch screens and change visual information input. The rationale was that with the vibro-haptic device, the user wouldn't have to switch as often and would therefore save time.

These two performance metrics were plotted as a histogram, and a normal probability distribution was calculated from the data. We decided not to use data points where the subject failed both the non-haptic and haptic version of the mission. We made this choice because their failure represented a fundamental issue with the subject, misunderstanding of the task, or some other external factor and didn't reflect on the performance of the vibro-haptic device. We decided to use data points where the subject failed either the non-haptic or haptic version but not both, since this could potentially reflect on performance of the device.

A preliminary experiment was conducted on 16 human subjects from a volunteer population consisting of visitors to the Bradbury Science Museum in Los Alamos, NM. As you can see in Figure 5 and Figure 6, we achieved a slight positive mean in our performance metric. This would imply that the haptic interface is on average slightly reducing performance. However, these histograms are interesting in that the variance is very high. It appears that there might be persons and testing scenarios for which the haptic device is a great help, and other persons/testing scenarios for which the haptic device greatly hinders performance. In general for this preliminary test the haptic interface seems to have marginal effect. Based on our experience with the preliminary testing we think it may be worthwhile to conduct future tests on more homogenous, targeted population. For instance, in this test persons of all ages were invited to take part. However, age is going to have an effect on the proprioceptive sense as well as reaction time. It may be possible to try and control for these effects in the analysis, but from a statistical power point of view, limited resources are available for testing participants and we may be able to better discern the effect we are looking for with a more homogenous population. In the future we might target the test to persons who are likely to use the proprioceptive interface in their daily lives (*e.g.* robot operators). We think it would also be advantageous to recruit a population with similar levels of familiarity with computers/video games.

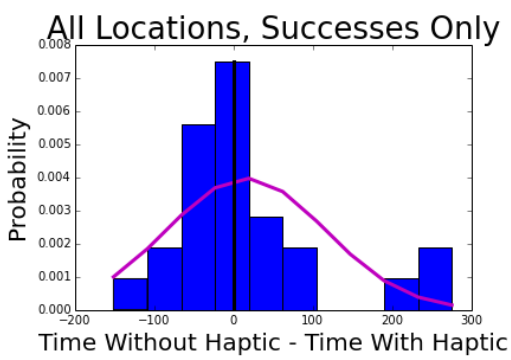


Figure 5. Histogram of the difference in time taken to successfully complete the task with and without the haptic interface. μ: 15.68, σ: 100.27

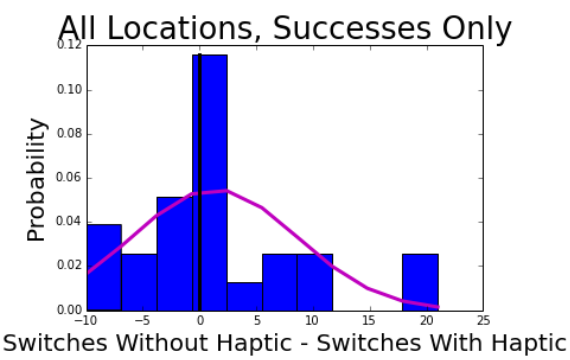


Figure 6. Histogram of the number of the difference in the number of screen switches with and without the haptic interface. μ: 1.16, σ: 9.34

After completing the preliminary experiment, we began to realize that one problem with our current task and test methodology is that it is really a combination of a search task and a proprioceptive task. We believe we can modify the test so it primarily focuses on proprioception. One possible way to do this is to adopt the Standard Test Methods For Response Robots, developed by NIST[25]. The "Manipulator Dexterity" tasks seem particularly suitable for testing proprioceptive performance. Especially the Inspection (Balloting) test and the possibly the Retrieving/Inserting Objects test. The tests could be modified so that there is almost no search aspect to the task at all.

It is also worth noting that in this preliminary test the subjects only used the device once. It would be preferable to be able to track a subjects ability to use the device in many sessions spread out over the course of months. Another issue with the preliminary test methodology is it is hard to tell whether or not a specific subjects change in performance in the task is due to the haptic interface, or the test subject simply getting more used to the task. We have come up with the following scheme to try and address this issue (see Figure 7). In future tests, instead of giving each subject a fixed number of training scenarios, each human subject will repeatedly be given new training scenarios until the change in their performance is seen to plateau. It is expected that any given subject will perform relatively poorly at the task at first, but with practice they will quickly improve. After some number of trials their performance will pretty much reach a plateau. This plateau level of performance will be considered the baseline performance for that subject. At this point the haptic interface will be introduced and the performance with the haptic interface will be measured. The human subject will repeatedly be exposed to trials until their performance is found to once again plateau. This plateau can be referred to as the "haptic baseline." The haptic baseline can then be compared to the original baseline for that person in order to assess the change in performance caused by the haptic interface. It should be noted, each human subject should probably be exposed to a certain minimum number of scenarios using the haptic interface, in the event that it takes some minimal number of scenarios before a person begins benefiting from the interface. This alternative testing methodology is expected to be better normalized for each participant. Figure 7 provides a graphical representation of how we think performance would progress as the number of trials increases.

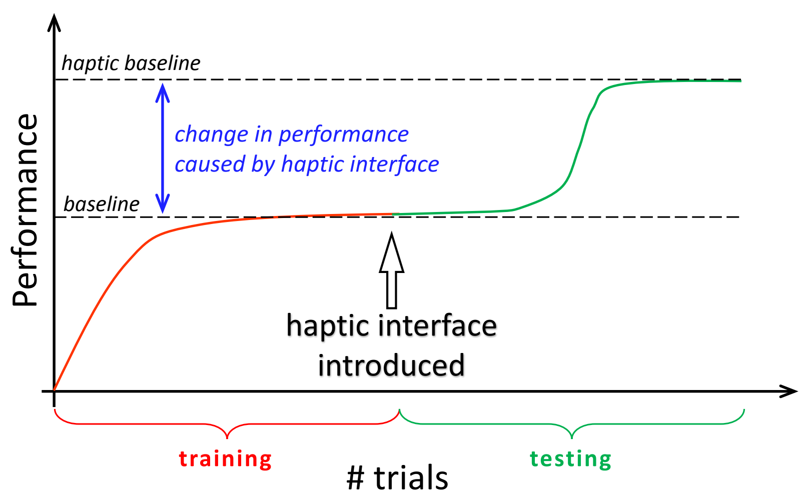


Figure 7. Expected progression of performance of a subject when using the plateau-based testing methodology. This methodology may help isolate the effect the haptic interface has on the overall change in performance.

Finally, in future testing we plan to record all movements executed by each subject in order to perform more detailed analysis of what each human subject is doing. We expect that collecting this data will not only result in more finely refined analysis of the proprioceptive device in question, but will also provide insight into human-robot interactions, as well as suggest new lines of research for novel human-machine interfaces and strategies for human-machine teaming.

5. CONCLUSIONS

In this work we developed a prototype human-machine interface to extend the proprioceptive sense of a cyber-physical system such as a robot to a human's nervous system. The prototype coupled with some preliminary testing has provided a solid platform to further iterate on. The simulated robot and software setup provides an excellent base to expand upon in order to improve the test methodology. Our improvements will be focused on the hardware components as well as the test methodology. With regards to the hardware we plan to improve on the response time of the vibrators to provide the subject with a cleaner sensory input. The slow response time of the Eccentric Rotating Mass did not provide sufficient resolution for the successful use of the funneling illusion on the test subjects. Further work along these lines would require the use of Linear Resonant Actuators or piezoelectric motors which would provide a quicker response time to aid the funneling illusion. We believe the test methodology can be improved in a couple of ways. First, we suspect increased testing time would improve performance. Second, an improved testing procedure would involve training a given subject until their performance reaches a plateau and using the plateau performance as a baseline. Then the haptic interface could be introduced and the human subject would be tested until their performance one again plateaus. The difference in the performance plateaus would be better representative of the effect the haptic interface has on the human subject's performance. Third, the testing task should be modified to remove as much need to "search" the space as possible. We believe this is possible by adopting/modifying some of the Standard Test Methods For Response Robots, developed by NIST[25]. This work represents the first foray into the possibility of extending human proprioception to cyber-physical systems.

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