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Improving Depth Perception in 3D Environments Using Funneling Illusion

by

Ahmad Ali Barghout

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Abstract

A key challenge facing 3D interface designers, and operators who teleoperate remote environments is to develop effective techniques to depict objects in 3D space on a 2-dimensional physical medium; a flat computer screen. Spatial relationships among objects, their sizes and locations are of high importance for users in order to be able to locate and manipulate these objects. In particular, depth perception (z dimension) is a main challenge for researchers who have designed many depth cues in order to overcome it. The main trend of providing depth perception is stereoscopy; other approaches utilize shading and shadow, motion, reference frames, size, perspective and others. These visual cues, including stereoscopy, have certain limitations. In this work, we propose to exploit human sensory modality for perceiving depth in teleoperated 3D environments where complex visual information - which may distract the operator - is presented. We exploit the funneling illusion phenomenon to provide a high resolution tactile depth display on the forearm. It utilizes stimulus location perception rather than stimulus intensity perception. One psychophysical experiment is conducted to study the resolution of the funneling illusion method on the forearm, and another experiment to evaluate its performance in a Telepresence and teleaction (TPTA) system scenario where a fragile dangerous object is being manipulated. Experiments show that our approach can replace the visual feedback methods and outperforms the stimulus intensity perception method.

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"Read: And thy Lord is the Most Bounteous. Who teacheth by the pen. Teacheth man that which he knew not."

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Lastly, and most importantly, I wish to thank my parents for everything, for raising me, supporting me, teaching me and loving me. To them I dedicate this thesis.

Ahmad Barghout

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Chapter 1

Introduction

1.1 Background and Motivation

Telepresence and teleaction (TPTA) systems immerse a human user into a remote or inaccessible environment by connecting to a remote teleoperator over a communication link. They provide powerful solutions for a wide field of application scenarios from micro assembly to safety critical applications, minimally invasive surgery all the way to military applications such as disarming of explosives [28]. Typical TPTA systems consist of a human-system-interface (HSI) device and a teleoperator (TOP). The HSI allows a human operator (OP) to remotely control a teleoperator, which is a robot equipped with multimodal sensors and actuators.

To enable a realistic immersion into the distant environment, the HSI presents visual, auditory and haptic information to the human OP which is received from the remote environment. Therefore, the performance of TPTA systems strongly depends on the multimodal stimuli recorded by the TOP and presented to the OP.

In many telepresence application scenarios such as defusing of mines, dealing with dangerous materials or touching fragile objects, careful navigation and precise movements of the remote TOP within the remote teleoperator environment are of upmost importance. Especially, precise spatial perception within the remote environment often becomes a critical factor and determines the performance of TPTA systems.

A main obstacle for providing a realistic and accurate perception of the remote environment is the depth information display. The better this information is presented, the better the performance will be.

In a real 3D environment, humans use their senses, such as vision, audition, and touch, to interact with surrounding environments. A coherent percept is formed by the convergence of information derived from these various senses. In general, the information provided by the sensory organs is overlapped and redundant but it makes it easier for the brain to perceive the environment. For visual modality, in particular, perspective distortions, shading, motion parallax, or the disparity between the two eyes' images are partly redundant signals which aid the brain to perceive the 3D layout of the visual scene [18]. However, when a 3D environment is to be projected on a 2D physical medium (screen), such as in a teleoperation task, these cues are not always present, and thus 3D perception becomes more complex. On a 2D screen, x and y dimensions are simply scaled from the real environment, but z dimension is not appropriately portrayed in the scene. Providing cues for depth perception, in this situation, has been a target for many researchers for the recent few decades.

The main trend in enabling 3D visual perception is the use of stereoscopy [30, 38]. However, stereoscopic displays are known to require a high bandwidth for a double video stream which is not always possible, in addition to having several limitations affecting the visual spatial depth perception, such as image disparity [20], distance compression [27, 35, 56], inappropriate focus cues, inappropriate motion parallax [30], spatial errors [51] as well as perceptual overloading of visual information [2]. Moreover, when the stereoscopic view needs to be streamed through network, for example, in a teleoperation system, it requires a high bandwidth due to sending two video streams. Therefore, the video quality needs to be degraded for stable transmitting, which degrades the quality of depth perception and even annoys users. All these effects degrade the quality of the stereoscopic visual feedback and provide a motivation for finding other methods to overcome them.

The alternative to stereoscopy for displaying depth of a target is to use additional visual gadgets like a progress bar, or something like the car speed gauge, or simply a digital display of the value of this distance. However, in certain circumstances (like driving a car) or tasks (like a teleoperation task for defusing bombs), overloading the visual modality is not favorable and may cause distraction of the operator and consequently have dangerous side effects. This is especially correct when the visual scene is already complex and the operator has to pay attention to many things at the same time. Consider a simple scenario of driving a car. It is necessary for a driver to have an estimate, or a "feeling", of the distances of the surrounding vehicles. Basically, a driver focuses on the vehicles in front of him/her in order to avoid colliding with them. Concurrently, a driver should have cognition of the moving speed of the car for the same purpose. Now although this information (speed) is important and is presented precisely through the speed gauge, how frequently a driver looks at it? This rarely happens while driving. The reason goes back to the fact of focusing on the main task (driving) and identifying the surrounding environment. Looking at the speed gauge may distract the driver from the main task, and even cause accidents. In this scenario, the visual modality is overwhelmed with the main scene and the speed information - although important - will overburden this modality especially that the placement of the gauge does not lie in the field of view of the driver. This situation becomes more difficult and more relevant to our work if the driver is not actually in the real environment. In the real environment, the driver's brain can reconstruct the 3D scene through the different modalities and the redundant signals passed through them seamlessly. Nonetheless, if this scene is presented on a 2D screen, it would be of high importance to have cues and measurements of speed, distance to other vehicles, etc...

Similarly, in TPTA systems, a remote environment might be monitored and the scene is displayed to the operator on a screen. Consider a landmine disarming task performed through a teleoperator. This is a dangerous task that requires high accuracy and full attention of the operator. Depth information is critical for navigating the environment without hitting the bomb strongly. Although it can be presented through stereoscopy, as mentioned before it has limitations, not always feasible and may distract the operator from the main task. Some might question that it might be appropriate to present this information simply through the audio modality, but audio is also usually engaged in the act of perceiving the surrounding environment.

On the other hand, the evolution of haptics, especially integration of vibrotactile feedback for multimodal information display, has been shown to contribute to a variety of applications [17, 16, 23]. Haptic feedback has been used to convey information in several applications utilizing the touch modality and thus increasing the bandwidth of information transfer to the users of these applications. Tactile haptics, specifically, has been used both as an independent and assistive modality according to the type of application. From an earlier stage, researchers have attempted to replace vision systems for blind people with tactile system to provide verbal information or situational information [46]. Recently, tactile cues were utilized for presenting extra information such as directional cues in a car [41], and even to convey touch sensation in remote interpersonal communication [12]. In telemanipulation related applications, Murray et al. [39] used tactile stimulation to display the quantity of grabbing force in teleoperation in order to substitute for force feedback. Cockburn et al. [14] proposed multimodal feedback to assist targeting of small graphical user interface components, and most interestingly, a first approach on improving depth perception by using vibrotactile feedback is proposed in [50] in which they use a binary vibrotactile stimulus to alarm the user of approaching a target object. Hence, there is a notably growing trend of multimodal human-computer interfaces in which human body surface is considered as an additional means of presenting information.

In line with the progress in the haptics field and in favor of overcoming the previously mentioned problems of stereoscopy, our proposal is to provide a high resolution tactile feedback method to present depth information. This proposal has been shown to be more effective in TPTA scenarios that need careful manipulation of a remote target. The main trend of using tactile modality for displaying physical quantities is to change the intensity of vibration in relation to the displayed quantity. Our proposal is different from this approach in the display method. Instead of using the stimulus intensity as the indicator of the displayed value, it uses the stimulus location. The stimulus is moved on the forearm of the operator indicating the distance to a target object in the z-direction. The vibrotactile stimulus is created by the funneling illusion and is moved by controlling the engaged vibrators in a way that creates an apparent movement on the human skin. We developed a tactile device, based on the work of a Master's thesis done in the University of Ottawa, to serve the purpose of creating the moving stimulus. To prove the efficiency of our method, we conducted two psychophysical experiments. First, we test the resolution of the stimulus location method in providing distinct positions on the forearm. The results show that this method has a higher resolution than stimulus intensity. Next, we develop a virtual environment to simulate a teleoperation task in which we test the validity of our method to replace the visual feedback. We compare our method to a simple visual feedback method (progress bar) and stimulus intensity method. The results show that our method outperforms the stimulus intensity method, and is able to replace visual display as the visual scene becomes more complex.

1.2 Objective and Contribution

The previously mentioned depth perception problem in 3D environments exerts an increasing demand for proper solutions. The limitations of current solutions, the distraction and overwhelming of visual modality, and the engagment of the audio modality in perceiving the environment, all pushed towards a haptics oriented solution. Hence, the objectives of this research can be summarized by the following:

- To provide depth information tactually by a high resolution funneling illusion method applied to the forearm of a human operator
- To reduce overloading the visual modality of the operator

Fulfilling these objectives results in:

- Overcoming the limitations of stereoscopy for depth perception
- The ability to operate a telemanipulator with a relatively low bandwidth (monoscopy)
- The increase of information transfer bandwidth by utilizing the haptic modality for displaying depth information

Therefore, the contributions of this thesis as a whole can be summarized by the following:

- Verifying the possibility of using funneling illusion to present a high resolution display of a physical quantity
- Experimentally studying the resolution of this method in providing distinctly perceived stimulus locations on the forearm
- Applying this method to a TPTA system and evaluating its performance experimentally by comparing it to visual and tactile intensity methods
- Improving spatial perception for TPTA systems using this method

1.3 Publications Resulting From This Research

The product of the research done in this thesis is the following list of papers.

1. Jongeun Cha, Ahmad Barghout, Julius Kammerl, Eckehard Steinback and Abdulmotaleb El Saddik, "Improving Spatial Perception in Telepresence and Teleaction Systems by Displaying Distance Information through Visual and Vibrotactile Feedback". This paper is submitted to Presence Journal.
2. Ahmad Barghout, Julius Kammerl, Jongeun Cha, Eckehard Steinbach and Abdulmotaleb El Saddik, "Spatial Resolution of Vibrotactile Perception on the Human Forearm when exploiting Funneling Illusion". This paper is accepted in HAVE 2009 conference.

1.4 Thesis Organization

The remainder of the thesis is structured as follows:

Chapter 2 presents an overview of background literature and related works. Background study on visual cues for depth perception, stereoscopy and its limitations, tactile feedback applications in assisting other modalities and tactile interfaces importance is presented. Then, a few related works are discussed highlighting their common aspects and differences from this work.

Chapter 3 presents the proposed method for depth display with a description of the incorporated phenomena and elaborates on the system design and implementation. The used system is a tactile device based on a Master's thesis in the University of Ottawa for optimizing the continuous feeling obtained via funneling illusion.

Chapter 4 covers the evaluation of the proposed method by two psychophysical experiments: one for studying the resolution of the method and another for evaluating its performance in a real application (TPTA application).

Chapter 5 summarizes this work and provides a view of potential future work.

Chapter 2

Background and Related Work

2.1 Background

Chapter 1 has introduced the problem statement and major contributions in this thesis, in addition to a brief description of the thesis contents. This chapter (Chapter 2) lays the foundation knowledge about the various techniques used for depth perception in 3D environments, in addition to the applications of tactile interfaces in aiding other modalities. Furthermore, we present an overview and a discussion of the related work and finally conclude the chapter by highlighting the distinguished features in our proposed method.

2.1.1 Depth Perception in 3D environments

The exponential increase in the computation power of computers and modern workstations has enabled the proliferation of three dimensional interfaces for a wide spectrum of application domains including entertainment and gaming, education and training, data visualization, tele-operation, among others [48]. However, one of the key challenges in 3D-based interface development is the ability to present a 3D object in a 2D display (a flat computer screen). That is, the ability of users to depict spatial relationships among objects in 3D space with respect to the depth dimensions (so called depth perception).

Depth perception is defined as the ability of humans to perceive the world in three dimensions. Depth perception arises from a variety of depth cues that are traditionally acquired visually. In real environments, depth cues such as perspective, size difference, occlusion, shadow, accommodation, convergence and disparity, provide higher comprehension of the environment which results in a significant increase in the quality of performance [30]. Visual depth cues can be classified into either monocular (requires input from one eye) or binocular (cues that require input from both eyes) [24].

Monocular cues

Monocular cues provide depth information when viewing a scene with one eye. A brief explanation of these cues is presented below based on [1, 40, 21, 57]:

- Motion parallax: When an observer moves, the apparent relative motion of several stationary objects against a background gives hints about their relative distance. Motion parallax can provide absolute depth information if information about the direction and velocity of movement is known.
- Depth from motion: The dynamic change of object size during motion provides a kinetic depth perception which is one form of depth from motion cues. As objects in motion become smaller, they appear to recede into the distance or move farther away; objects in motion that appear to be getting larger seem to be coming closer.
- Perspective: The convergence of parallel lines at infinity allows us to reconstruct the relative distance of two parts of an object, or of landscape features.
- Relative size: Relative size cues can provide information about the relative depth of two objects when they have unkown absolute, but same size.
- Familiar size: The relative apparent sizes of known objects provide a depth scale for these objects, and vice versa.
- Vertical position in field: More distant objects seem to be higher in the field of view if they are below the horizon, and lower if they are above the horizon
- Aerial perspective: Due to atmospheric attenuation and scattering by dust, distant objects are bluer and less sharp than nearby objects.
- Accommodation: This is an oculomotor cue for depth perception. When we try to focus on far away objects, the ciliary muscles stretche the eye lens, making it thinner. The kinesthetic sensations of the contracting and relaxing ciliary muscles (intraocular muscles) is sent to the visual cortex where it is used for interpreting depth.

- Interposition and partial occlusion: Blocking the sight of objects by other objects is also a clue which provides information about relative distance. It allows to create a "ranking" of relative nearness.
- Texture gradient: While standing on a gravel road, the nearby gravel can be clearly seen in terms of shape, size and colour. As vision shifts towards the distant road the texture cannot be clearly differentiated.

Binocular cues

Binocular cues provide depth information when viewing a scene with both eyes. These cues include stereopsis and convergence:

- Stereopsis (or binocular) disparity: Information derived from the different projections of objects onto each retina can be used to judge depth. By using two images of the same scene obtained from slightly different angles, it is possible to triangulate the distance to an object with a high degree of accuracy. If an object is far away, the disparity of that image falling on both retinas will be small. If the object is close or near, the disparity will be large.
- Convergence: is a binocular oculomotor cue for distance/depth perception. Convergence happens when the two eye balls focus on the same object by virtue of stereopsis. The convergence will stretch the extraocular muscles and kinesthetic sensations from these extraocular muscles help in depth/distance perception. The angle of convergence is smaller when the eye is focusing on far objects.

Most of these various cues are relative (they tell which objects are closer relative to others). Only convergence, focus and familiar size provide absolute distance information. However, the most binocular depth perception technology that have gained significant interest in both research and industry is stereoscopy.

Stereoscopy, first invented by Charles Wheatstone in 1840 [55], is a technique capable of providing visually the illusion of depth in 3D interfaces. The basic idea supporting stereoscopic visualization is to provide the eyes of the viewer with two different images, representing two slightly different perspectives of the same object, similar to the perspectives that both eyes naturally receive in binocular vision. Several researchers have been investigating the use of stereoscopy for depth perception in 3D environments.

For example, the research in [26] demonstrated that stereo viewing is more powerful than the use of object shadows in providing depth cues about the relative size and position of objects in space. Another interesting conclusion indicated that stereoscopic viewing was a dominant depth cue; stereoscopic viewing was superior to monoscopic viewing, and to any shadow condition, for enhancing positioning and resizing accuracy and response times.

The authors in [30] investigated the use of stereoscopic visualization in applications related to Tele-guided robots using both synthetic and real images. The user's ability to estimate egocentric distance and self-motion is been tested under both static (computer controlled motion) and dynamic conditions (user controlled motion). The authors found that stereoscopic viewing improves performance under static conditions, while it did not show significant improvements under dynamic conditions. Ferre and colleagues studied stereoscopic image visualization for Tele-operated robots in [20].

The authors in [2] performed experiments to determine the effect of different types of rendering on visual performance, the upper and lower display bounds and after-effects for activities on a stereoscopic workbench display. The results showed that stereoscopy has improved the perceivable distance whereas map texture has reduced depth perception.

Even with all the widespread use and applicability of stereoscopy-based depth visualization, there exist several challenges that limit the use of stereoscopy for depth perception. First of all, stereoscopy stereoscopic depth cues do not define the depth of large, homogeneous, horizontal objects. The variance of operator's depth estimates for the same target increases as the orientation of the target's major edge is rotated from a vertical position to a horizontal position. Secondly, as reported in [18], these digital displays could create visual cues that distort depth perception such as inappropriate focus cues, pixelization and inappropriate motion parallax during head movement. Thirdly, as reported by many researchers [35, 57, 58], distances are perceived to be compressed when comparing distance perception in real world to distance perception in immersive virtual environments . Fourthly, the visual modality might become saturated by providing too much visual cues and deficits in depth perception can be attributed to the overload of visual information [30]. Additionally, in teleoperation tasks stereoscopy requires a high bandwidth for transmitting two video streams over the network which makes it not always feasible like in wireless networks. Instead, we can use tactile feedback that decreases the confusion caused by the overwhelming visual feedback and hence avoid these limitations.

2.1.2 Information Transfer Through Tactile Feedback

The term haptics, originating from the Greek language, refers to the science of sensing and manipulation through the sense of touch. In recent years, the term has been associated mostly with technology that interfaces users to various computing devices through tactile and force feedback. Such haptic interfaces give users the ability to sense and manipulate virtual environments or remote real environments through touch [16]. Our focus in this thesis is on the tactile part of haptics where tactile displays range from a single vibrating element (like those in mobile phones) to matrices of elements covering the torso of a pilot, soldier, driver or other operator.

General Applications

In [45], an oral tactile interface capable of two-way communication is presented. The prototype is implemented as a mouthpiece with an oral tactile display for receiving messages and a tongue touch keypad for sending out controls and commands. Psychological experiments indicate that identification on left or right moving patterns is highly accurate while errors on forward or backward moving patterns vary considerably among subjects.

In a similar work, an oral tactile interface was designed and evaluated to provide directional cues, through the tactile feedback, for a blind traveler to obtain directional guidance in outdoor navigation [46]. Directional cues were presented to the user in the form of a line or arrow with four moving directions (leftward, rightward, forward, and backward). Experimental results showed identification of leftward or rightward movements was highly accurate while performance on forward or backward moving patterns was mixed and varied considerably from subject to subject.

The authors in [41] investigated the use of valuable source of information available in the auditory, tactile and visual feedback modes and its importance for new vehicle control systems such as Intelligent Cruise Control. In particular, providing tactile feedback is shown to be valuable and underused mode of driver feedback that could help to solve the problem of too much information being on a display, in addition to the problem of distraction when the driver takes his eyes off the road for a while.

Another application for tactile feedback is the use of vibration devices to build rhythm instruction tool for school children, named T-RHYTHM [36]. The tactile stimuli are synchronized with the music. The preliminary evaluation of the procedure indicated that T-RHYTHM could effectively support children's ensemble performances and therefore could be a useful rhythm instruction tool.

When is the use of tactile displays necessary?

The use of tactile interfaces in a number of dangerous tasks is highly demanded. Specifically in the military field, various challenging situations such as those encountered by military pilots are often a major thrust for the development of advanced multimodal and intuitive interface techniques to counteract the danger of visual, auditory, and cognitive overload. Tactile interfaces are usually used for this purpose. Examples of these tactile interfaces are the TNO Tactile Torso Display (TTTD) shown in Figure 2.1 and the Naval Aeromedical Research Laboratory Tactile Situation Awareness System (TSAS), which both provide three-dimensional spatial information [49].

Figure 2.1: A helicopter pilot showing a TTTD consisting of a matrix of vibrating elements covering the torso.

The NATO technical report [8] held in 2002 concludes that "The most important advance of recent years with the potential to combat spatial disorientation has been the use of tactile stimuli to give information on spatial orientation". The urgent need for tactile displays in this field arises mainly for fulfilling two objectives: providing spatial disorientation countermeasures and counteracting the threat of sensory and cognitive overload. Although visual displays are usually easy to comprehend, the development of computer driven displays provides the opportunity to provide a vast quantity of information that can overload the individual's capacity to process the information provided. This fact pushes human-machine interfaces designers to increasingly apply multimodal interfaces. Traditionally, the auditory channel is considered as an alternative or supplement to visual displays. Examples include the presentation of route navigation [44] and tracking error information [22]. However, there are situations in which the visual and auditory channels of an operator are both heavily loaded or in which the visual and/or auditory information is degraded or not available. These situations, as listed in [49], include:

- Operators in complex environments who work at the limits of their visual and auditory processing capacity, such as pilots [43].
- Operators whose visual or auditory attention is preferably focused on a specific area of interest, such as car drivers who need to concentrate on the road [19], and dismounted soldiers who want to focus on the environment and possible threats.
- Operators who work in a visually or auditorily deprived environment, such as remote operators [33], virtual environment users, divers in dark waters, and drivers of fast boats.
- Operators who work under conditions that require minimization of the transmission of light or sound, as during night or covert operations.

In these situations, it may be beneficial to employ a tactile display.

In addition to sensory overload, cognitive overload of an operator is another incentive for tactile displays. Navigation information in cars, for instance, may result in an over demand of the (momentarily available) cognitive capacities of the driver. The drivers' scanning behaviour and attention maybe negatively influenced by the crowdness of visual in-vehicle information systems, which means distraction of the driver. "There is a general belief that driver overload and distraction resulting from the actions of in-vehicle support systems can form a threat to the positive effects expected from these systems" [49]. Visual displays in cockpits is a good example of this overloading. Presenting three dimensional (3D) navigation information using these displays has a certain disadvantage because the displays are flat (2D). Presenting 3D information on a 2D display means that one (or more) dimension(s) must be compressed. This results in loss of information and usually requires a cognitive component to reconstruct the 3D picture from the 2D display. This is exactly what happens when depicting a bird's eye view of a set of waypoints in a 2D planar display. The third dimension - altitude in this case - is displayed alphanumerically.

2.2 Related Work

In this section we introduce three related works that are considered to be the pillars of our work, and compare them to the work done in this thesis.

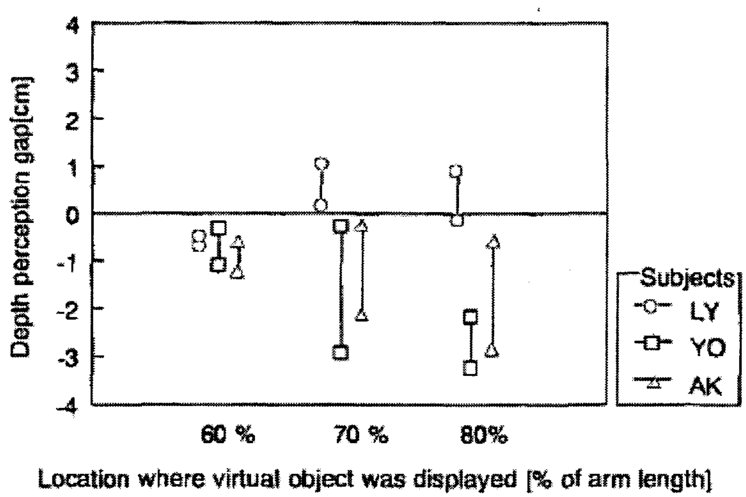
2.2.1 Correcting depth perception using tactile feedback

Interestingly, a first approach on improving depth perception by using vibrotactile feedback is proposed in [50]. Wada et al. propose to correct depth perception of virtual objects by using binary tactile feedback. The targeted application is minimally invasive surgery (MIS) in a mixed reality (MR) context. MIS can be facilitated by projecting 3D medical graphics of the diseased part on the human body in MR. To accomplish this, a see-through head mounted display (STHMD) is used to impose this information. However, depth perception of virtual objects is not precise in MR environment. Therefore, the authors propose a method to improve the precision of depth perception using tactile feedback.

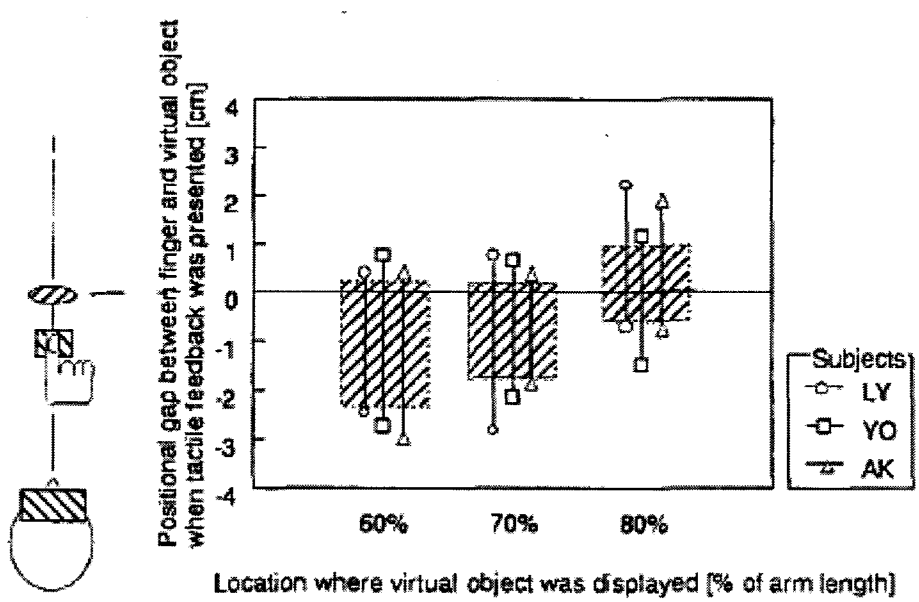
To this end they conducted three experiments. In the first experiment they measure the visual accuracy of depth perception when virtual objects are displayed through a STHMD. The results showed that real objects were perceived to be 1-2 cm closer to subjects than virtual objects. In the second experiment, they decreased the visual depth gap, and measured the accuracy with which subjects moved their fingers towards the exact location of an imposed virtual object. The distance to the virtual object was a percentage of the subject's arm length. The depth gap between the real objects (fingers) and the virtual object was found to be between 4 cm in front of the virtual object and 1 cm behind it.

In the last experiment, they tested the efficiency of their proposal of using vibrotactile feedback to correct the depth perception gap. In this experiment, a "binary" vibrotactile feedback was presented to the fingertip with a frequency of 200Hz when the finger moved within a range of between 4cm in front and 4 cm beyond the location where a virtual circle was displayed. A comparison of the results arising from using visual feedback only vs. integration of visual and tactile feedback is shown in Figure 2.2.

Subjects felt they had touched the virtual object when their fingers were at some point between the two symbols. When no vibrotactile feedback was presented in Figure 2.2(a), the gaps between the fingers and the virtual circle were mostly in the minus category which means that the subjects felt the virtual circle closer to them than the location where it was actually displayed (at the 0 level). Moreover, the depth perception



(a) Results of depth perception gap when vibrotactile feedback was not presented



(b) Results of depth perception gap when vibrotactile feedback was presented

Figure 2.2: A comparison of depth perception gap results without (a) and with (b) vibrotactile feedback [50].

gap was dispersed by individual differences. However, with the tactile feedback (Figure 2.2(b)), the gap dispersion by individual differences became smaller. Additionally, there was more common localization of the virtual object among the subjects which is shown in the shaded regions.In brief, the results of this work show that depth perception can be improved by integrating visual and tactile feedbacks.

The importance of this work to us is in promoting the idea of improving depth perception through the tactile modality, and in comparing it to ours, we provide a list of the common aspects followed by a table of the differences (Table 2.1).

Common aspects:

- The two works have similar goals of correcting/improving depth perception.
- Both works propose the usage of tactile feedback to achieve this goal.
- In both works there is a comparison of the visual feedback/display with the tactile (or combination of visual with tactile) feedback/display.

Related Work	Our work
The visualization device is a STHMD	The visualization device is a 2D screen
Depth perception correction is done for virtual objects	Depth perception improvment is done for real objects in a remote site, captured by a video camera
The experimental setup is done in a local environment	The experimental setup comprises teleoperating a remote site
The tactile stimulation is provided on a single point (fingertip)	The tactile stimulation is provided on the forearm utilizing the location of the stimulus
The tactile stimulus is binary (ON-OFF feedback) and no measurement of depth is performed i.e. The same stimulus is provoked when the finger is in a virtual sphere around the target	The tactile stimulus is location based i.e. The distance to the target is always measured and displayed on the forearm on a location directly related to value of the measured distance

Table 2.1: The differences between the work done in [50] and the work done in this thesis.

2.2.2 Tactile feedback to display physical quantity

In an interesting work [39], Murray et al. tried to convey information from a remote environment to an operator in a telemanipulation task through the tactile modality. The final goal of this study was to evaluate the efficiency of displaying the value of the gripping forces of a teleoperator by providing proportional intensity of vibrators located on the fingertips (tactile glove) of a human operator. Analogous to our work, there is a remote site, a physical quantity that is being measured, and a tactile feedback to display this measurement. The preference of tactile modality, in this scenario, over auditory or visual feedback for example is the ability to apply a differential vibratory stimulus across multiple fingers to indicate the relative shape and contact point forces of the end-effector's grasp in relation to the object in the remote world. In a previous work, they provided a binary tactile feedback on each finger which showed no significant gain in operator performance over visual feedback alone. For this reason, in this work they provided a proportional feedback where the intensity of vibration on each finger changes in accordance to the measured gripping force. With this intention, a series of psychophysical experiments was conducted.

They start by studying the effects of frequency and amplitude on the perceived vibratory magnitude concluding that a simultaneous change of frequency (up to a limit of 300Hz) and amplitude gives a more distinguishable effect than changing either component alone. They use this result for providing tactile feedback via a tactile glove in later experiments. Then they objectively evaluate the glove's effectiveness in conveying grasp force information to the wearer through two telemanipulation tasks: an adaptive force-limited pick-and-place task in which subjects are asked to control their gripping force to lift an object of known relative weight without overgripping it, and a sorting task for objects according to their relative weight where subjects are required to adjust their gripping forces to lift the object and interpret the vibratory feedback intensity when it is provided. In each of these tasks, three feedback modes were compared: visual mode (no tactile feedback), binary tactile feedback mode, and proportional tactile feedback mode.

The results of the first task showed that proportional vibrotactile feedback outperforms binary feedback and visual mode in terms of mean, peak and variance of grip forces. The second task results showed that users could translate the vibratory stimulation to judgments of relative weight and both tasks proved that proportional feedback is significantly more effective than visual and binary tactile feedback.

This work is considered the second pillar for our work since it motivated the concept of conveying relative values of properties of objects or physical quantities through vibratory stimulation. However, the main differences are highlighted in Table 2.2.

Related Work	Our work
The measured/displayed physical quantity is the grip force on each finger	The measured/displayed physical quantity is the distance to a single target
The display method is based on modulating the tactile stimulus intensity	The display method is based on modulating the tactile stimulus location (although these two methods - intensiy and location - are compared in our work)
Tactile stimulation is provided on fixed points (fingertips)	Tactile stimulation is provided on any point on the forearm

Table 2.2: The differences between the work done in [39] and the work done in this thesis.

A number of similar previous works were conducted to substitute for force feedback in teleoperation systems by utilizing the auditory and tactile senses [34, 32, 31]. In these works, authors used auditory and tactile feedback to provide the human operator with force information without some of the disadvantages of force reflection (such as stability). Results showed an improved performance for peg-in-hole tasks without instabilities, during degraded visual conditions, and in detecting small forces.

2.2.3 Localization of vibrotactile stimulation on the forearm

The last related work is the work done by Cholewiak in [13]. This work explores the ability to localize vibrotactile stimuli on the forearm where stimuli are provided via a linear array of tactors. It investigates the influence of a number of stimuli paramters on the localization of the stimulus. The examined parameters include: the frequency of the vibratory stimulus, the locations of the stimulus sites on the body relative to specific body references or landmarks, the proximity among driven loci, and the age of the observer. The experiments were conducted with a dense array of 7 tactors on the forearm separated with a distance of 25mm using two different frequencies for stimulation, 100Hz and 250Hz. Our interest in this work arises from the fact that the tactile display method we use is experimented on the forearm whose psychopysical localization properties are investigated in this work. The resolution of this display method relies on the localization properties of the forearm.

In this work [13], the part of relevance to our work will be further described in Chapter 4. However, here we provide a brief listing of the results, and highlight the differences of this work to ours in Table 2.3.

Results:

- An average localization rate of 47.28% on the forearm was shown with significant differences among the different locations along the arm
- Best performance was found to be in the vicinity of body joints (elbow and wrist)
- Low effect for stimulus frequency (above recognition threshold) and age group on the localization ability was observed
- As the separation between the tactors increased, the localization performance was considerably improved

Related Work	Our work
A linear array of 7 tactors is used	A linear array of 4 tactors is used
Localization of 7 locations on the lower forearm is examined	Localization of 13 locations on the lower forearm is examined
Stimulus at a certain location is created by activating the corresponding tactor	Stimulus is created using the funneling illusion method

Table 2.3: The differences between the work done in [13] and the work done in this thesis.

Chapter 3

Proposed Method For Displaying Distance Information

Distance between two objects can be represented by a numeric, one-dimensional quantity, and therefore it can be displayed to the human OP in several ways. Correspondingly, in a TPTA scenario, depth or distance in the z-direction between a teleoperator and a target object can be displayed in many ways. In this thesis, we propose a vibrotactile feedback method for displaying critical distance information in TPTA systems. In Section 3.1.1 we introduce some simple visual display methods for depth information as an introduction to our method. In Section 3.1.2 we propose our method in analogy to the visual methods. Next in Section 3.2, we describe the psychophysical effects incorporated in realizing the method and in Section 3.3 we describe the tactile device used for testing.

3.1 Methods for displaying distance information in TPTA systems

3.1.1 Visual display of distance information

Distance information can be represented visually by many ways, such as mapping an absolute distance measurement to the intensity of a light or an on-screen region's color, gradually changing from light to dark (at the point of contact). However, the intensity representation requires absolute knowledge of the dynamic range of the light device/element in order to have a precise interpretation of the displayed value. Another method is to deploy an on-screen progress bar element that can be integrated into the graphical user interface or superimposed on the video of the remote environment. It visually maps the distance measured at the remote site to the progress amount in the progress bar, i.e. the status of a displayed progress bar element grows as the distance decreases. Hence, its progress range is easily identifiable which supports quick reading and interpretation of the displayed information.

3.1.2 Vibrotactile display of distance information

The addition of more visual feedback components requires the human OP to simultaneously monitor multiple visual elements, which in complex TPTA scenarios leads to the risk of overburdening and distracting the OP. To reduce the visual cognitive load, we propose to haptically display distance information; employing a different modality for distance information presentation. As with visual display, the distance can be displayed using vibrotactile stimulus either by intensity or by spatial displacement of the stimulus. Accordingly, the intensity of the vibrating actuator can change with varying distance, or we can adopt the progress bar approach by presenting a moving vibrotactile stimulus on the forearm between the elbow and the wrist. The latter is our proposed method. Therefore, our proposal is to use a vibrotactile stimulus on the forearm that moves in accordance to the changing distance between a telemanipulator and a target object in the remote 3D environment. Figure 3.1 illustrates the possible visual and vibrotactile methods in (a), (b) and (c) in addition to our proposed method in (d).

3.2 Psychophysical effects among multiple vibrotactile stimuli

The effect of a moving vibrotactile stimulus can be achieved by sequentially activating multiple vibrotactile actuators. However, since each actuator has a certain volume (ours are 12mm (0.5") diameter with 3.4mm (0.134") thickness), the density of the actuator array is physically limited. From psychophysics it is known that the minimum distance of the vibrotactile spatial discrimination ability of the human skin is limited to around 35mm at the human forearm [53]. We propose to exploit psychophysical effects among multiple vibrotactile stimuli to improve physical resolution while reducing cost, size and complexity of the vibrotactile actuators. Therefore, the human OP can make exact interpretations of vibrotactile information and receive precise distance information with high resolution using a low-density actuator array.

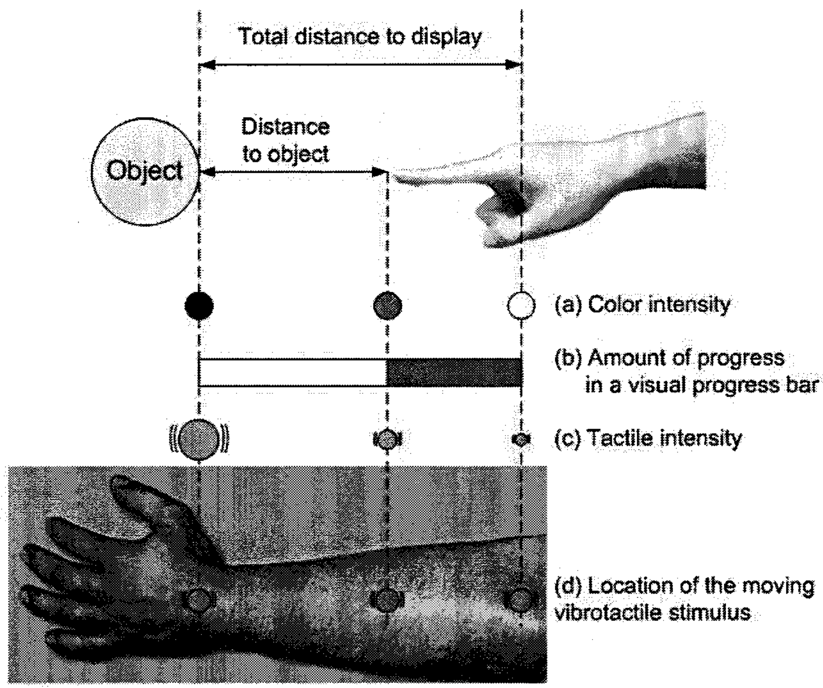


Figure 3.1: Schematic overview of visual and vibrotactile methods for displaying distance information. Measured distance is mapped to color/light intensity (a), status of an on-screen progress bar element (b), vibrotactile intensity (c), location of vibrotactile stimulus (d).

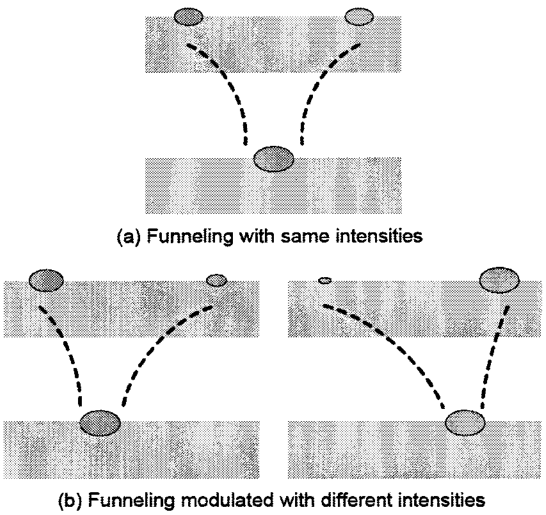


Figure 3.2: Illustration of funneling illusion. Two stimuli are perceived as one stimulus where the location can be varied by funneling tricks.

3.2.1 Funneling illusion

The funneling illusion describes a phantom sensation midway between multiple stimuli when they are presented simultaneously at adjacent locations on the human skin [7, 3].

Interestingly, the location of the phantom sensation can be modified in two ways [7]. When activating the adjacent vibrotactile actuators with different time intervals in a particular pattern with same intensity, the perceived location moves towards the earlier stimulus. However, the funneling illusion disappears as soon as the time interval between two stimuli exceeds a certain threshold. Alternatively, when the vibrotactile actuators are activated simultaneously but with different intensity, the presented stimuli are "funneled" and shifted towards the actuator with higher intensity. Compared to the former method, the modification of the actuators' intensity provides a stronger midway sensation and is therefore adopted in our work.

Figure 3.2 illustrates the funneling phenomenon [11]. The ellipses in the top layer represent the location of the stimulus while its size indicates the applied vibrotactile intensity. Two stimuli are funnelled into one midway sensation, illustrated at the lower layer. Note that the ratio between the perceived intensity of the midway phantom sensation and the applied stimuli is non-linear.

3.2.2 Apparent movement sensations

The funneling illusion allows us to create the illusion of an apparently continuously moving vibrotactile stimulus [42, 12, 11]. An illustration of our approach is described in Figure 3.3. By varying the intensities of two adjacent actuators, we can smoothly shift the in-between sensation from one actuator location to the other. That is, the intensity of one stimulus changes from a low to a high level while the other changes from a high to a low level and the discrete perceived stimuli can be felt as one continuously moving stimulus. An optimal distance between two actuators for displaying the apparent movement sensation on the human lower arm is around 40-80mm [11]. As the average adult's lower arm length is 252mm [4], four vibration motors spaced at intervals of 80mm are enough for utilizing most of the skin in that region.

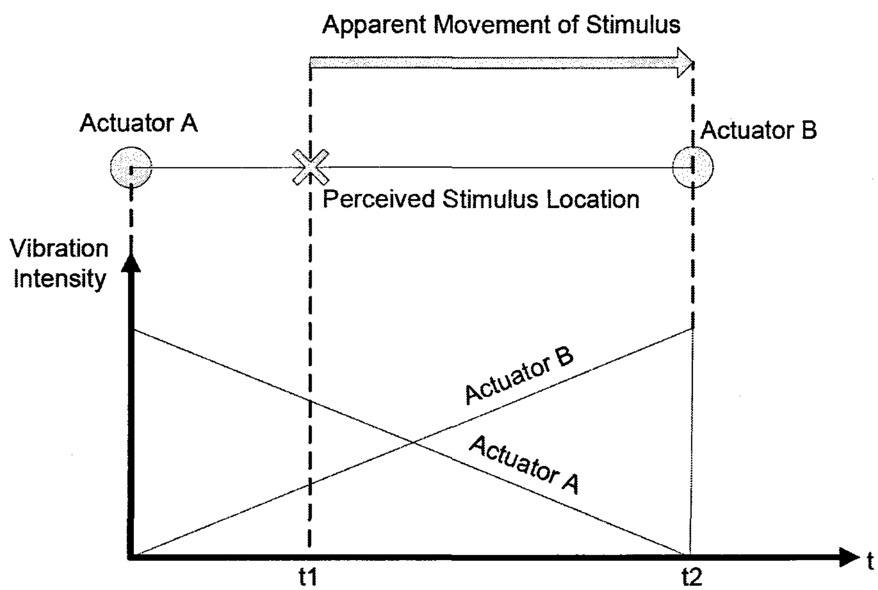


Figure 3.3: Illustration of exploiting the funneling illusion to create a continuously moving vibrotactile stimulus.

Therefore, by exploiting the psychophysical funneling illusion and the apparent movement phenomenon, we are able to display a continuously moving vibrotactile sensation with high spatial resolution using only few actuators. In this work, we propose to map distance information perceived by a remote teleoperator to vibrotactile feedback displayed spatially along the operator's forearm. By this means, lack of depth perception in remote telepresence environments is to be compensated.

3.3 Device Description

3.3.1 Body Site Selection (forearm)

The tactile feedback device is designed to be worn on the forearm. The reason for choosing the forearm to be the site for presenting the tactile feedback is to make the device easy to wear, to represent depth information intuitively (by easily resting the forearm along the direction to a screen), and to utilize the reasonable space afforded by the forearm. In addition, the forearm provides a continuous, relatively flat surface to study, permitting the required separation of the vibrators [13]. Consequently, it has been used to study the efficacy of several tactile aids such as the Queens aid and the Tactaid-7 developed by [54].

3.3.2 Actuators

The tactile feedback device consists of four pancake-type vibrating DC motors that are usually used in a cell phone. These motors vibrate tangentially to the skin. This preference is based on the recommendation of [3] in reporting that the phantom sensations produced by mechanical stimuli tangential to the skin's surface are better defined than the sensations produced by stimuli normal to the surface. In addition, they are lightweight, consume little power, inexpensive and easy to deploy. Their operating voltage is 3.6 volt and their operating frequency range is up to 220Hz. They can be attached to and detached from the arm using Velcro. To fix the vibrators, an arm band is wrapped around the forearm so that it softly presses the actuators to the skin. Figure 3.4 shows the placement of four actuators at the forearm.

3.3.3 Block Diagram

The block diagram of the tactile device with its interfacing to a PC is shown in Figure 3.5. The ATmega128 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. It can execute powerful instructions in a single clock cycle achieving throughputs approaching 1 MIPS per MHz and allowing optimization of power consumption versus processing speed [6]. It operates at 4.5 - 5.5V and has 53 programmable I/O lines. Through these lines, it can control the connected devices/actuators (in case of

Figure 3.4: Tactile Device

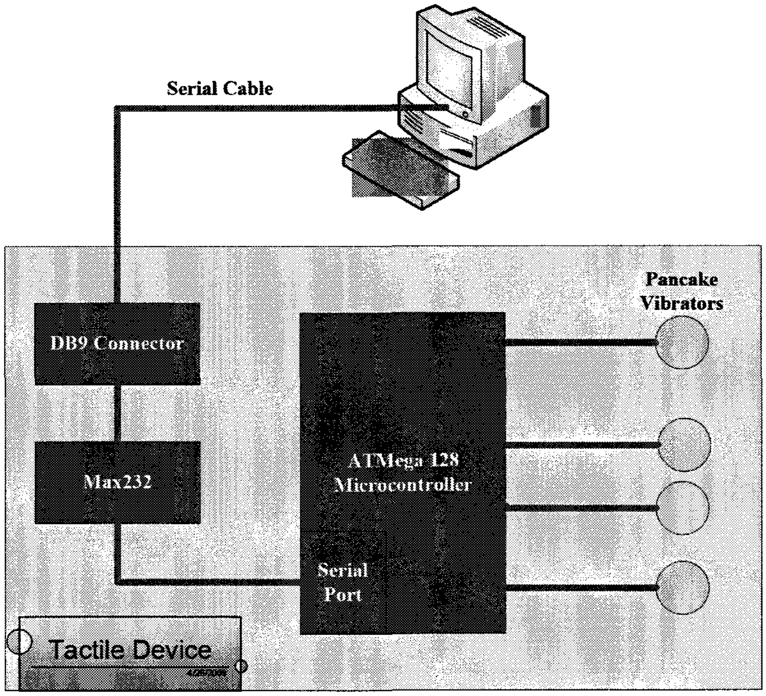


Figure 3.5: A block diagram for the tactile device with its interfacing to the PC.

output), or sense the input from devices/sensors (in case of input). In our implementation we use 4 output lines to control the actuators as seen in the Figure. The control mechanism will be explained in the next section.

In communicating with the controlling PC, the microcontroller's Universal Synchronous and Asynchronous serial Receiver and Transmitter (USART) is used in order to provide a highly flexible serial communication. Due to standards differences, a Max232 IC is used to convert voltage standards from RS232 (-12V, 12V) level that is used by the PC to the (5V, 0V) level used by the ATMega 128 microcontroller and vice versa. Finally, the microcontroller is connected to the PC by a serial cable through a DB9 connector.

3.3.4 Control

In order to control the intensity of the actuators, the ATMega 128 microcontroller is used to generate a pulse-width modulation (PWM) signal which provides 16 levels of applied intensity. Table 3.1 shows the digital PWM signal for each level of applied intensity.

Level of applied intensity	Digital PWM signal
0	0000000000000000000
1	1111100000000000000
2	1111110000000000000
3	1111111000000000000
4	1111111100000000000
5	1111111110000000000
6	1111111111000000000
7	1111111111100000000
8	1111111111110000000
9	1111111111111000000
10	1111111111111100000
11	1111111111111110000
12	1111111111111111000
13	1111111111111111100
14	1111111111111111110
15	1111111111111111111

Table 3.1: PWM signal corresponding to the level of applied intensity

The microcontroller is programmed to receive simple commands from the controlling

PC through its serial port and act accordingly. An API for the microcontroller was developed in order to be simply used in any application. A typical example for configuring vibration of the actuators is as follows:

```
//Actuate the first two actuators with medium intensity for 1 second
tactile_device->setIntensity(0,0,6); //set intensity of actuator 0 to 6
tactile_device->setIntensity(0,1,6); //set intensity of actuator 1 to 6
tactile_device->setIntensity(0,2,0); //set intensity of actuator 2 to 0
tactile_device->setIntensity(0,3,0); //set intensity of actuator 3 to 0
tactile_device->assembleBuffer(); //Arrange commands according to protocol
tactile_device->actuate(); //send the commands via serial port
Sleep(1000); //Sleep for 1 second (actuation time in this example)
////////////////////////////////////////////////////////////////////////////

//Stop vibration of all actuators
tactile_device->setIntensity(0,0,0); //set intensity of actuator 0 to 0
tactile_device->setIntensity(0,1,0); //set intensity of actuator 1 to 0
tactile_device->setIntensity(0,2,0); //set intensity of actuator 2 to 0
tactile_device->setIntensity(0,3,0); //set intensity of actuator 3 to 0
tactile_device->assembleBuffer();
tactile_device->actuate();
////////////////////////////////////////////////////////////////////////////
```

In this example, a simple function "setIntensity" is used to select a certain actuator and set its intensity to a certain level (0 to 15). This API enables controlling a 2-dimensional array of actuators, so the first parameter of "setIntensity" is for selecting the first dimension value, the second is for selecting the value of the second dimension, and the third is to assign the required frequency. These values are arranged according to a predefined order (communication protocol between PC and microcontroller) in the function "assembleBuffer". Finally, the command is sent to the microcontroller. When the microcontroller receives the command, it activates the actuators according to table 3.1. In other words, it receives the intensity value for each actuator, matches it with the PWM signal, and sends this PWM signal to the corresponding output port.

3.3.5 Actuators Intensities Study

The perceived level of vibrotactile intensity might differ from the applied energy as the PWM-based level control changes both the frequency and the amplitude of vibration that affect vibration perception at the same time [39]. In order to find the relationship between the applied and the perceived intensities, we used the results of the work done in [11]. The results are illustrated in Figure 3.6. It shows that the applied intensity levels are approximately proportional to the perceived intensity up to level 12. For higher applied intensities, subjects could not easily distinguish between the different levels anymore. In our work, we limit the range of control levels from zero to 12 to assure a linear tactile excitement when driving the actuators.

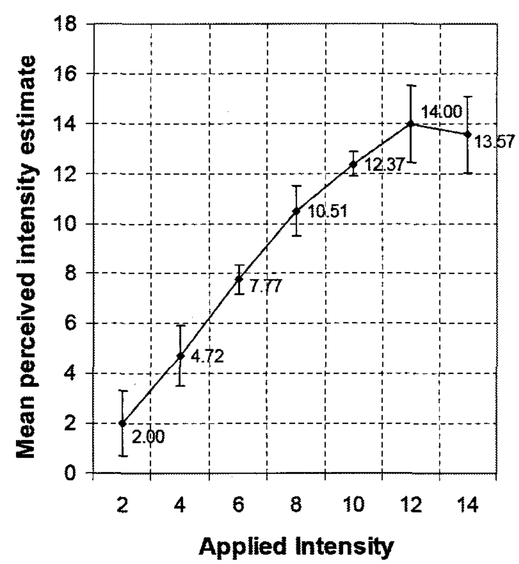


Figure 3.6: Relationship between the applied and the perceived intensities.

Chapter 4

Experiments and Results

4.1 Display Method Resolution Experiment

In order to apply our method to the forearm of a human operator, it is important to evaluate the resolution of this method knowing that its feasibility is highly dependent on the spatial psychophysical perception of the arm. In other words, the funneling illusion method is based on changing the location of the vibrotactile stimulus on the forearm, and thus the distinctly perceivable locations in this region are to be studied. This is mostly important when, later on, this method is used in a TPTA system scenario to present distance information. Hence, this experiment allows quantizing the error or the discrepancy between the perceived depth on the forearm and the real distance.

Our application scenario for the funneling illusion depth display method is a TPTA in which depth (distance from the teleoperator to the target in z-direction), normally, is a continuously changing value. However, in other scenarios, this method might be used to represent a physical quantity that changes at a low frequency (e.g. temperature), and thus the stimulus seems to be static for a while before moving. For these reasons, we conducted this experiment in two phases: one to evaluate the resolution for static stimuli and another to evaluate the resolution for moving stimuli.

A previous work was done in [13], for investigating the vibrotactile localization on the arm and the effects of place, space and age on it. In their experiments, the authors used a tactile array of seven piezoceramic tactors as shown in Figure 4.1. Their tactors were separated by 2.5 cm starting at a point 8 cm from the elbow. They tested the accuracy of seven static stimulus locations provided by these tactors at 100Hz and 250Hz frequencies. At the end of this experiment we will compare our results to theirs knowing that both experiments serve the same purpose.

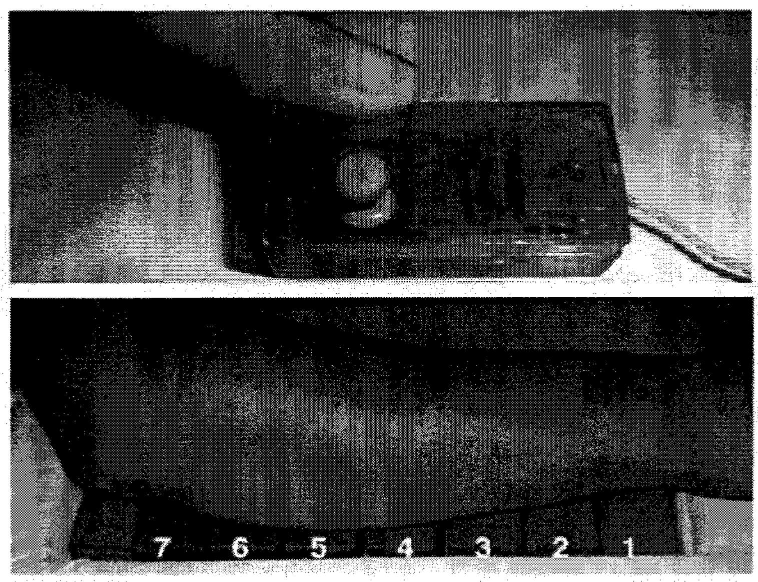


Figure 4.1: 7-tactors tactile array implemented in [13].

4.1.1 Participants

Twelve participants (mean age of 26.5, age range from 23 to 35 years; 11 males and 1 female), all students at University of Ottawa, took part in this experiment. All of the participants self-reported having normal or corrected-to-normal vision and a normal sense of touch. Eleven of the participants were right-handed, one was left-handed. Each experiment lasted for approximately 45 minutes.

4.1.2 Apparatus and Experimental Design

An overview of the experimental setup is shown in Figure 4.2. The experiment apparatus incorporated a PC to provide the experiment's Graphical User Interface (GUI), the previously described tactile device to generate the vibrating stimulus, and a ruler (made of paper) placed on the arm for aiding the subject to locate the stimulus.

The GUI is shown in Figure 4.3. It contains the subject's information, the experiment mode selection (static stimulus or moving stimulus), a start button for starting the experiment, a group of radio buttons indicating the studied positions (mappings of the

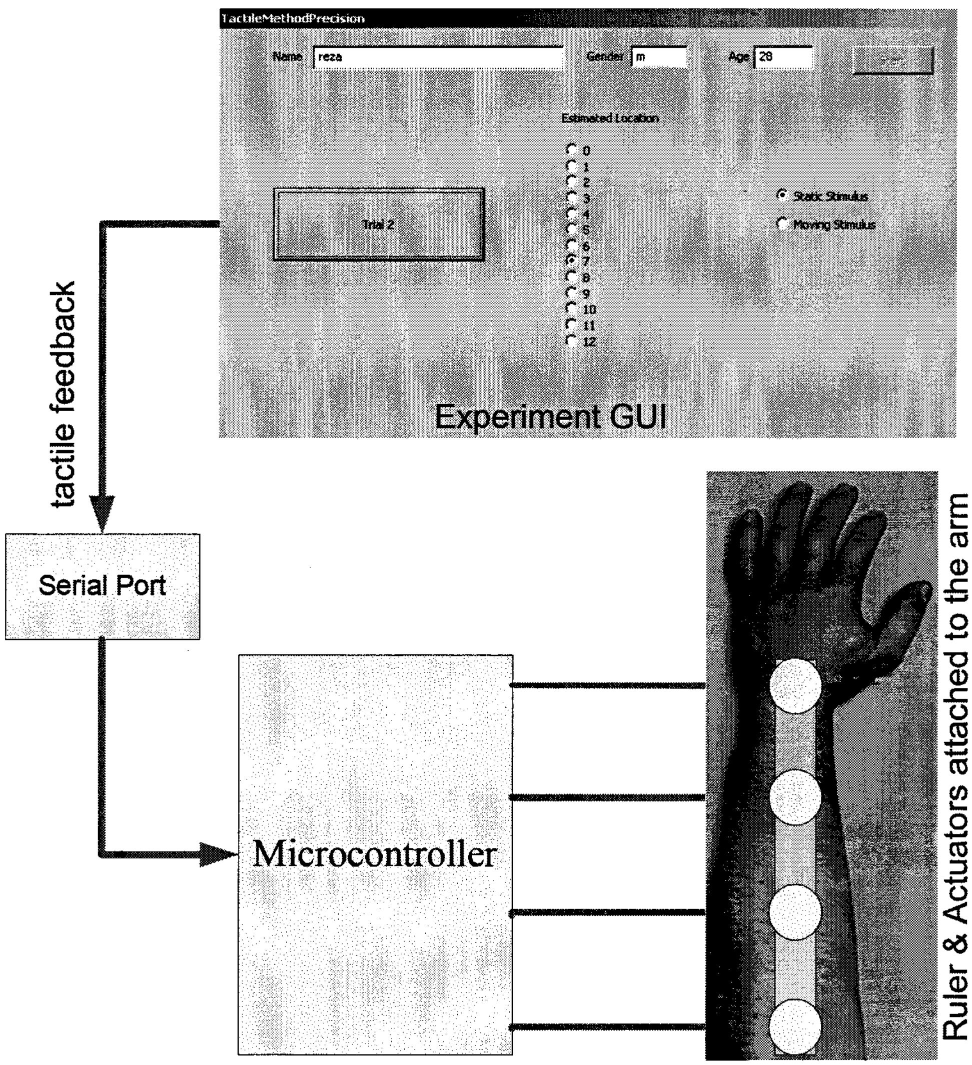


Figure 4.2: Overview of the experimental setup.

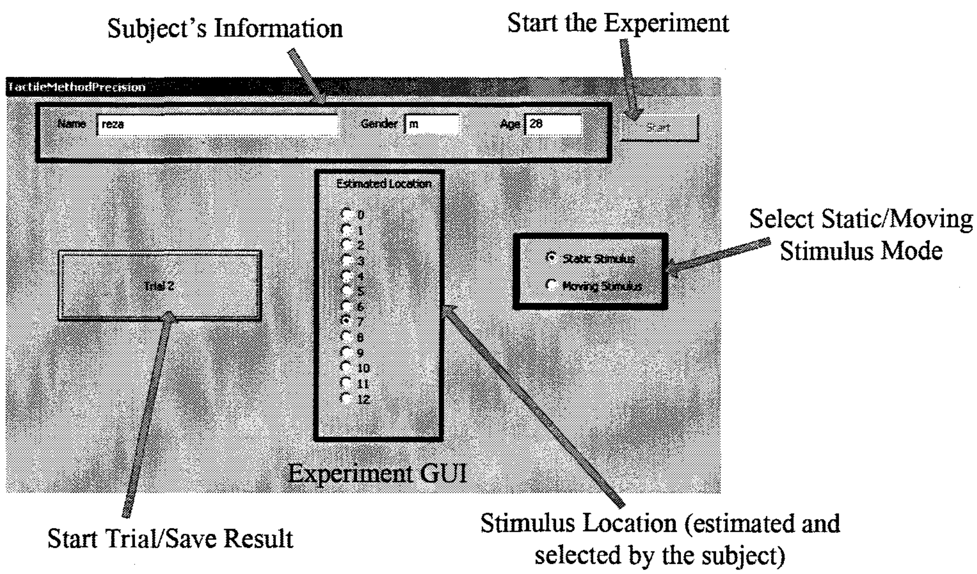


Figure 4.3: Screen shot of the GUI of the experiment.

ruler positions to be explained later on), and a Trial start/save button for starting each trial and saving the corresponding estimated location (that is selected from the radio buttons group).

The tactile device described in Chapter 3 is used to provide tactile feedback on the human operator's forearm. The four actuators of the device are separated with a distance of 80mm as explained in Chapter 3. This will cover 240mm from the wrist towards elbow. In [13], 7 stimuli were located on the forearm. Even with this low resolution, perception did not have high accuracy, so in our experiment we did not target a very high resolution. Originally, our method can generate up to 37 locations using 4 actuators including the 4 real locations of the actuators and 29 virtual (funneled) locations; however, we limited our study to 13 locations. There are 5 levels (locations) between adjacent actuators (inclusive); in total 13 locations numbered from 0 to 12 on the ruler with 0 near the elbow and 12 at the wrist. The actuators are attached at positions 0, 4, 8 and 12 as shown in Figure 4.4 and local cues due to actuators were dealt with by changing their positions frequently. The ruler is attached to the arm with the actuators in order to assess the subject's estimation of the stimulus location.

Stimulating a certain location is achieved by assigning a certain combination for the intensities of the 4 actuators. Back to Figure 3.6, there are 12 perceivable levels of

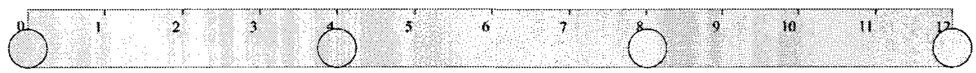


Figure 4.4: Ruler used to aid the subjects in assessing the stimulus location estimation.

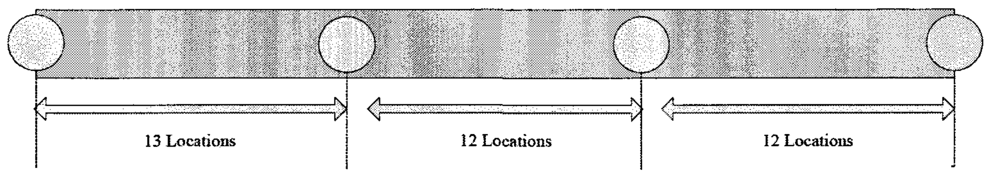


Figure 4.5: Total number of locations that can be generated by 4 actuators using funneling method.

actuator vibration intensities in addition to the OFF-status (0 intensity). Therefore, by using these intensity combinations the device is able to create 13 locations (12,0), (11,1), (10,2), (9,3), (8,4), (7,5), (6,6), (5,7), (4,8), (3,9), (2,10), (1,11), (12,0) between two actuators A and B. These 13 locations include the real locations of the actuators themselves i.e. 2 real locations and 11 virtual (funneled) locations. (Interestingly, as explained in Chapter 3, when these combinations are displayed in sequence with a short interchanging time delay a smooth continuous sensation would be generated traveling from actuator A to actuator B). If we are to use all the allowed locations, this would result in a total of 37 locations as shown in Figure 4.5. 37 locations is a very high resolution (based on related work [13] which has tested 7 locations with an average recognition rate of 47.28%) and is expected to have a very low rate of recognition.

In our setup we need 13 locations for the whole arm (or most of it). So we utilize only 13 locations by the 4 actuators as previously shown in Figure 4.4. For generating these stimuli locations we use the following set of intensity combinations: (12,0,0,0), (9,3,0,0), (6,6,0,0), (3,9,0,0), (0,12,0,0), (0,9,3,0), (0,6,6,0), (0,3,9,0), (0,0,12,0), (0,0,9,3), (0,0,6,6), (0,0,3,9), (0,0,0,12) for actuator A, actuator B, actuator C and actuator D respectively. In combination (12,0,0,0), for instance, we activate actuator A with the highest intensity (12) and deactivate the remaining actuators (intensity 0). This provokes location 0. In combination (9,3,0,0), we activate actuators A and B with respective intensities of 9 and 3 while deactivating actuators C and D. This generates a virtual (funneled) stimulus closer to the actuator with higher intensity (actuator A), and thus provokes location 1. In combination (6,6,0,0), we activate actuators A and B with the intensity 6 and deactivate actuators C and D. This generates a virtual stimulus on the midway between actuators A and B which provokes location 2, and so on..

The experiment is presented in two modes that are performed separately: testing location recognition of a static stimulus and testing location recognition of a moving stimulus. Each mode is tested in 91 trials per subject. This allows testing each of the 13 locations on the arm 7 times. The 91 locations (evenly distributed among the 13 locations) are randomly generated upon starting the experiment and saved in an array in order to enable fetching a random location for each trial. In order to counterbalance trends of task learning, the order of the two modes is randomized for each subject. After completing one mode, subjects had a 10 minute break before switching to the second mode. The whole experiment took on average 35 minutes plus the 10 minutes break.

The static stimulus was presented on the specified location for a period of 1 second based on our pilot study. However, displaying the moving stimulus was controversial. If we are to restrain all moving stimuli to start from the same location (preferably location 0 on the elbow), subjects may be able to recognize the stimulus location based on traveling time instead of tactile perception i.e. In this approach, the longer time the stimulus takes to reach its destination, the farther is this destination from the starting point. Hence, to assure the user is not able to perceive the location of the stimulus from its traveling time, the moving stimulus was set to take the same time for each location by following the trajectory shown in Figure 4.6, starting and ending at the same point. This ensures that all stimuli take the same traveling time. Although it gave double chance for the subject to recognize the location (at the starting and at the ending point), the two given chances were both based on tactile perception. We preferred this approach over the approach allowing mental cognition based on traveling time that might spoil the results. At the ending point, stimulus persisted for 0.5 seconds as recommended by [3].

The experiment was self-paced and recordings of the stimulated location (according to the vibrators intensity combination) and the perceived location (selected by the subject) were saved for each trial.

4.1.3 Procedure

The subjects are comfortably seated at a desk facing a visual display for instructions and feedback. The left lower arm is exposed and oriented so as to be available for stimulation. Responses are made by assigning the point of stimulation on the ruler and selecting the corresponding position on the experiment GUI. Initially, the participants

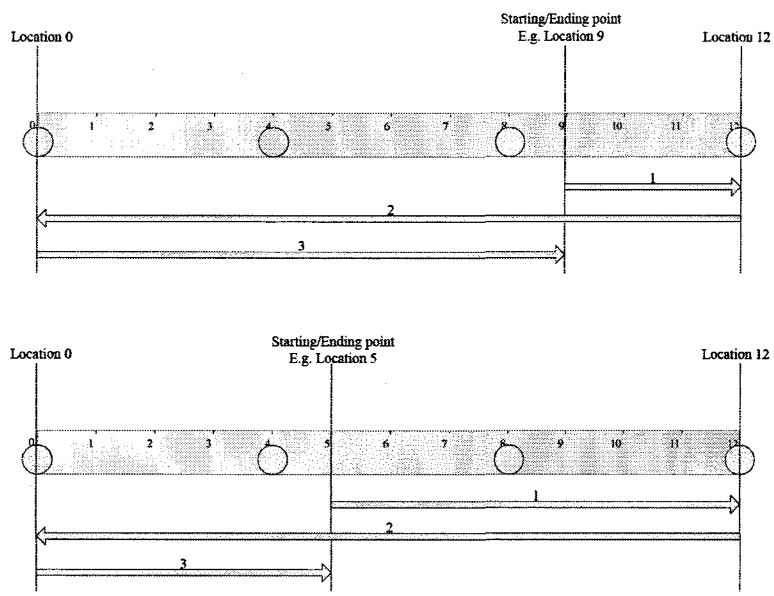


Figure 4.6: Two examples of the path followed by the moving stimulus for a certain location (9 and 5 in this example).

are trained at the feedback methods. Once they felt comfortable, the experiment started. The experiment procedure is explained referring to Figure 4.3.

After entering the subject's information and selecting the stimulus mode, subject presses the "Start" button to start the experiment. This generates a file for saving the results, randomizes the order of the locations to be stimulated and saves them in an array, and enables starting the first trial.

When clicking the "Start Trial/Save Result" button, the stimulus is presented at a certain location on the arm. When stimulation is over, the "Estimated Location" radio button group is enabled so that the subject can select the location at which he/she perceived the stimulus. To assign the location number, subjects refer to the ruler attached to the arm and select the closest number (location on the ruler) to the perceived stimulus location.

After selecting the location from the radio button group, the subject clicks again on the "Start Trial/Save Result" button to save the results of the trial which include: the trial number, the stimulated location (according to the intensities combination) and the perceived location by the subject.

Next, the subject clicks again on the "Start Trial/Save Result" button to start the next trial, and so on This is repeated 91 times for each stimulus mode (static or moving) with a 10 minute break in-between the two modes in order to minimize effects of fatigue and skin saturation on performance.

Figure 4.7 shows the general flow of the experiment.

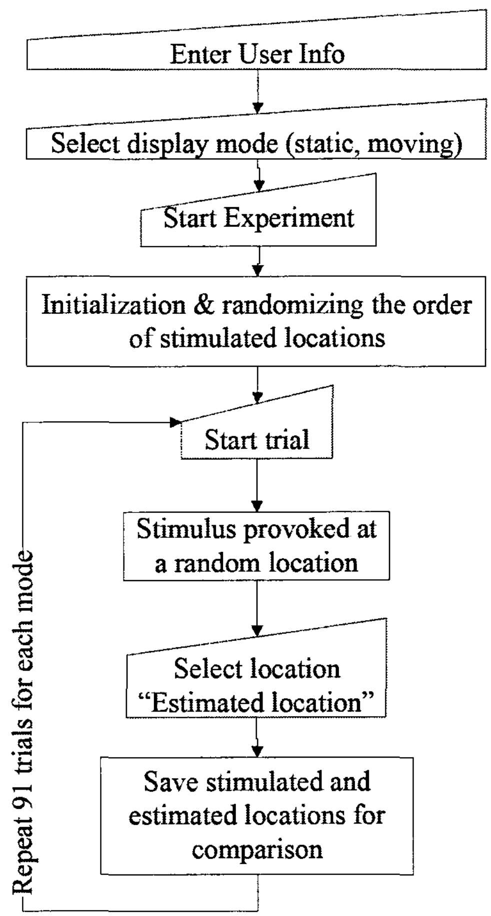


Figure 4.7: Experiment1 flowchart.

4.1.4 Results and Discussion

Results are based on data collected from the 12 participants, each performing both modes of the experiment: static and moving stimulus. As previously mentioned, each mode had 91 trials in which each location is tested 7 times per subject. Therefore, in total each location is tested 84 times in each mode (12 subjects X 7 tests for each location/subject).

In our analysis, we study the average value for the guesses of each location, the percentage of correct localizations of each location, and the distribution of localizations for each location. We analyze the static stimulus and the moving stimulus results and compare them to each others.

First we start by finding the average value of subjects' guesses for each location which is shown in Figure 4.8(a). This study allows finding the relationship between the real location of the stimulus and the location perceived by the subject. The ideal result would be a strictly increasing linear function that emphasizes the discrimination of each location; more specifically the first bisector linear function. However, in psychophysical experiments and especially human perception of tactile acuity, perfection is far from attainable. In our experiment, we expected a monotonic function and aimed at high differences in the perceived location. The expected result is obtained, as shown in Figure 4.8(a), but sometimes with small differences between some adjacent locations such as 0 and 1, 4 and 5. This indicates a higher difficulty of discriminating these adjacent locations. The trend in the Figure is confirmed by the one-way ANOVA analysis shown in Tables 4.1 and 4.2 with $F(12,143) = 179.57$, $p = 8.24E^{-80}$.

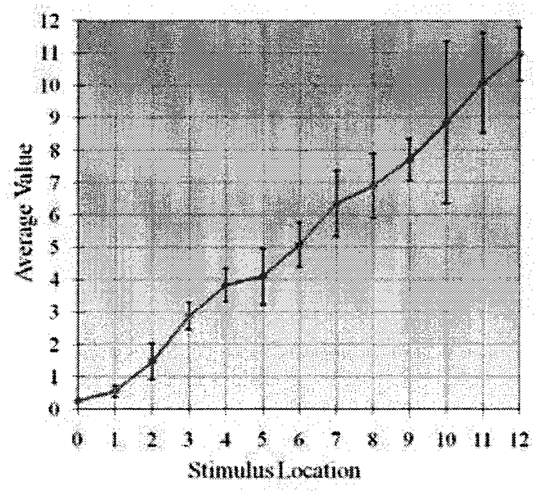
Table 4.1: ANOVA data summary

Groups	Count	Sum	Average	Variance
0	12	3.142	0.261	0.081
1	12	6.571	0.547	0.177
2	12	17.714	1.476	0.554
3	12	34.571	2.880	0.414
4	12	46	3.833	0.504
5	12	49.142	4.095	0.876
6	12	61	5.083	0.680
7	12	76.285	6.357	1.014
8	12	82.714	6.892	0.994
9	12	92.428	7.702	0.639
10	12	106.2	8.85	2.495
11	12	121	10.083	1.537
12	12	131.571	10.964	0.820

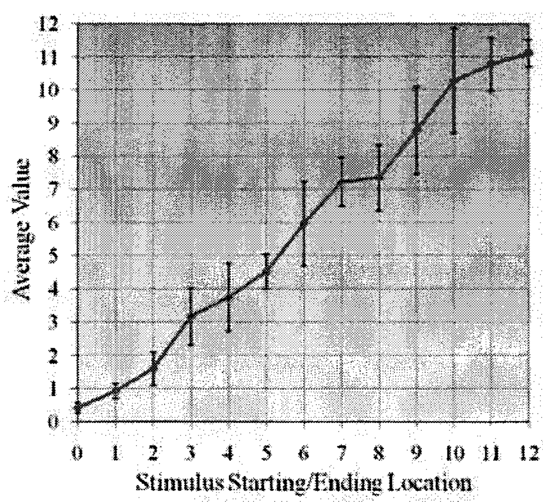
This observation applies to the moving stimulus averaging analysis shown in Figure 4.8(b) as well and is confirmed by the ANOVA result $F(12,143) = 211.73$, $p = 1.3E^{-84}$.

Table 4.2: ANOVA Result

Source of Variation	SS	df	MS	F	P-value
Between Groups	1788.985	12	149.082	179.571	$8.235E^{-80}$
Within Groups	118.720	143	0.830		
Total	1907.706	155			



(a) Static stimulus



(b) Moving stimulus

Figure 4.8: The average value of the perceived locations of the static and moving stimuli for each location.

The results in Figure 4.8 (for both modes) shows that each location can be distinguishable on averaging subjects' performances. In addition, the two modes have almost similar graphs except for a slightly steeper trend at the edges for the static stimulus over the moving one, and the converse for the locations in the middle (steeper slope for the moving stimulus over the static one). This gives a hint that there is a gain in performance in the moving stimulus mode in localizing stimulations in the middle, while there is a deterioration in localizing stimulations at the edges. Another interesting observation is the superiority of the moving stimulus in matching the average perception of each location with the location itself. This can be easily seen at locations 1, 3, 5, 6, 7, 9, 10, 11 where the moving stimulus better matches the correct location. It is also worth mentioning that for the static graph, most of the average values are less that the location index as if the guesses were shifted towards the elbow.

Next, we analyze the accuracy of localizing each stimulus location in two ways. First, we find the percentage of correctly localized stimuli (for both static and moving stimuli) and present them in Figures 4.9 and 4.10. Second, we present the distribution of guesses for each location. This analysis is shown in Figures 4.12, 4.13, 4.14 and 4.15.

The first thing to note in Figures 4.9 and 4.10 is the remarkable differences in localization performance over the length of the arm. Generally a U-profile with sparks at each actuator location is obtained and in both the static and moving stimulus graphs, we note that the highest performance is at the edges of the array which are the locations closest to the elbow and wrist. Localization of the static stimulus at location 0 (elbow) reached an accuracy above 75% and at location 12 (wrist) above 60%. For the moving stimulus, localization accuracy at these locations(0 and 12) exceeded 65% and 55% respectively.

However, localization of other location had a variable quality of performance ranging from 11-48% in the static stimulus mode and 18-42% in the moving stimulus mode. In all cases, however, these values are well above the $100/13 = 7.7\%$ chance performance level for 13 alternatives.

The first explanation for this pattern of responses was probability-based. The interpretation was that the enhanced performance at the edges was due to the increased likelihood of localizing these vibrations since there were fewer available alternatives at these points. In other words, location 0 could be confused with location 1 and less likely with location 2. However, location 10, for instance, could be confused with locations 9 and 11 equally (probability-wise) and less likely with locations 8 and 12. This gives more chance to guess stimulations at the edges.

However, a careful look at the literature, and in specific at [13], shows that this result at the edges is not caused by the difference in the number of alternatives as explained before. In [13], a similar result was obtained with a 7-tactors array that shows better performance at the edges. When researchers moved the array of tactors to have the middle tactor (number 4) at the elbow (having the array to start from the upper arm), they still got the best localization results at the elbow. Figure 4.11 shows their results. The solid line shows localization results when the 7 tactors are at the lower arm and the 7th tactor is at the elbow. The dashed line shows localization results when the 7-tactors array is shifted upwards so that tactor 4 is at the elbow. Comparing the two lines emphasizes the higher localization ability at the elbow.

In fact, studies have shown that "localization is more precise when stimulus is close to some anatomical point of reference that can provide a perceptual anchor that the observer could use in identifying the site of stimulation" [52]. In later studies, these anchor points were related to body joints. In our experiment, the wrist and elbow are examples of these references and the results are in agreement with these findings. The closer the stimulus was to these joints, the better localization performance was. The least performance obtained in the middle is also in agreement with the results of [25].

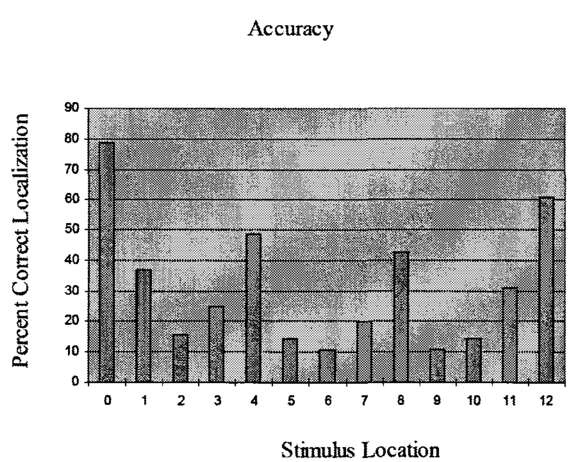


Figure 4.9: The percentage of correctly perceived locations of the static stimulus for each location.

On an anatomical and physiological level, this foundation is supported by many resources. Acuity, as defined in [10], "refers to the ability to locate the site of the initiation of a stimulus. High acuity allows for fine distinction and requires a greater

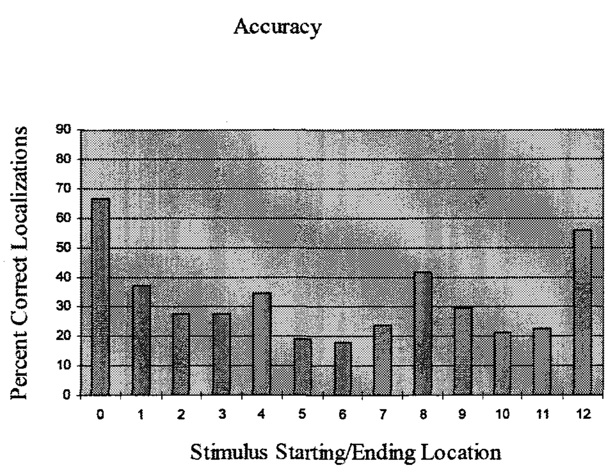


Figure 4.10: The percentage of correctly perceived locations of the moving stimulus for each starting/ending location.

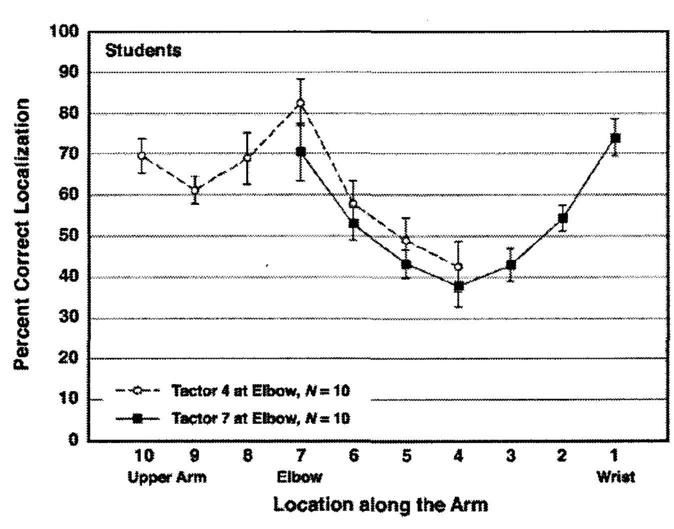


Figure 4.11: The percentage of correctly perceived locations in [13] for each location.

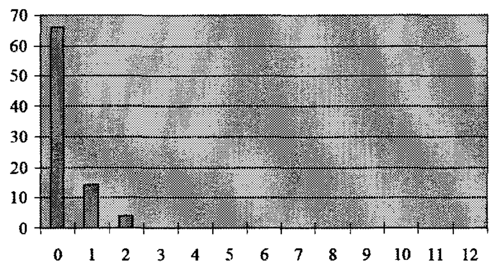
density of neurons". In addition, receptors in muscles and joints may contribute to the tactile sensations besides the receptors in the skin [29]. Although different receptors seem to respond best to particular types of stimuli, they also respond to some degree to all types of tactual stimuli [37]. This is the case here as the body joints, tendons, and muscles hold a large amount of tactile receptors [37, 9]. More specifically, Pacinian corpuscles, tactile receptors mostly sensitive to vibrations [10, 15], normally found under the skin, are scattered within the body, particularly around muscles and joints [15]. This physiological distribution of tactile receptors is behind the superior localization performance at the edges of the actuators array.

The second noticable phenomenon is that performance is better in the vicinity of the actuators than in-between them where the virtual locations are generated. By looking at Figure 4.9 we can see that the minimum accuracy is realized at locations 2, 6 and 9. Note that each of locations 2 and 6 lies exactly in the middle of two adjacent actuators. This observation is further confirmed in the moving stimulus accuracy as well where the lowest performance quality in Figure 4.10 is at locations 2, 6 and 10. Additionally, by looking at the distribution of guesses in both modes, we see that the most scattered distributions are for the locations between the actuators (virtual locations) whereas a more congregate distribution is at the locations of the actuators. To explain this finding we propose two hypotheses. First, the tendency to assume that stimulation is located at the actuator position is more intuitive and more perceivable for human mind. Hence, subjects tended to favor the belief that stimulations are normally generated at the actuator sites, and in cases of confusion between a number of points around an actuator they tended to choose the actuator site itself. The other hypothesis is that the generating the virtual locations was not perfected. However, this topic (perfection of generating funnelling illusion) is out of scope of our study.

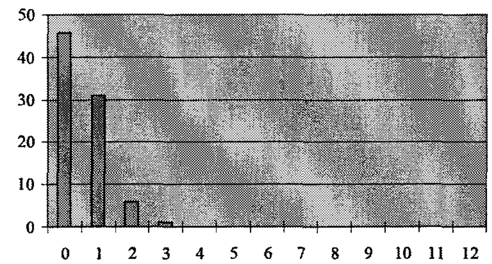
After all, this result is consistent with the findings of Weinstein [53] which states that two-point discrimination threshold - when asking the question: Do you feel one or two points - on the same site ranges from 38mm to 40mm. Although previous studies were conducted with taps or pressure pulses, rather than with the durative vibrotactile stimuli used in the present work, a comparison is still warranted. Knowing that our actuators were located 8cm away from each others allowing a 2cm distance between adjacent locations, we were not looking for absolute localization of the stimulus. Instead, we are looking for the validity of this method to represent depth, a physical quantity when visual modality is overwhelmed. The feeling of approaching the target or moving away from it is required, in addition to a moderate accuracy in the vicinity of the target which is possible using this method when the target location is mapped to the wrist or elbow.

The last observation pops out when comparing performance in the two modes. Interestingly, the moving stimulus mode further improved localization of most of virtual locations (2, 3, 5, 6, 7, 9, 10) on the expense of localizing the actuators locations (0, 4, 8, 12) when stimulated. This can best be seen by comparing Figures 4.12(c), 4.13(d), and 4.13(e) with 4.14(c), 4.15(d), and 4.15(e) respectively. The average accuracy for localizing static stimulus is found to be 31.5% within which virtual locations have 19.84%. On the other hand, the average accuracy for the moving stimulus is 32.69% within which the accuracy for virtual locations is 25.13%. Our hypothesis for this result is that the moving stimulus opens a space for mental analysis and estimations. In other words, the guess in this mode is not solely based on skin perception, but rather on relating the movement of the stimulus to the fixed positions of the actuators besides skin perception. Mental cognition interferes with skin perception on the arm to skew the results to an estimation of how far did the stimulus bypass a certain actuator location rather than having a short static stimulus where the guess is based just on skin perception.

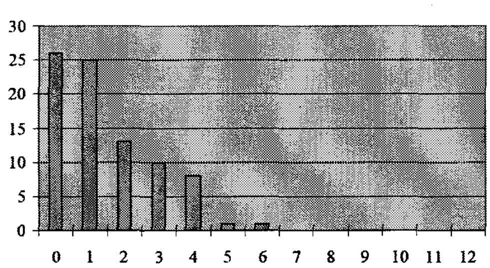
At the end, the results of this experiment are favorable for our application especially for the moving stimulus mode which is employed in the application itself. An average accuracy of 32.69% was attained with an array of 4 actuators spanning 13 different locations on the lower arm when a vibrotactile stimulus is traversing it. An accuracy of around 67% and 56% is obtained near the elbow and the wrist respectively showing a better performance in these regions. Compared to previous work done in [13], this array has a lower actuator density (4 compared to 7) and consequently lower price, higher resolution (13 locations vs. 7 locations) yet lower average accuracy (32.69% compared to 47.28%) due to the higher number of alternative locations (13 vs. 7) and consequently the shorter separating distance between them (20mm vs. 25mm). Nonetheless, this 4-actuator device is easier to wear as explained in Chapter 3. For the next experiment, we will use a moving stimulus that moves in proportion to the depth of a target object relative to a teleoperator end-effective. Careful touching will be a requirement so the target location could be mapped to the elbow or the wrist in order to utilize their high localization ability. However, to make it more intuitive so that the moving stimulus moves in the same direction of movement of the teleoperator when the arm is stretched towards the target, the target location will be mapped to the wrist.



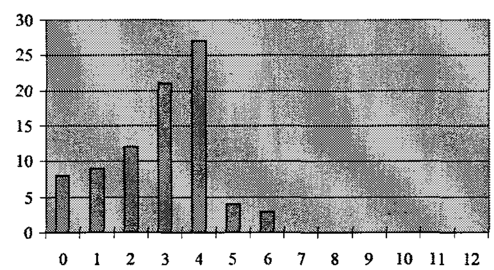
(a) Location 0



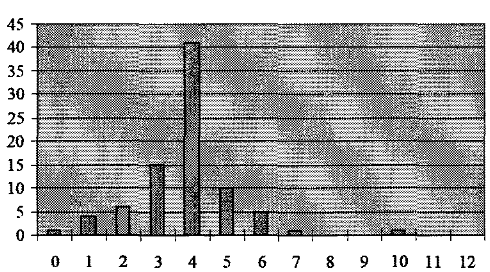
(b) Location 1



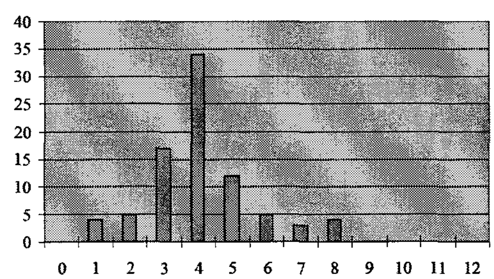
(c) Location 2



(d) Location 3

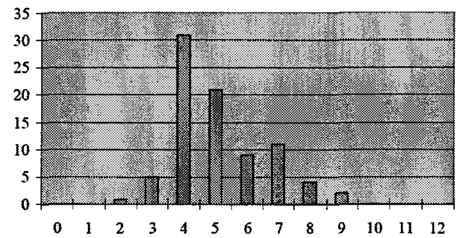


(e) Location 4

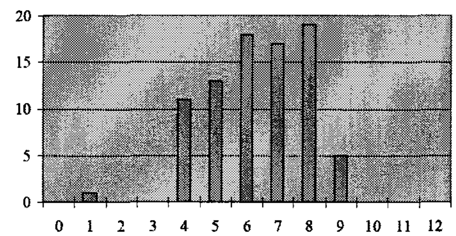


(f) Location 5

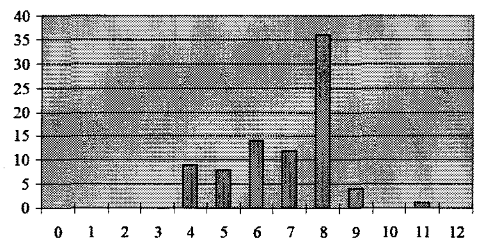
Figure 4.12: Distribution of guesses of static stimulus (perceived locations by subjects) for locations from 0-5.



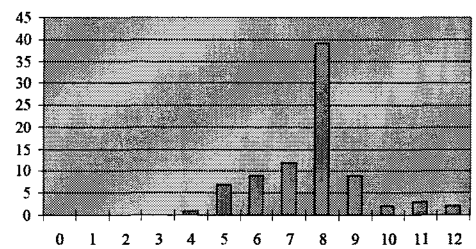
(a) Location 6



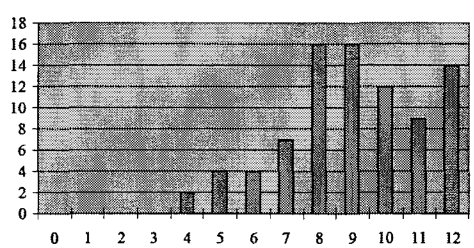
(b) Location 7



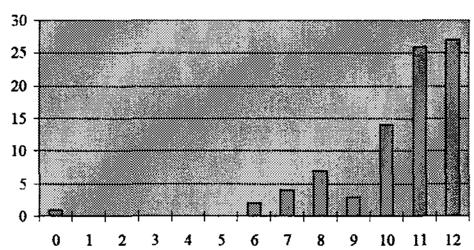
(c) Location 8



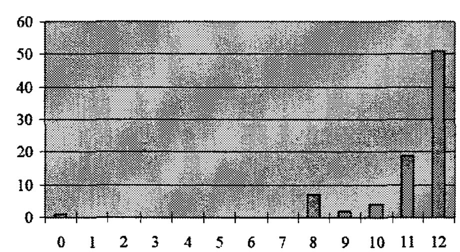
(d) Location 9



(e) Location 10

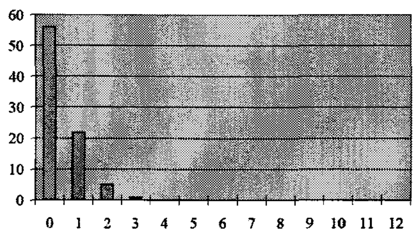


(f) Location 11

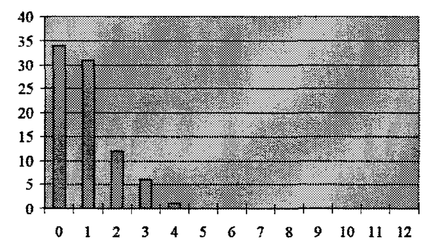


(g) Location 12

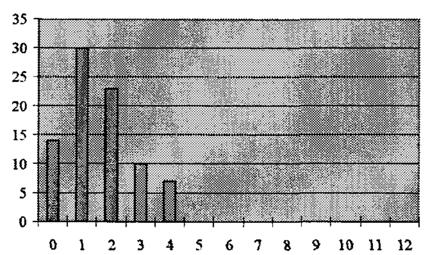
Figure 4.13: Distribution of guesses of static stimulus (perceived locations by subjects) for locations from 6-12.



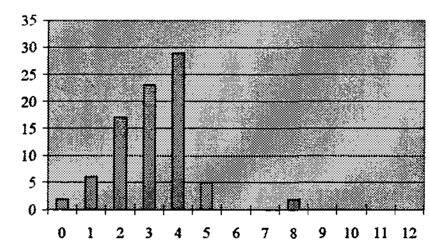
(a) Starting/Ending Location 0



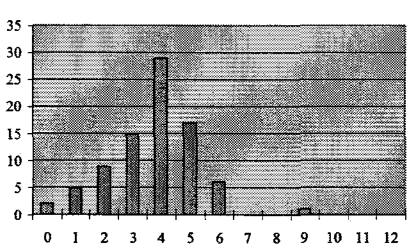
(b) Starting/Ending Location 1



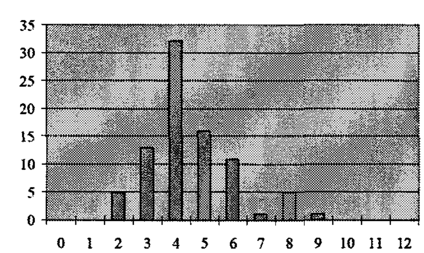
(c) Starting/Ending Location 2



(d) Starting/Ending Location 3

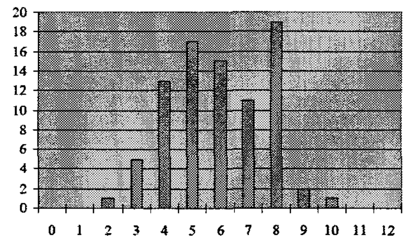


(e) Starting/Ending Location 4

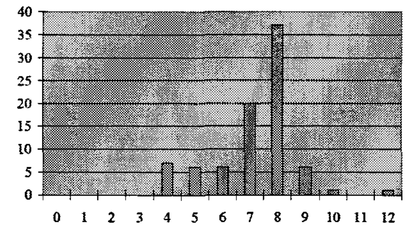


(f) Starting/Ending Location 5

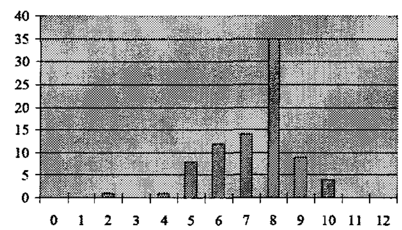
Figure 4.14: Distribution of guesses of moving stimulus (perceived Starting/Ending Locations by subjects) for locations from 0-5.



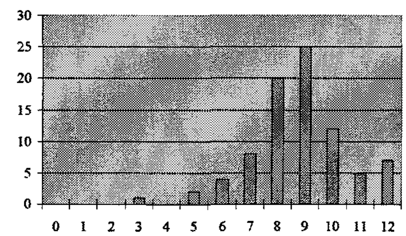
(a) Starting/Ending Location 6



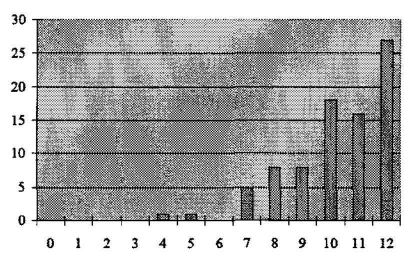
(b) Starting/Ending Location 7



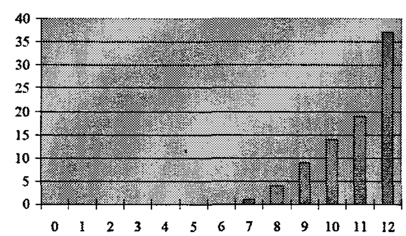
(c) Starting/Ending Location 8



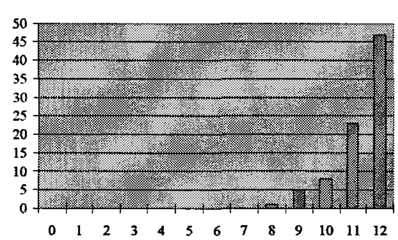
(d) Starting/Ending Location 9



(e) Starting/Ending Location 10



(f) Starting/Ending Location 11



(g) Starting/Ending Location 12

Figure 4.15: Distribution of guesses of moving stimulus (perceived locations by subjects) for locations from 6-12.

4.2 Telemanipulation Task Experiment

After studying the resolution of the proposed funneling illusion method on the human forearm in the previous experiment, we evaluate spatial perception for TPTA systems when using the visual progress bar element, the vibrotactile intensity and our method via a psychophysical experiment. Therefore, the main objective of this experiment is to compare three methods: visual progress bar, vibrotactile intensity, and moving stimulus (funneling illusion method) according to a set of criteria. In this experiment, we assume a TPTA system in a landmine defusing task, so the criteria of evaluation in order of importance are as follow: careful approaching of the target (touching with minimum force), precise approaching of the target (touching at a specific point), and finishing the task in the shortest time (with least priority). Depth perception is important for attaining these goals. Hence, the experiment will determine the depth perception improvement using each of the mentioned feedback modes, and whether our proposed method can replace the visual mode in certain circumstances or not.

4.2.1 Apparatus

An overview of the experimental setup is shown in Figure 4.16. We used a PC to simulate a 3D virtual telepresence environment shown in Figure 4.17 with its GUI. It contains a target object represented by a pink sphere and a virtual teleoperator illustrated by a smaller yellow sphere. The position of the teleoperator is controlled by a SensAble PHANToM Desktop device, which tracks the operators hand movements while providing kinesthetic force feedback as soon as contact with the target object occurs. This device has six-degrees-of-freedom positional sensing and automatic workspace calibration and all its specifications can be found on its vendor website [47]. It is located 25 cm in front of the monitor and in direction of the subjects' dominant hand and used to control the virtual teleoperator. Finally, the tactile device described in Chapter 3 was used to provide tactile feedback on the human operator's forearm in case of tactile feedback. Note that in case of tactile intensity feedback only one actuator on the wrist was used whereas in case of moving stimulus method we used the array of four actuators.

During the experiment, the distance between the teleoperator and the target object is continuously measured to be displayed either through a visual progress bar element integrated to the graphical user interface or through a tactile feedback device. In a real teleoperator environment, distance to the target object can be easily measured using certain sensors placed on the teleoperator and controlled by the PHANToM device (moves

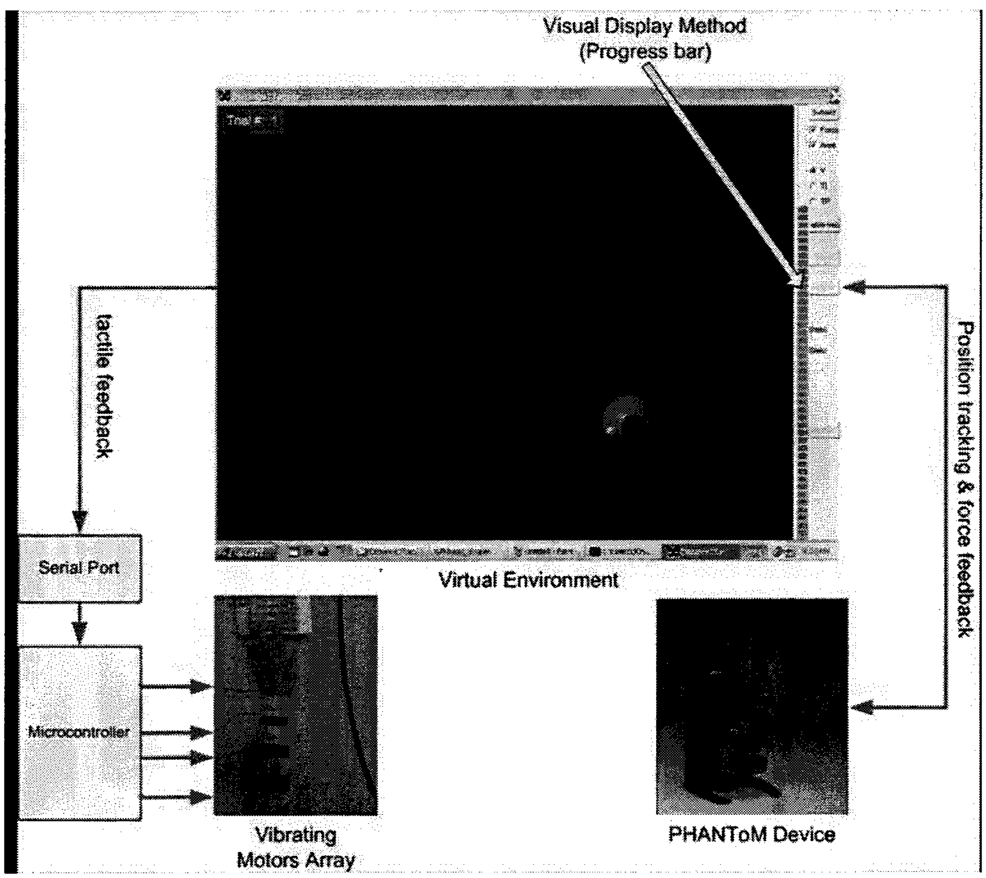


Figure 4.16: Overview of the components of the experimental testbed.

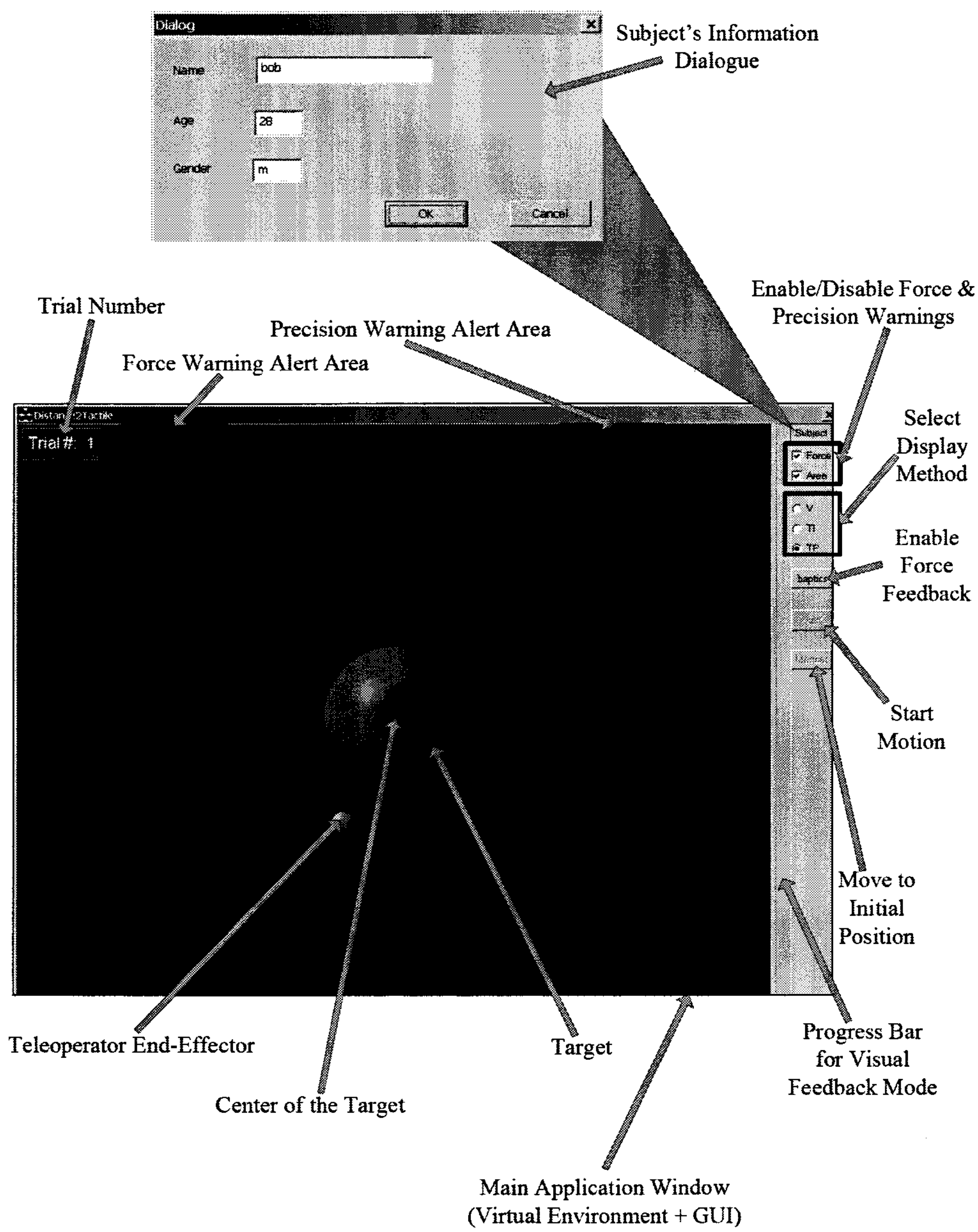


Figure 4.17: Screen-shot of the virtual remote environment.

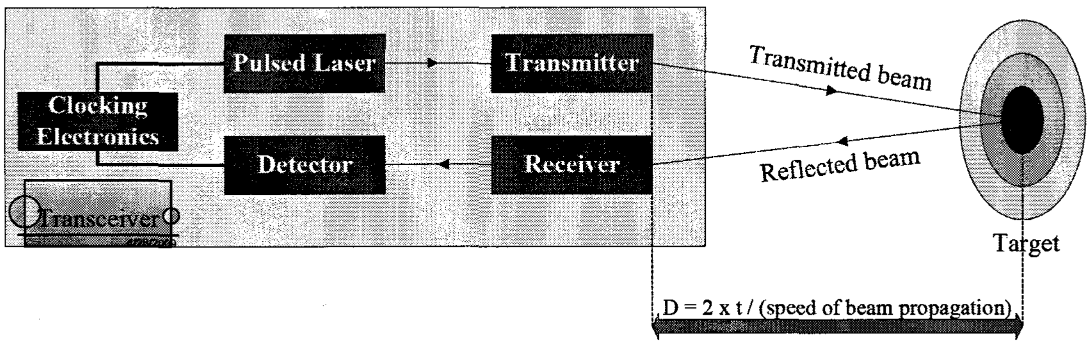


Figure 4.18: Distance measurement system block diagram and the time-of-flight measurement method

with the teleoperator movement). For example, a simple laser transceiver can be used pointing to one target object at a time and measuring its distance from it using the time-of-flight measurement method.Distance measurement transceivers are heavily used in a variety of applications such as surveying, ground profile measurements, gun fire ranging measurements (military), space radars, satellite and missile tracking, industrial machine tool control, etc...The authors in [5] provide a general review of the usual techniques for distance measurement, and Figure 4.18 shows a simple time-of-flight distance measurement approach. A device operates by transmitting a short high-power pulse toward the target. A photodetector in the ranging system receives a reflection of the pulse. By measuring the time interval taken by the signal to travel from the transmitter to the target and back to the receiver, it is possible to calculate the distance between the system and the target.

4.2.2 Participants

Twelve participants (mean age of 27.5, age range from 24 to 37 years; 10 males and 2 females), all students at University of Ottawa, took part in this experiment. All of the participants self-reported having normal or corrected-to-normal vision and a normal sense of touch. Eleven of the participants were right-handed, one was left-handed. Each experiment lasted for approximately 45 minutes.

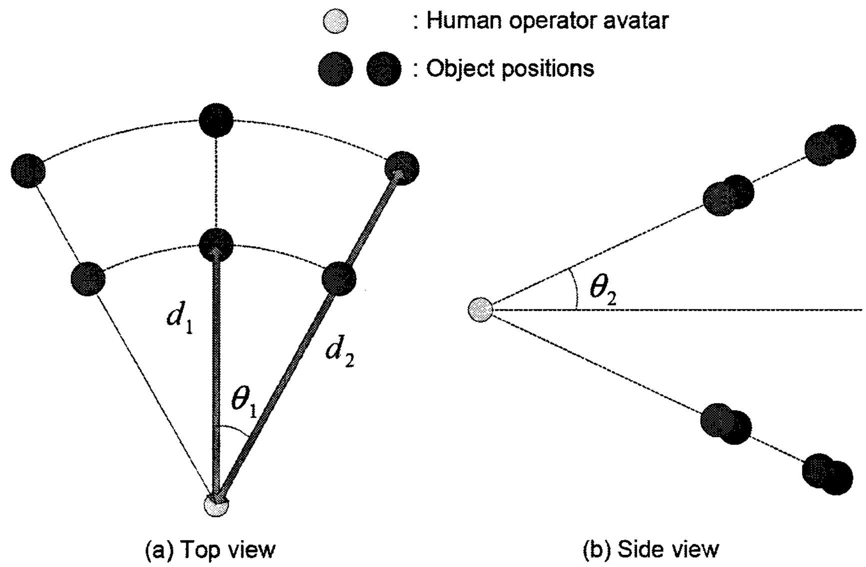


Figure 4.19: Illustration of possible spatial locations for the target object applied in horizontal and vertical direction. Therefore we have a total of 12 different target object location that are randomly selected.

4.2.3 Experimental design

For a realistic comparison between the distance feedback methods, the experiment is designed in a way that obliges the subject to focus on the distance to the target object. Hence, to assure the user is not able to perceive the distance to the target from its visually displayed geometry, the size and spatial location of the target are randomly selected from 36 different configurations.

The target object positions are determined by taking three different angles in horizontal (0, $\theta 1$, or - $\theta 1$) and two in vertical direction ($\theta 2$ or - $\theta 2$) into consideration, followed by selecting one of two different target object distances. The possible positions are shown in Figure 4.19. Additionally, each position was tested with three different sizes of the target object. Hence, the total number of different spatial and geometric configurations of the target object is 3 (size) x 12 (position) = 36.

Each distance displaying method is investigated separately in 36 trials. In order to counterbalance trends of task learning, the order of the investigated distance displaying method is randomized for each subject as shown in Table 4.3. At the beginning of each trial, the subject is guided to an initial position by giving force through the force feedback

First Mode	Second Mode	Third Mode	Number of Subjects
V	TI	TP	2
V	TP	TI	2
TI	V	TP	2
TI	TP	V	2
TP	V	TI	2
TP	TI	V	2

Table 4.3: Counterbalancing of the feedback order among the 12 subjects. V (visual mode) (progress bar), TI (tactile intensity), TP (tactile position i.e funneling illusion method).

device, which allows starting the experiment by pressing a button on the keyboard.

During the experiment, the contact force and the point of contact are monitored in order to trigger two types of notification messages: a warning and a failure alert. The warning message appeared on the screen when a contact force warning threshold is exceeded. In case of further increasing the contact force above a second predefined threshold, the trial is cancelled as the task fails. Additionally, the precision of contact is monitored. Two circular areas surrounding the target spot indicate a warning region in green enclosed by a failure region in red. Touching beyond the warning region (within the failure region) triggers a warning notification. Accordingly, further drifting and touching beyong the failure region results in cancelling the trial. The mentioned regions are illustrated in Figure 4.20.

A failed trial, however, is not repeated directly, but is randomly repeated in-between the remaining trials. Thresholds for contact force and the contact surface warnings and failures are determined by a previous pilot study.

As spatial perception is of most importance in the vicinity of the target object, an approaching region around the target object is defined as shown in Figure 4.21. Within this region, the distance to the target object is measured and displayed to the subject. At the event of contact, a full progress bar (in visual mode), the maximum vibration intensity (in vibrotactile intensity mode), or the vibrotactile position representing minimal target distance (the wrist in moving vibrotactile stimulus mode) is presented. During contact with the target object, additional kinesthetic force-feedback is displayed to the subject by the PHANToM device preventing the subject from penetrating the surface of the virtual object.

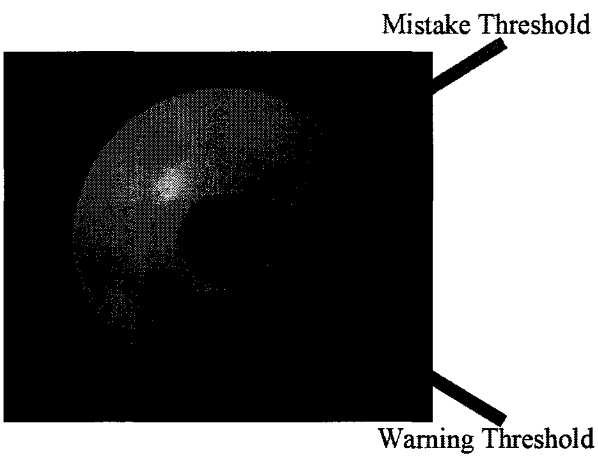


Figure 4.20: Warning and error borders on the target sphere

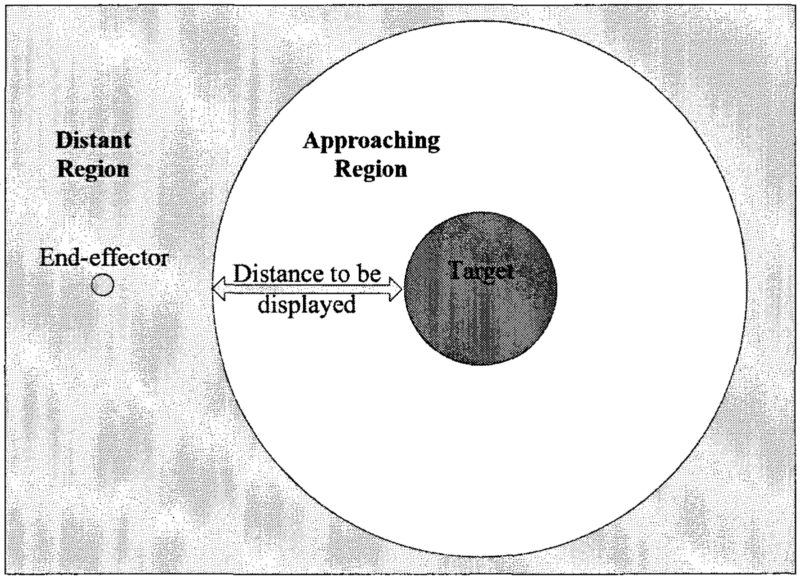


Figure 4.21: A sideview diagram showing the approaching region where to display the distance information

4.2.4 Procedure

Initially, the participants are trained at the feedback methods when touching the virtual target object, besides the driving force of the PHANToM device for the initial position guidance. Once they felt comfortable, the experiment started.

All subjects are instructed to navigate as quickly as possible to the target in order to carefully touch it and maintain contact for a time period of 1 second at the center of the marked regions with minimal contact force. The subjects were told to prioritize small contact forces and contact precision over minimal completion time.

During the experiment, the contact force and the point of contact is monitored to detect warning and task failure events. They are immediately displayed to the subject on the upper-right and upper-left of the screen, respectively.

To minimize effects of fatigue on performance, there is a 10 minutes break before switching the display method.

During the experiment, all relevant parameters of the simulated TPTA session, such as the position of the end-effector, distance to the target object, its spatial configuration, contact force, and the distance to the center of the target spot is recorded with 1 KHz sampling rate.

In addition, the number of triggered contact force and contact position warnings including the number of repeated trials due to task failures are stored together with the task completion time, the time spent before entering the approaching region and the time spent in the approaching region until the first contact.

Figure 4.22 shows the general flow of the experiment. Note that there are three states within the experiment. Initially the STATE IDLE is started where no feedback is provided. The next state is the STATE MAGNET. It starts when the user wants to start the trial. In this state, the user's hand is guided towards the initial position. Once the user's hand is at the initial position, the STATE MOTION is started in which the user can move the PHANToM device freely towards the target.

4.2.5 Results and Discussion

Each subject's performance measurements are normalized by the subject's mean followed by multiplying with the grand mean for all subjects. This allows for directly comparing individual results. An exemplary normalization procedure for data analysis (force in this example) is as follows:

- Contact force f(i, x) - the force of subject i in display mode x - is recorded during

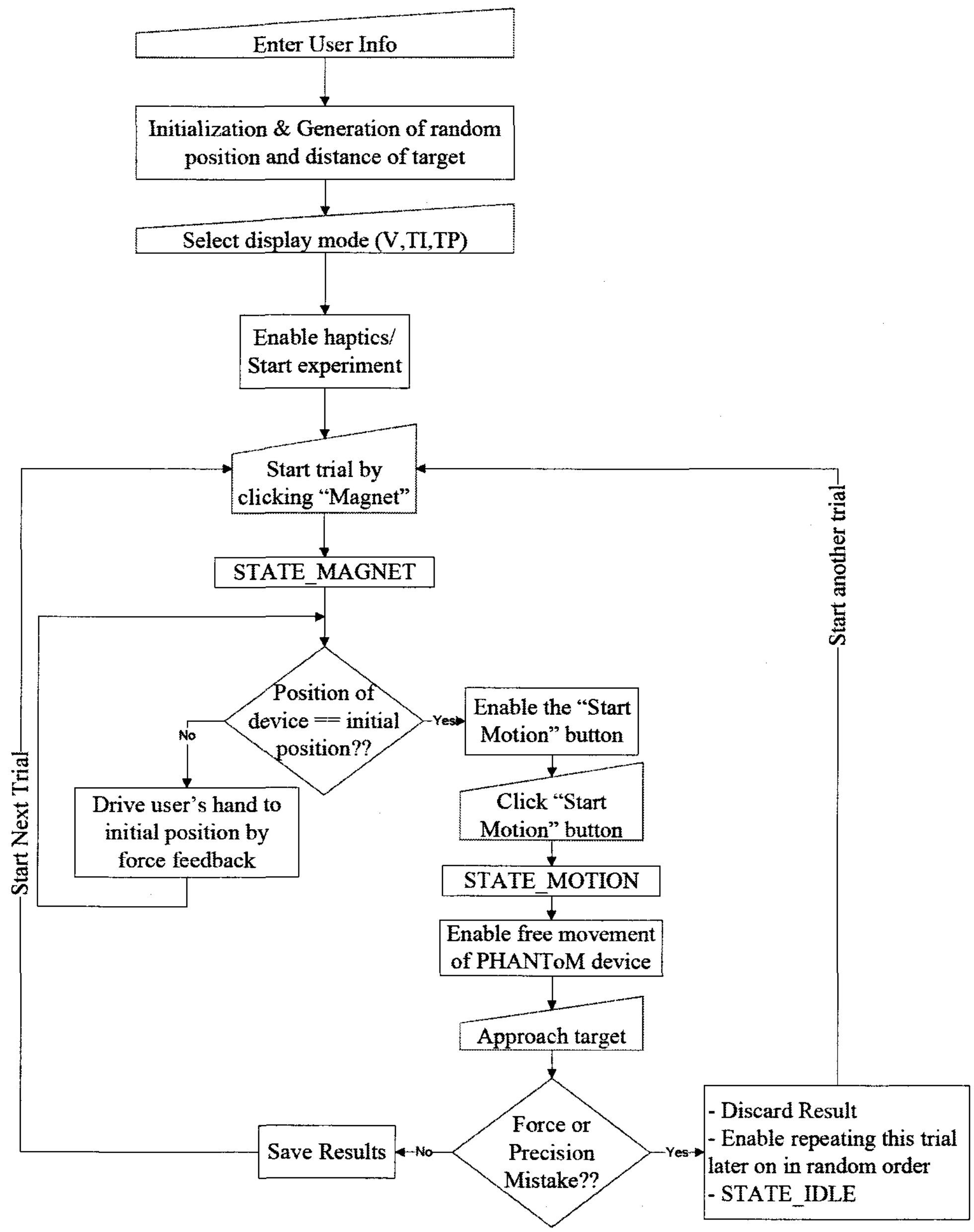


Figure 4.22: Experiment2 flowchart.

the experiment with a 1KHz frequency (i is the subject number and x is the display mode (V, TI or TP))

- We define F(i, x) by the average force of subject i in display mode x during contact with target. We find F(i, x) for each subject in each display mode by:

$$F(i,x) = Avg(f(i,x)at \quad each \quad instant \quad during \quad contact) \tag{4.1}$$

- We define Fn(i, x) by the per-subject normalized force of subject i in display mode x. We find Fn(i, x) for each subject in each display mode by:

$$F_n(i,x) = F(i,x)/Avg(F(i, all \quad x)) \tag{4.2}$$

- We define the grand mean M by the average of all the per-subject normalized forces in all display modes:

$$M = Avg(all \quad F_n(all \quad i, all \quad x)) \tag{4.3}$$

- We define FN by the final normalized force which is the per-subject normalized force multiplied by the grand mean M. We find FN for each subject in each display mode by:

$$F_N(i,x) = F_n(i,x) \times M \tag{4.4}$$

- The final normalized forces FN's are the basis for our analysis (averaging, standard deviation, ANOVAs, T-tests, etc). All other performance parameters are normalized in the same way followed in this example.

Analysis of initial contact force and contact position

Usually, shortly after contact with the target, human operator minimized their contact force to a just-touching value. Hence it is more beneficial for evaluation to consider forces before this adjustment. To determine the averaging force window, exemplary recordings of the contact force were taken such as the recording shown in Figure 4.23. We found that the average time for the force to reach its maximum (just before adjustment) is at around 300ms. Therefore, in our analysis we average the contact force in a

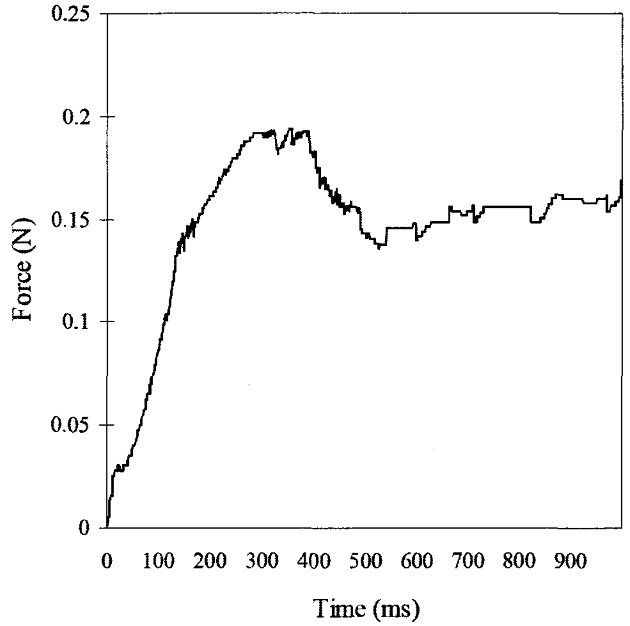


Figure 4.23: A time history of a trial in the V display mode for the contact force for 1 second after the first contact

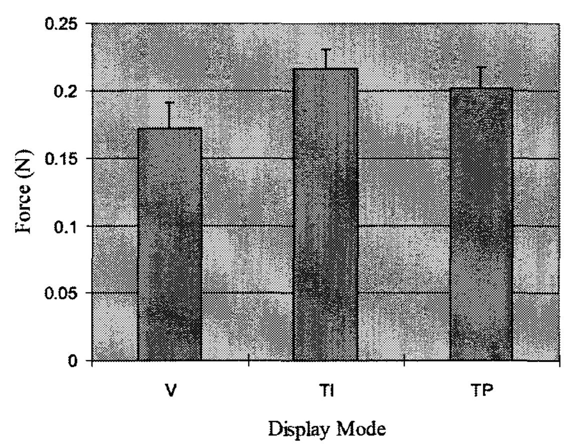


Figure 4.24: The average value of the contact force for 0.3 seconds after the first contact

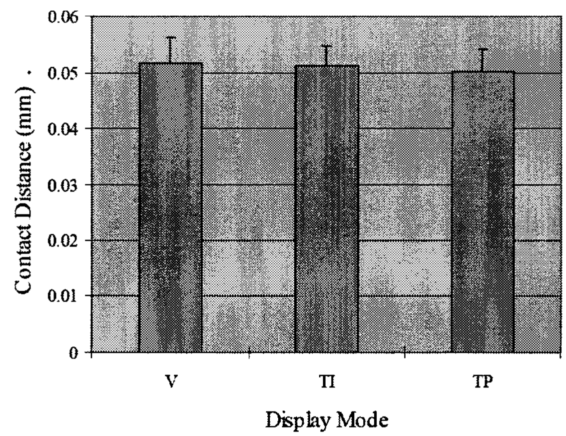


Figure 4.25: The contact distance from the center of target when touched for the first time

300ms window just after the first contact. The results are shown in Figure 4.24, indicating a significantly better performance of the visual distance display method (ANOVA $F(2,33) = 22.9, p < 0.0001$). Additionally, a T-test ($t(22) = 2.4, p = 0.03$) between the two virbotactile feedback methods reveals significantly smaller contact forces for the distance to vibrotactile position coding method. Therefore, in this aspect (contact force) which has the highest priority in our evaluation, TP method outperformed TI method and is able to replace the visual feedback as the complexity of the scene increases.

To evaluate the precision of the initial contact, the distance to the center of the target area has been taken into consideration. Figure 4.25 reveals that there is no significant difference in accuracy between all investigated distance feedback methods. An ANOVA supports this finding ($F(2,33) = 0.380, p = 0.7$).

Analysis of warnings events

The average number of warnings for contact force and contact precision is shown in Figure 4.26. A one-way ANOVA analysis ($F(2,33) = 14.4, p < 0.0001$) for contact force warnings, and a one-way ANOVA analysis ($F(2,33) = 7.39, p = 0.002$) for contact position warnings indicates that the subjects significantly performed better with visual than with the vibrotactile feedback. Between the two vibrotactile display methods, no significant difference in contact force warnings performance is achieved. A T-Test with

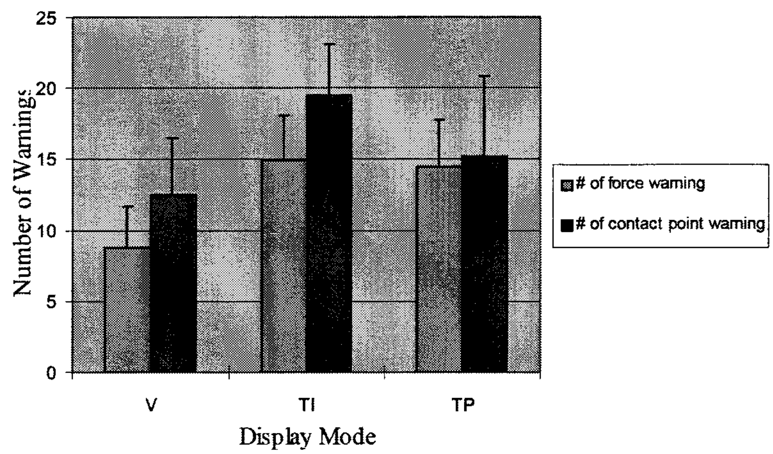


Figure 4.26: The average value of the number of warnings for each display mode (V - Visual progress bar, TI - tactile intensity, TP - tactile position).

$t(22) = 0.3, p = 0.8$ confirms this observation. The average force - from the previous section - for TI is around 0.22N while for TP 0.2N. Therefore, TP could further minimize the contact force, but both methods had the majority of contact forces below the force warning threshold predefined to be 0.4N. Consequently, having a smaller force warning threshold could have caused more warnings for TI method and exposed the difference in performance between the two methods (TI and TP).

Now for the contact position warnings, the vibrotactile position mapping method performs significantly better compared to the vibrotactile intensity feedback. A T-test between both vibrotactile methods shows $t(22) = 2.2, p = 0.04$. In addition, a T-test of contact position warnings between visual and the vibrotactile position feedback shows $t(22) = -1.3, p = 0.2$, which indicates no significant difference in performance. Therefore, better performance in V and TP methods over TI method was obtained.

However, better performance in V and TP modes over TI for the number of contact distance warnings does not seem reasonable because the subjects could focus on the target area (green circle) visually in the three display modes. In other words, the same given - which is the view of the target - is used in the three modes and consequently there should be no difference in performance for reaching this target especially that in the previous section, we reported similar performance for the contact point precision over all

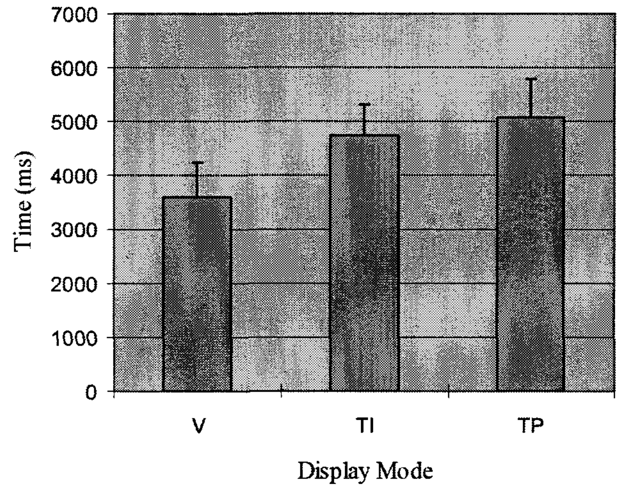


Figure 4.27: The average value of approaching time for each display mode. (V - Visual progress bar, TI - tactile intensity, TP - tactile position)

feedback methods. For further investigation, we looked again into the average force and the first contact distance (contact precision). Tactile intensity showed less contact precision (according to warnings) although the first contact performance is similar to other methods. Therefore, the low precision did not occur on the first contact, but sometime after. Investigating this phenomenon and knowing that tactile intensity average force is higher than other methods (although still less than average force warning threshold) revealed that the larger contact force leads the teleoperator to slip over the surface of the target and therefore deviate from the target center and cause extra warnings. This effect was also reported by subjects during the experiment.

Analysis of the approaching time interval

Figure 4.27 illustrates the average period of time taken in each feedback method between the instant of entering the approaching region until the first contact. Our results show that visually displaying the distance information allows to approach the object significantly faster compared to tactile distance feedback. This observation is also observed by an univariate analysis of variance (ANOVA) of the approaching time period ($F(2,33) = 17.04, p < 0.0001$). According to a T-test ($t(22) = -1.3, p = 0.2$), no significant difference in the approaching time is found between the performance of distance to

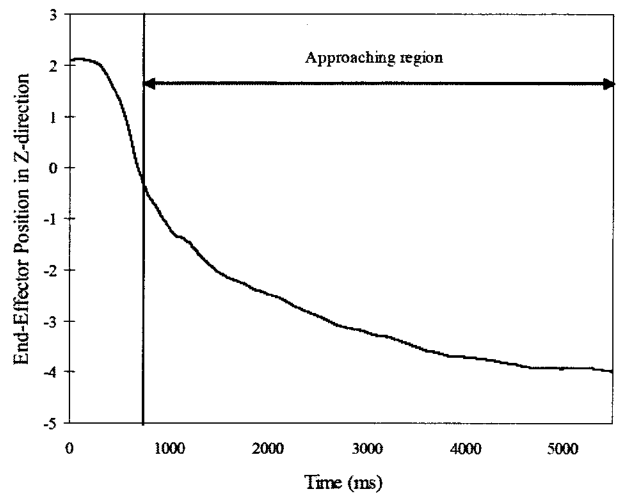


Figure 4.28: Exemplary recording of the end-effector position along the Z axis before the first contact. As soon as the subjects enter the "approaching region" which triggers additional distance feedback, velocity of the teleoperator descreases in order to carefully approach the target object.

tactile intensity and distance to tactile position mapping.

During the experiment, subjects quickly navigate towards the target object. As soon as they enter the predefined approaching region within which distance feedback is presented, they slow down in order to carefully touch the object with minimum speed. This behavior is observed for all three displaying methods and illustrated in Figure 4.28. The rate of change of position (velocity) decreases as the virtual teleoperator approaches the target.

To explain the almost similar performance of TI and TP for approaching time we refer again to Fig. 4.28. The subjects spent most of the time of a trial approaching the object and then precisely controlled their movement in the vicinity of the object. Their focus on the tactile display was mainly in the very proximity of the target which is a very short period and a difference in timing during this period can hardly be noticed. Therefore the two tactile display modes did not make a big difference in the approaching time.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we presented a new way for displaying depth information in 3D environments. The main trend of providing depth perception is the use of stereoscopy which has certain limitations. Other methods encompass visual cues such as shadows, occlusion, etc... which usually give clues about the relative positions of objects in 3D environments rather than their distances to an operator's location. Additionally, presenting depth information with simple visual methods (such as a progress bar) overloads the visual modality with this additional information and might cause distraction from the main task (depending on the complexity of the scene itself). Our proposed method is to use funneling illusion for moving a vibrotactile stimulus analogous to a progress bar on the arm to indicate the distance of a certain (one) target. Although this method can be generic for representing any physical quantity, it is more successful in a risky teleoperation task (like disarming bombs or landmines) in which depth information is important for carefully touching the target with minimal force, maximum precision and full concentration on the main task.

To this end, we developed a 4-actuators tactile device (based on a work done in a Master's thesis in the University of Ottawa for optimizing continuous movement using funneling illusion) that utilizes funneling illusion to move a vibrating stimulus on the lower arm. This device is used to conduct two psychophysical experiments to verify the applicability of our method for representing depth information in 3D environments, and more specifically in TPTA systems.

The first experiment tested the resolution of the funneling illusion method as to the number of distinguishable stimulated locations on the lower arm. Static and moving stimuli were tested on 13 different locations with an accuracy above 30%. Both stimuli modes produced best localization accuracy in the vicinity of the joints (elbow and wrist), followed by the locations of the actuators themselves, then the least accuracy at the virtual locations between the actuators. However, the moving stimulus which is the one to be used in the application (TPTA) improved localizing the virtual locations and had an overall average accuracy of 32.69%.

In the second experiment we tested the proposed method in a TPTA scenario with critical conditions for approaching the target. The operator moved a 6-DOF PHANToM device - which moved a small sphere in a simulation of the remotely operated environment - to carefully approach the target. The distance between the teleoperator and the target was continuously measured and displayed to the human operator by one of three modes: a visual mode that uses an on-screen progress bar, a tactile intensity mode that changes the intensity of a vibrator on the wrist, and the funneling illusion method that changes the location of the stimulus on the arm. The three methods were compared according to the quality of performing the task based on the average force used upon touching the target, the precision of the touch and the task completion time. The visual method was superior in all aspects except in precision of the touch. Our method outperformed tactile intensity method and proved to be able to replace the visual method as complexity of the scene increases.

To sum up, the proposed method can represent depth information with the advantages of: reducing overloading of the visual modality, avoiding operator's distraction (information display doesn't need to be in the field of view), and achieving a high information bandwidth (by utilizing the tactile modality) with a relatively low data rate (no need for two video streams). Therefore, the method is convenient for presenting information in situations involving complex visual scenes, much distraction for operators and requiring significant accuracy of performing the main task (such as disarming of bombs, minimal invasive surgeries, etc).

On the other hand, displaying depth tactually on the human forearm suffered certain limitations. On the psychophysical level, the human forearm showed non-uniform sensitivity where the provided stimulus was better identified at certain points than others. This was clear in the high localization ability at the elbow and the wrist compared to other points on the arm. Second, the stimulus at the funneled positions was not optimized (out of our scope at this level) which resulted in better localization ability at the actuators' positions. Finally, adaptability for some users was an issue because they felt distracted by the stimulus on the arm, or that their arms became numb after a while. Therefore, when a simple non-dangerous task is performed in a simple environment where little information is to be displayed, it is recommended that this information be displayed visually in the field of view of the eyes.

5.2 Future Work

A number of future works is proposed to potentially improve the results of this method. First we plan to investigate the influence of training and learning paradigm on the localization performance of the first experiment. This can be done by displaying the correct answer for the stimulated location after each trial which might allow the subjects to adapt their answers for subsequent stimulations of the same location. Comparison can be done between a non-feedback-mode and a feedback-mode - where answers are displayed as explained - for the same subject in order to discover this influence and whether it improves localization or not.

Another potential improvement to be done is to calibrate the intensities of the incorporated actuators for each intended location. For instance, providing a higher loudness for the virtual locations might positively affect their localization especially that subjects repeatedly reported that the virtual stimuli were felt less loud than the real ones. Calibration can be done by stimulating a certain location and asking the subject about the site of stimulation, and continuously adjusting loudness until the stimulated site is correctly localized. After calibrating the intensities for each location (by averaging of many subjects), the in-between intensities can be interpolated in order to provide the continuous feeling.

A third potential improvement of the method is to extend the area covered by the device to include the whole arm. This allows more spacing between the actuators and consequently higher localization accuracy. When this was done in [13], results improved significantly and average localization rate increased from 47.28% to 79.86% for seven distinct locations.

Additionally, it is worthy to conduct the second experiment with a reversed direction of stimulus motion. In our experiment the stimulus moved from the elbow to the wrist in order to be aligned with the motion of the teleoperator and to maintain intuitivity. Eventhough the reversed direction from the wrist to the elbow is less intuitive, it might improve the results especially that the first experiment showed a better performance at the elbow than at the wrist. This could mean a higher accuracy at the proximity of the target when mapped to the elbow.

Furthermore, we plan to re-conduct the telemanipulation experiment with more visual distractions including a crowded visual scene and a more complex task. This more realistic visual scene might skew the results to our method. In addition, our future work will investigate the performance when combining visual and vibrotactile feedback. Furthermore, additional psychophysical experiments on cross modal perception can be used to further improve parameters of the presented feedback techniques.

Besides these improvement proposals, we plan to investigate the applicability of this method to the fingers in an attempt to build a tactile glove. The purpose of the glove would be to display the penetration depth of the fingers in a certain object. This can be beneficial for telesurgery applications for example when proper techniques for extracting this depth are available. The importance of applying our method for such a glove lies in the significance of space utilization on the fingers. As there is not much space on the fingers to place many actuators, using the funneling illusion method for generating the in-between locations can be a great advantage. However, psychophysical properties of the fingers would be studied as well.

The last future work to be mentioned here is to explore the applicability of this method in games. It can display many quantities important for a game player, but at the same time might cause distraction when looking at them. For example, in many car racing games a certain button has to be pressed in order to look in the mirror at the cars approaching from behind. Providing the distance to the cars behind tactually might omit this distraction. Additionally, in fighting games (like street fighter), the lifespan or armor or number of remaining bullets in a weapon before reloading can be displayed tactually on the arm. In fact, this idea seems to have a good potential in gaming.

Finally, we are glad to contribute for the utilization of the haptic modality which has not yet been exploited properly, especially when this utilization is non-invasive and beneficial for alleviating other modalities.

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