# 3-D Virtual Maze with Multiple, Bimanual Feedback Mechanisms: A Comparative Analysis of Feedback Effectiveness

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*Abstract*— **The purpose of this research project is to rank the effectiveness of various computer-controlled, bimanual feedback mechanisms (BFMs). Bimanual feedback (BF) is a fairly new and unexplored area of haptics. The purpose of ranking these BFMs is to identify which methods would prove most effective when implemented in novel, upper limb rehabilitation devices, namely for individuals recovering from stroke or extreme neurological or physical trauma and damage (such as muscular dystrophy or atrophy) and training for prosthetic usage. To facilitate BFM ranking, experiments were done with a virtual 3-dimensional maze, two SensAble PHANToM OMNI haptic devices, and force- and position-based guidance programs. Collected data was evaluated based on time required to complete each maze. The data collected suggest a constant force feedback has the highest efficacy between the three modes tested. Mirror symmetry was most confusing for users. One participant traversed the maze with no feedback and was unable to find the finish point within 3 minutes, suggesting a benefit to all feedback methods tested.**

## I. INTRODUCTION

Haptics utilizes an understanding of human beings interactions with environments to create useful and realistic human-robot interactions. Examples of haptic devices include the Da Vinci Robot, Oculus Rift, and humanoid robots. Much research has been put into understanding human proprioception and kinesthesia– our personal, physical positioning awareness and how we sense, interact with, and identify our surroundings. Understanding these processes and human physical sensing limitations has enabled researchers to develop several technologies and methodologies to advance the medical, entertainment, and defense industries. Understanding people's learning styles and compensatory strategies is not as well known or researched, but this knowledge holds the key to improving haptic technologies and making them more useful and available in academic and rehabilitative forums. These psychological and physiological aspects are far more time consuming and difficult to study, but researchers have been putting more effort and funding into understanding them [1].

A key component to any successful haptic device is the use of appropriate feedback mechanisms (FMs). Most of the FMs currently used take advantage of the body's senses and nervous system in various fashions. Feedback methods are broken down into different overall classes based on the sensory organs and pathways used: visual, physical, auditory, etc. These sensory classes are then subdivided based on the specific type(s) of mechanoreceptors used [1]. Some examples of physical mechanoreceptors include: Merkel Receptors that measure pressure, Meissner Corpuscles that measure tapping on the skin, Pacinian Corpuscles that measure vibrations, and Ruffini Cylinders that measure skin stretch [2]. Basically, FMs in the physical class will use vibrations, heat, pressure, skin stretch, etc. to relay information from a robotic device to its user. Much attention and research efforts have been concentrated on physical FMs, specifically those that use vibration and force appliance. Acoustic and visual FMs have also been extensively used. Some cutting edge research is incorporating more of the body's anatomy with robotic devices by dealing with nerve reinnervation for amputees, but this is still in the developmental stages [3]. The efficacy of bimanual FMs (BFMs) is one area that has not been explored in-depth. BFMs incorporate both pairs of limbs– as in either both arms or legs– to apply customized feedback based off of the user's input and abilities. BFMs can be represented as a closed loop system operated from user inputs with designated responses executed by an algorithm. BFMs not only rely on physical qualities to work efficiently, but are also heavily dependent on psychology– the qualitative aspects of interpretation, reaction, learning, teaching, and memory. Understanding these psychological aspects will provide pertinent information for advancing haptic technologies used for rehabilitation and training.

To help facilitate understanding of the psychological and physical (commonly referred to as 'psychophysical') human factors, the body's information pathways can be analyzed on two macroscopic levels: the body's efferent and afferent information pathways. Afferent studies focus on how the body acquires and relays information from sensory organs to the nerves and brain. Efferent studies deal with how the brain interprets and passes along commands through the nerves to various tissues. These types of studies are outside of the scope of this preliminary analysis, but will be explored in future experiments. This is especially important as the long-term goal of this research is to identify the most efficient devices, methods, and modules for rehabilitation and training.

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## II. BACKGROUND

Implementations of haptic devices have been proven to be an equal if not superior method of rehabilitation and training compared to traditional physical and occupational therapy methods [5], [4], [6], [8], [7]. Depending on the user interface and exercise routines, robotic devices have also been shown to be more interactive and enjoyable for users [9], [6]. Robotic systems also provide more quantitative information and a potentially higher cost-to-benefit ratio than the current traditional methods. These systems provide a level of applied consistency and customizability, user independence, and device portability which traditional methods cannot offer due to the variability of human-human interactions, physician dependency, and facility limitations [6].

The purpose of this project is to compare three types of BFMs and rank them according to guidance effectiveness: which encompasses ease of user understanding and interpretation of feedback with appropriate reaction execution. An effective BFM will positively affect the user's long-term memory, motor control, and coordination [1]. Ranking BFMs will allow recommendations to be made concerning which BFM is most appropriate for a specific haptic application. Ultimately, these mechanisms and methods will be used in novel rehabilitation, gaming, and training devices, especially for individuals recovering from stroke, extreme neurological or physical trauma (such as muscular dystrophy or atrophy), or training to use a prosthetic limb.

The two forms of BFMs explored in this project are position- and force-based guidance systems. Force-based guidance is achieved by exerting a constant force through a robotic arm to the user's hand. This force traces out desired pathways the user must mimic using his other hand. These pathways are created voxel to voxel– a designated digital space– based on the mimicking hand's position within the maze. Position-based guidance is achieved by exerting a sudden change in position from the robotic arm's origin followed by a less-forceful movement back to the origin. This movement is interpreted as a sudden jerk, with the leading direction from the origin representing the direction that must be traveled by the other hand. The jerk direction is controlled by the user's location within the maze and always points toward an empty voxel nearer to the maze completion point. Within the position based guidance scheme, two forms of interpretation were explored: visual and mirrored (joint-space) symmetry. Under visual symmetry, the user senses the jerking direction and translates identical directions to the other hand (Fig. 1). Under mirrored symmetry, the user translates all the directions of the guidance feedback with the same directionality except for in the right and left directions, which are mirrored (Fig. 2).

Only the right-left directions were mirrored to replicate natural, human arm motion. People naturally move their arms up-down and in-out with common directionality while moving right-left in opposing, mirrored directions to create stability. When moving in the same right-left directions with both arms, moments and instability are created, which goes against natural human tendencies; this theory is tested with visual symmetry trials.

## III. EXPERIMENTAL SETUP

To draw comparisons between the two position symmetries and the force guidance BFMs, a 3-D, virtual maze was constructed which could be navigated by a person using two SensAble PHANToM OMNI devices. One OMNI was used for navigation within the maze and the other was unconstrained and used for feedback (guidance). The navigation OMNI was manipulated by the participant's dominant hand and was completely controlled by the user. The proxy point associated with this navigation OMNI was confined to the 3-D maze's channels. The guidance OMNI was not constrained by the maze in any form and was assigned to the participant's non-dominant hand and strictly used for feedback application to the user. To ensure only physical sensing and interpretation of the guidance OMNI was being used, no visual displays were provided to participants (Fig. 3). Although other researchers have explored learning and feedback interpretation with OMNIs and similar devices, most have used a single device and highly differentiated interfaces with visual displays [10], [11], [12]. The designated functionality of the dual Omni setup, virtual object interaction, and elimination of visual cues makes this project uniquely designed for evaluation of BFM efficiency based on solely haptic interactions (Fig. 4).

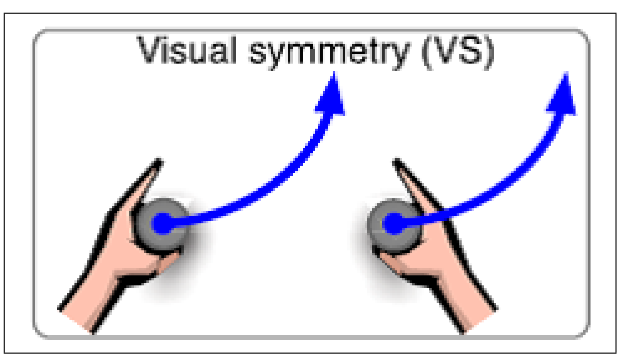


Fig. 1. Visual Symmetry Interpretation in Position-Based Guidance [11]

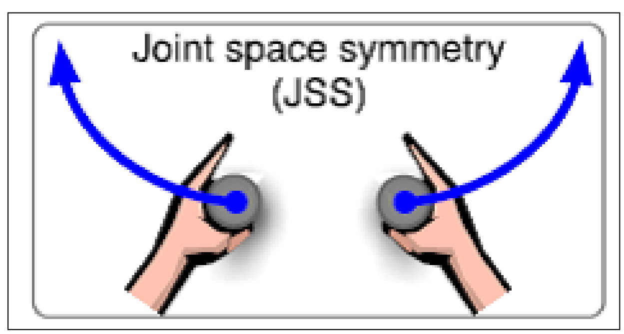


Fig. 2. Mirrored Symmetry Interpretation in Right-Left Directions in Position-Based Guidance [11]

## IV. PROJECT MOTIVATION / ORIGIN

This project's inspiration is based off of creating a virtual system that mimics an old wooden maze and using the navigational methodologies to better understand proper haptic guidance systems as applied to rehabilitation and training. The wooden maze has channels cut inside of it and players simply insert a small marble into the maze box and blindly navigated it through the channels into the exit slot. The only way for the player to navigate the marble through the maze is by solely using their senses of touch and sound, which makes this task quite challenging at first. They can feel the changes in weight distribution as the marble moves, the impact forces generated when it hits dead-ends and bounces off walls, and all the noises associated with the physical glass-on-wood interactions (rolling and impact). With practice and patience, players can begin to build muscle memory of the maze and complete the task quite efficiently. This exercise (which is essentially a fun game) can be made into quite a useful training mechanism to help hone in on physical awareness, conditioning, and control without the use of sight, which is exactly what kinesthesia and proprioception are all about. This game incorporates several tactile senses and exercises, such as mental focus, patience, and memory. All these factors are detrimental to properly rehabilitating or training people.

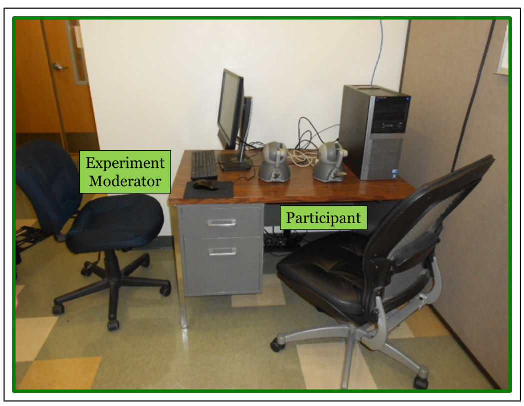


Fig. 3. The experiment setup is shown. Subjects have no visual feedback.

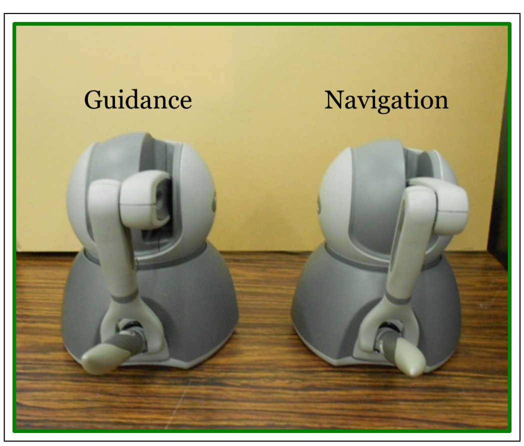


Fig. 4. Dual OMNI Setup (Right-hand Dominant Front View)

If developed properly, BFMs can be used in rehabilitative and training applications to simulate this type of 'game' and generate all of the same benefits for the user. In addition, users can increase muscle conditioning and mass, long-term muscle control, and their overall happiness, well-being, self-esteem, and independence through repetitively completing virtual, BMF driven tasks. (These benefits and their link to traditional rehabilitative and occupational methods have been discussed in the introduction.) The bettered physical and psychological health of the users will trickle out to others and ultimately make society happier and healthier as well [13]. Additionally, using a game based system and interface can help make rehabilitative and training exercises more enjoyable (especially for children) and incorporate a bit of competition; all of which can increase patients' willingness to use it and generate positive responses for its usage. A possible product that can be developed from this research project is a bimanual program and device that would not only provide a way to increase patient's physical abilities through proprioception and kinesthetic exercises, but also exercise patience and memory.

## V. PARTICIPANTS

All subjects were healthy individuals between 21 and 59 years of age with no physical or psychological limitations. This was a preliminary study, so we needed a normal subject population to gage the effectiveness of the three BFMs. This BFM ranking will allow for the identification of appropriate feedback mechanisms for individuals with various limitations. 8 people participated: 7 male and 1 female; 5 right-handed and 3 left-handed. All participants majored in mechanical engineering except for 2, who had no educational linkages to haptic devices. Half of the participants had no prior experience with robotics or haptic devices. The participants were recruited by word of mouth and email of this opportunity and received no compensation for participation. The experiment was conducted in accordance with the University of South Florida Institutional Review Board ethical guidelines.

## VI. EXPERIMENTAL PROCESS

Before beginning, each participant filled out a few general questions about relevant robotics experiences. Then, each participant explored a simple, training maze module to familiarize themselves with the Omni and what virtual channels feel like (Fig. 5). No BFMs were activated during the training module so first time response data could be analyzed. Once they became comfortable with the system, they were transitioned into the more complex, experimental maze module (Fig. 6, 7, and 8). Participants never viewed images of the mazes before or during the trials to ensure their responses and interpretations were solely based on haptic feedback and not sight with logistics for navigation. BFM order was always presented with force guidance second and alternately chosen position guidance symmetry for first and third. This was done to avoid any confusion when switching between visual and mirror symmetries while maintaining

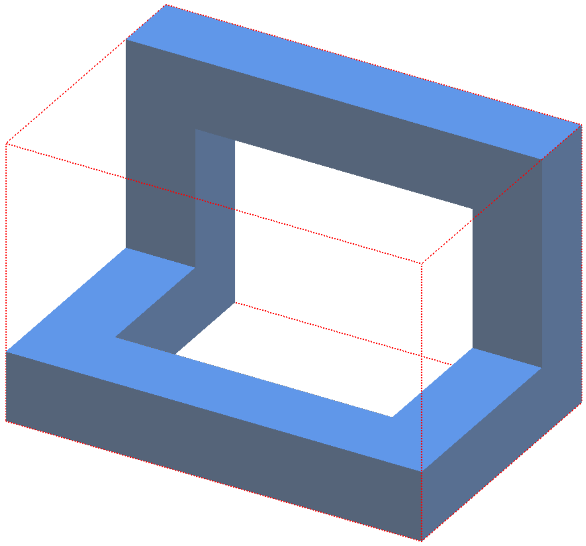

Fig. 5. Training Module Maze

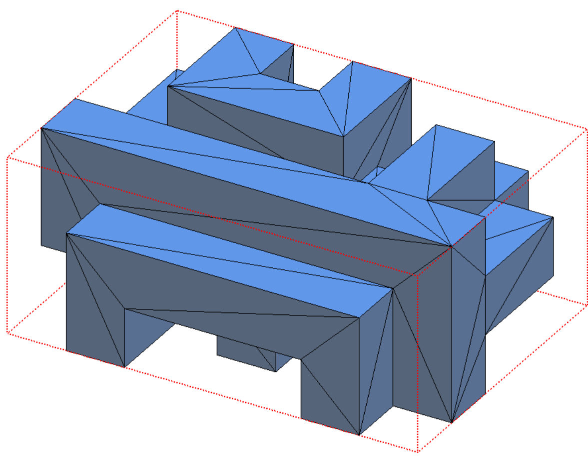

Fig. 6. Experimental Module Maze (Front Oblique)

a level of random variation. Three trials were conducted per BFM before moving on to the next with 30-60 second breaks between each trial and between BFMs. The complete experiment lasted approximately 30 minutes per person. Once the participants completed all BFMs, they filled out a questionnaire for qualitative feedback on their experience.

## VII. Analysis

### A. Quantitative Analysis

A total of three BFMs were tested: one force- and two position-based. Matlab was used to plot images of the pathways taken and find the time required to complete the maze. These values were compared and ranked on effectiveness: highest effectiveness corresponds to the fastest time to completion and most direct pathway taken.

### B. Qualitative Analysis

Users were surveyed on the relative difficulty of navigating with the assistance of each BFM.

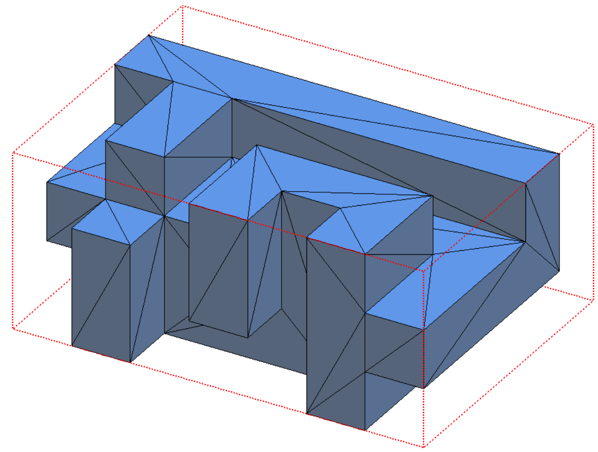

Fig. 7. Experimental Module Maze (Rear Oblique)

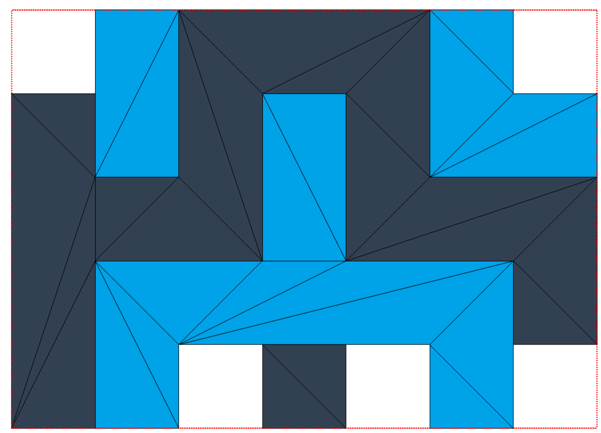

Fig. 8. Experimental Module Maze (Bottom Face)

## VIII. Results and Discussion

### A. Quantitative Analysis

Using the mirror symmetry position-based BFM, users were able to navigate the maze in an average time of 61.9 seconds. With visual symmetry position-based BFM, users completed the maze in an average time of 45.5 seconds. A constant force BFM resulted in an average completion time of 40.3 seconds.

### B. Qualitative Analysis

Tallying the post-experiment questions revealed some interesting participant interpretations about the experiment overall. Table I shows that the vast majority of participants agree that visual symmetry in position based guidance is the easiest method to follow, while mirrored symmetry in the same guidance mode is the most difficult to follow.

TABLE I

Number of Participants Ranking Difficulty of Each BFM

| BFM | Easiest | Most Difficult |
|---|---|---|
| Visual | 6 | 0 |
| Force | 1 | 2 |
| Mirror | 1 | 6 |

## IX. CONCLUSION

This research project is aimed at ranking the effectiveness of various computer-controlled, bimanual feedback mechanisms (BFMs). Ranking the BFMs allows for identification of the most effective method(s) for implementation in novel, upper limb rehabilitation devices, namely for individuals recovering from stroke or extreme neurological or physical trauma damage (such as muscular dystrophy or atrophy) and training for prosthetic usage. Qualitative data suggests that that administering position based feedback and implementing visual symmetry as the response motions is the most easy to interpret and follow while implementing mirror symmetry is the most difficult method.

## X. FUTURE WORK

There were several position errors within the data collected. These were detrimental to the analysis of total distance traveled and amount of time spent more than one cell backwards from the furthest progressed point. Future experiments would better filter the data to allow these analyses.

Several relatively simple amendments to this project would improve the results. First, activating trials for the three BFMs within the training module would allow participants to acquire a general sense of how to react. This would eliminate analyzing learning curve data, which would be best for a more reliable evaluation of the results. Doing this would also lessen any discrepancies between participants who are experienced and inexperienced with Omni-like devices. A second amendment is to increase the force based guidance's strength and make its motions less exaggerated. Participants complained that the constant force applied to their non-dominant hand was too weak and made it difficult to interpret. They also wrote that the exaggerated motions would confuse their perceived orientation within the maze and which direction they should move. Third amendment, eliminate the jittering experienced periodically in position based guidance. This might be solved by replacing the spring force used to draw the jerk motion back to the origin. The last amendment is to program the experimental module maze to change from trial to trial. This would eliminate participants' abilities to memorize the maze and ignore the haptic components being tests. This could be done by one of two ways: (1) rotating the maze's orientation from trial to trial, which would create the belief of a new, unknown maze being presented without changing the mazes overall difficulty to maintain experimental consistency, or (2) initialize a new maze for each trial, geometry and complexity would have to be well thought out to maintain consistency. With either solution, the maze presented would be randomized for each trial within each BFM.

For future experiments, participants would use the functional amendments discussed above and perform an additional BFM: mirrored symmetry in all planes of motion. Additionally the designation of the Omnis and hands would change: navigation Omni used by the non-dominant hand and the guidance Omni by the dominant hand. This would better simulate someone with impaired limb mobility by designating the feedback sensing arm as the good arm and the impaired arm, needing rehabilitation or training, navigating the maze and being exercised. Additionally, similar testing regiments can be created for lower limb applications by replacing the Omnis with haptic shoes or a brace-like exoskeleton.

To progress the project towards its ultimate goal of developing a highly effective rehabilitative and training device, several other types of amendments would need to be made. First of all, the code would need to be refined overall to make sure there are no lines that can cause glitches or simply waste space if they are not needed. Second is preprogramming various paths, speeds, and applied forces for the guidance Omni. This will provide a simple to follow system that physical therapists can use to make rehabilitation routines with a patient. The speeds and forces will be made to be variable by the user to change the level of difficulty and allow customization and optimization of the system to each user'sneeds. Additionally, multiple mazes will be made available for different difficulty levels and to simply vary the task.

## ACKNOWLEDGMENT

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