

# Real World Haptic Exploration for Telepresence of the Visually Impaired

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## ABSTRACT

Robotic assistance through telepresence technology is an emerging area in aiding the visually impaired. By integrating the robotic perception of a remote environment and transferring it to a human user through haptic environmental feedback, the disabled user can increase one's capability to interact with remote environments through the telepresence robot. This paper presents a framework that integrates visual perception from heterogeneous vision sensors and enables real-time interactive haptic representation of the real world through a mobile manipulation robotic system. Specifically, a set of multi-disciplinary algorithms such as stereo-vision processes, three-dimensional map building algorithms, and virtual-proxy haptic rendering processes are integrated into a unified framework to accomplish the goal of real-world haptic exploration successfully. Results of our framework in an indoor environment are displayed, and its performances are analyzed. Quantitative results are provided along with qualitative results through a set of human subject testing. Our future work includes real-time haptic fusion of multi-modal environmental perception and more extensive human subject testing in a prolonged experimental design.

## Categories and Subject Descriptors

H.1.2 User/Machine Systems, I.2.9 Robotics, I.2.10 Vision and Scene Understanding, I.4.8 Scene Analysis, I.5.2 User Interfaces.

## General Terms

Algorithms, Measurement, Experimentation, Human Factors.

## Keywords

Haptic exploration, telepresence, 3D in-situ perception.

## 1. INTRODUCTION

One of the major functions of current robotic systems is to promote the welfare of human beings. The advancement in robotic technology has resulted in various forms of robotic support for human lives such as cleaning, entertainment, education, and even medical care, and has introduced new

application fields such as teleoperation [15] and telepresence [2]. However, robotic technology is usually targeted for general users, and it is still left with many challenging issues such as compensating for impaired or disabled sensory functionalities.

Assistive technology, on the other hand, has a long history of adopting new techniques to aid people with disabilities, and has opened new opportunities for individuals with disabilities [11,26]. Traditional aids, such as wheelchairs, canes, Braille readers, and hearing aids, have basically focused on generating passive and close-range sensory aids. Recent assistive devices, including electronic Braille adaptors and computer-screen readers for the visually impaired (VI) or electronic wheelchairs and prosthetic limbs for the motor impaired, have evolved to transfer more information to the user and have granted wider access to daily living for people with impairments, including education and employment [1]. Nevertheless, all of these tools are designed to (1) work passively with predefined sources of information, and (2) aid in mobility or manipulation to assist in daily living but only in specific conditions. In other words, there is no general solution yet that functions in various situations, and there is still a need to push forward research with a focus on providing more general and multi-purpose support for individuals with disabilities, as illustrated in Figure 1.

Given the current status of assistive technology and the advancement in robotics, we speculate that a mobile manipulation robotic platform will be a viable solution to serve as a multi-purpose assistive tool for people with disabilities. Mobile manipulation is a fast growing area [7] due to advances in robotic systems, increases in computing power, and a rising interest in applications for the home and indoor environment. As an assistive device, a mobile manipulator can aid an impaired person with manipulative tasks using its robotic arm and also provide mobility or remote access using its mobile base. Additionally, a mobile manipulator, being a robotic agent, can monitor the environment and form a



Figure 1. An image of a mobile manipulator robot serving a remote user with haptic exploration framework.

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haptic pathway to transfer the in-situ perception of the remote environment to the user. The concept of haptic exploration with a mobile manipulator (HEMM) [29] has been proposed to integrate a haptic device with a mobile manipulation system for the use of an assistive system in two ways: 1) as the controller for the mobile manipulation system and 2) as the generator for the environmental feedback to the human user.

This paper discusses our approach for a direct haptic rendering from sensed environmental data, and displays a framework of algorithms that can sense the environment, process the sensory data to get a point-cloud representation of the three-dimensional (3D) map, and finally transform the perceived environmental data into a haptic representation. Section 2 lists some of the related work in the current research of robotics, assistive technology, and computer vision. , and Section 3 briefly describes a platform for our haptic exploration using a mobile manipulator. Section 4 provides the details of sensory data processing algorithms that mainly incorporate several techniques of computer vision algorithms. Section 5 explains our haptic rendering algorithm based on a point-cloud spatial dataset. Then, Section 6 explains the experiment setup for human subject testing of our framework in a real-world environment. Finally, Section 7 displays the results of our system in observing and representing several indoor environments, and Section 8 concludes with discussion and future work.

## 2. RELATED WORK

Efforts to utilize robotic systems for assisting the VI can be found in recent literature [11,20]. However, few studies have focused on developing assistive robots to increase the sensory modalities for people with visual impairments (VI). Ulrich et al. developed a robotic cane [11] that can sense the environment and guide the individual through the environment with a robotic cane. Another approach from Kulyukin et al. incorporated a mobile-robot based guidance approach with RFID devices to help people with visual impairments navigate in their living areas [20]. Both systems, however, require the user to be either in contact with a device or in a preset environment to detect the user's surrounding environment, and they are not capable of transferring remote environmental perception to the user. More recent challenges consist of a driving system for the VI by utilizing a semi-autonomous car and a haptic vest [26], and a user study for robotic shopping using a robotic cart [25]. These efforts present pioneer studies in the field of assistive robotics in the sense that they intend to enable a person with a visual impairment to maintain independence in daily living. However, more challenging issues still remain.

For presenting environmental perception to a user with visual impairments, haptic representation of the data is the most direct and effective interactive modality, which can be easily derived from the fact that the most common assistive tools for VI people are canes and Braille-notes that stimulate tactile sensations. Haptics is a mature field of engineering research, with varying applications in the medical field [9], rehabilitation [21], virtual reality [13], and teleoperation [27]. Its ability to transfer tactile and textural sensations along with force feedback adds another dimension of interaction between the human and the system. With

the recent advances in virtual proxy methods [4,16,17,23,28] haptic rendering of 3D objects has become more convenient and effective with the aid of graphic libraries such as OpenGL. By building a detailed 3D model and with the aid of efficient physical simulation algorithms, calculating the virtual proxy force has turned out to be a fast and relatively easy process [18]. However, the calculation is based on the condition that the 3D model must be provided a priori. Haptic rendering of a real 3D environment is widely known to be quite difficult, and there remain many challenging problems even in the area of virtual reality systems [6].

The simplest solution to this dilemma would be to estimate the real world with various sensors, transform the estimation into a 3D model, and use the previously established haptic rendering solution. This method, however, does not solve the issue because transforming the estimated 3D data into a 3D model is far from simplistic. In fact, this process itself requires multiple stages of algorithms to work around issues such as occlusion and object identification. The reconstruction is usually processed off-line due to the high computation cost [5]. On the contrary, the other solution—a direct haptic rendering from the estimated data itself—provides a totally new approach and is one of the key contributions of this present work. Instead of creating a 3D graphical model, this method uses point-cloud based 3D data and directly applies a point-cloud based virtual proxy algorithm for haptic rendering. The advantages include fast computation time and a more flexible structure for coping with dynamic environments.

As discussed in [25], one of the most critical reasons that limit assistive tasks in daily living is the perceptual matching of the environment with the system it is handling. In this sense, this research focuses on the problem of presenting environmental perception to a user with visual impairments, and presents a novel solution framework that provides both active sensing capabilities and effective transference of the detailed environmental data through a haptic modality.

## 3. HAPTIC EXPLORATION SYSTEM

For our research platform, we utilize our previously proposed HEMM (haptic exploration with a mobile manipulator) system [29], and employ this system to implement and validate a set of algorithms for haptic exploration. The structure of the HEMM system consists of two main parts: a haptic interaction system and a mobile manipulation robotic system (Figure 2).

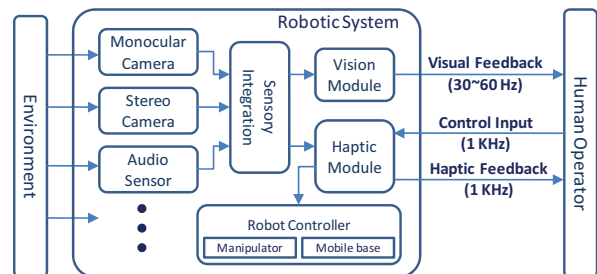


Figure 2. Basic architecture of the HEMM system.

The haptic device we use is the SensAble<sup>TM</sup> Phantom Omni, which is capable of taking 6-DoF inputs and generating 3-DoF force feedback. The mobile manipulator is composed of a Pioneer3AT and a Pioneer2Arm. It utilizes its various sensing modules to perceive the environment and generate visual and haptic feedback to the human operator. Through this HEMM system, the human can feel the environment and be more in control with the help of the mobile manipulator. Thus, the benefits expected from the HEMM system are as follows: (1) it enables a bidirectional linkage between a haptic device and a mobile manipulation robotic system and (2) it can convey environmental data to the user through haptic exploration.

#### 4. MULTI-SCALE VISON PROCESS FOR 3D PERCEPTION

People with visual impairments typically use canes for navigation or sense objects with tactile sensing. To develop a system that can provide similar multi-scale environmental feedback, our HEMM system is equipped with two different camera sensors: a stereo camera in front of the robot and a monocular camera mounted on top of the wrist. The stereo vision provides larger scale perception of an indoor environment, and the monocular camera enables up-close and more detailed observation of an object. The following sections explain the vision processes and disparity map generation algorithms for the camera systems.

##### 4.1 Stereo Vision Process for Indoor Spatial Perception

Stereo vision processes [10,12,19] have been widely adopted for spatial recognition due to their ability to embed in a simple hardware structure. A disparity map is the result of the stereo vision process that represents the depth distribution of the space. Although the algorithm side of generating the disparity map is not so simple, the computer vision society has come up with sound processes. One of the most favorable solutions is a graph-cut (GC) energy optimization method [8] using Markov-random fields (MRF) [24]. It represents the disparity image as a set of MRF variables with two energy functions representing the cost of estimated disparity and the cost of smoothness with neighboring pixels, and calculates the optimal solution by minimizing the total energy function.

The energy model for MRF-based stereo matching algorithm consists of a data term  $E_d$  and a smoothness term  $E_s$ , both represented in the form of energy functions. For a disparity map solution  $f$ , the total energy function  $E(f)$  can be represented by the following:

$$E(f) = E_d(f) + E_s(f) \quad (1)$$

$$E_d(f) = \sum_{p \in P} D_p(f_p) \quad (2)$$

$$E_s(f) = \sum_{p \in P} \sum_{q \in N(p)} C_s(f_p, f_q), \quad (3)$$

where  $f_p, f_q \in f$ ,  $N(p)$  is a set of 8 neighbor points of  $p$  in 3D space, and  $D_p(f_p)$  and  $C_s(f_p, f_q)$  are defined as

$$D_p(f_p) = |f_p - I_p| D_p(f_p) D_p(f_p) \quad (4)$$

$$C_s(f_p, f_q) = |f_p - f_q|. \quad (5)$$

Here,  $I_p$  is an observed value of the disparity value at pixel  $p$  of the stereo image pairs. Thus,  $D_p(f_p)$  is a cost function for the data term of the direct observation of the disparity map and  $C_s(f_p, f_q)$  is the cost function for representing the smoothness by estimating the discontinuities with neighboring pixels. This optimization process is combined with a rapid minimization process called “graph-cut,” which achieves a good local minimum in labeling the image and accomplishes a fast approximation of the disparity map with well segmented representation and minimal energy cost of the map.

The GC method generates results with quite good estimation. However, it is not sufficient to produce a clean 3D reconstruction. Effects from lighting and textures cause noise in the disparity map, necessitating post-processing to eliminate them. To further complete the 3D perception process, a ground plane is estimated using a statistical region merging algorithm [14]. This algorithm reduces noise and error terms in the disparity calculation, which are caused by the short distance to or the complexity in the texture of the ground. If properly estimated, it will also allow more freedom in the disparity calculation for non-ground objects that are of interest as shown in Figure 3.

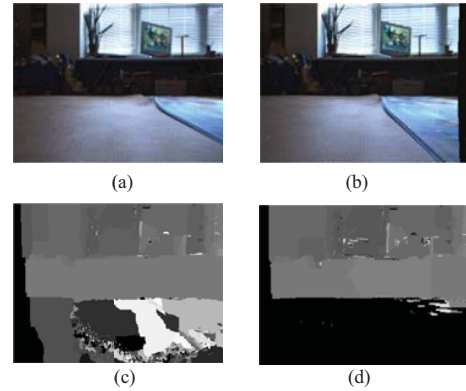
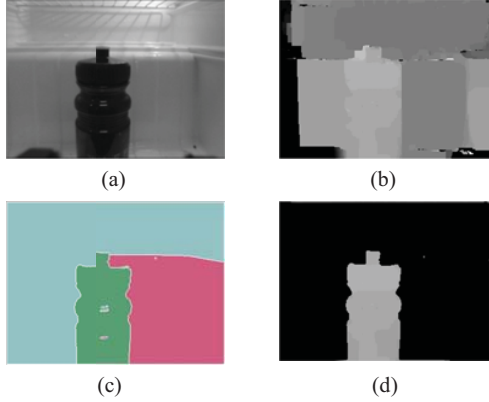


Figure 3. Stereo disparity estimation process: (a,b) Stereo pair images of a living room; (c) MRF GraphCut based disparity output; (d) final disparity result after ground estimation.

##### 4.2 Mono-Stereo Vision Process for Object Perception

For objects that are too close to get detailed spatial observation with the stereo camera, the monocular camera mounted on the wrist of the mobile manipulator is utilized. Several research efforts exist that employ monocular vision for 3D perception, for instance, mono-SLAM with probabilistic 3D map [22], which shows good results but requires large computation powers to process the stream of image sequences. On the other hand, we plan to make an instant observation of the object at its proximity. Therefore, the manipulator is controlled to move the monocular

camera sideways to capture a pair of images forming a small baseline between the image pairs, and the stereo matching process discussed is reused for disparity calculation. This process is named “mono-stereo process”.



**Figure 4. Mono-stereo disparity estimation process: (a) mono-stereo image; (b) initial disparity; (c) segmented regions after background / foreground estimation; (d) final disparity after background elimination.**

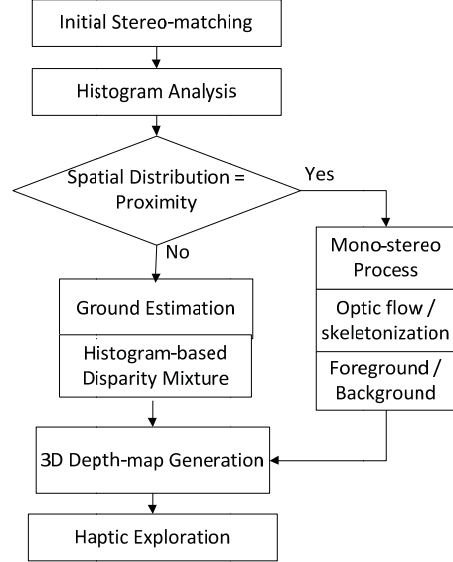
To acquire the stereo pairs with a single camera on the wrist of the manipulator, the robot’s wrist is moved sideways forming a baseline of 1cm between the image pair. The movement takes time, so the images are taken in sequence, making the process unsuitable for dynamic objects. On the other hand, the stereo process itself is not a real-time process yet (it takes a few seconds of processing time with a 2.4GHz CPU). In addition, similar to the case of the stereo estimation process, post-processing of the disparity image is required in the case of mono-stereo. The issues of the presence of interferences in disparity calculation due to background color and lighting are addressed along with the effort to resolve the problem in the following sections. An example of the mono-stereo process with post-processing results is illustrated in Figure 4.

As a post-processing sequence, foreground objects are separated from the background image to capture the right partition of the object in the disparity image. This foreground/background separation process first marks pixels with optic flows over a threshold, samples the points to form a set of skeletonized (silhouette-like) point markings, performs region selection with the points as seed points, and then subtracts large regions which can be assumed to be background elements. To eliminate background elements, adaptive thresholding is implemented to determine the right number of elements for removal based on the total number of segmentations and the total sum of regions of candidate background elements. More details on this post-processing will be discussed in our future papers.

## 5. HAPTIC EXPLORATION ALGORITHM

Once a reliable disparity estimation of the environment is acquired, a 3D map can be built from the disparity map (either from the stereo process or from the mono-stereo process). After

the 3D map is acquired, the haptic exploration process is then activated, which interactively searches the map with the movement of the haptic probe and efficiently calculates the haptic force feedback in real-time (Figure 5).



**Figure 5. Flow-chart of the 3D-perception process through heterogeneous stereo-matching.**

The proxy force is designed as a spring-damper system as in Equation (6)

$$f(t) = [Kd(t) + B\dot{d}(t)]\vec{n}, \quad (6)$$

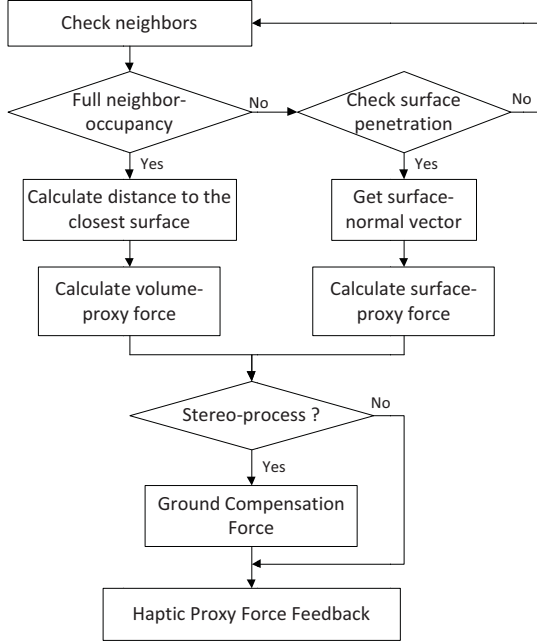
where  $d(t)$  is the penetration depth at time  $t$ ,  $\dot{d}(t)$  is the instant velocity of the probe at the penetrated position (that arises due to the exploratory movement of the user),  $K$  is the spring constant and  $B$  is the damping constant. Lastly,  $\vec{n}$  is the normal vector to the surface of the penetrated volume.

The usual process for 3D map generation from the disparity map involves a projection matrix built from the camera parameters. After the surface points are projected in 3D space, the volume beneath the surface points are filled outward, forming a set of volumetric point-clouds. Once the point-cloud based 3D map is constructed, the system enables a haptic device, Phantom Omni, to explore the 3D space and feel objects in it. For haptic force generation, a well-known proxy-based haptic volume representation algorithm [3] is implemented.

This paper mainly focuses on haptic-volume representation, so the virtual-proxy is placed on the surface of a volumetric object disregarding the effect of friction forces. From the distance between the virtual-proxy placed on a surface and the position of a probe (Omni’s end-point), the penetration depth of the probe can be calculated from the surface (the virtual-proxy), which is then used to generate force feedback for haptic volume representation. Since sparse grid-based 3D data are being used, the haptic interaction algorithm first checks for the occupancy of neighboring grid points with respect to the position of Omni’s probe in the 3D map, then calculates the penetration depth if the



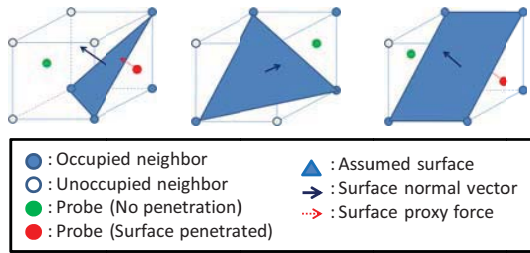
probe is totally inside the object's volume, or calculates surface penetration depth if the probe is near the surface (see flowchart in Figure 6.).



**Figure 6. Haptic virtual-proxy force calculation algorithm with 3D grid map.**

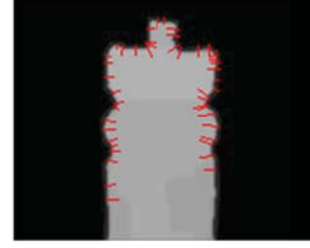
To get the distance vector, the volume proxy-force is generally calculated by searching for the closest surface. The surface proxy force is calculated by the convolution of the surface-normal vector and the penetration depth from the surface, which leads to an interpolation issue due to sparseness. To speed up the process, a look-up table of the surface normal vector is generated for all combinations of the neighboring grid points. A few examples are shown in Figure 7.

Processing time for the 3D-map search and proxy-force generation is crucial for a real-time experience of the haptic exploration. Our structure of the algorithms explained above results in an average processing time of 3.075ms for surface-normal depth calculation in the 3D grid map (STD=6.287ms over 7,035 measurements) and proxy-force generation.



**Figure 7. Examples of 3D interpolation for surface proxy force calculation.**

To illustrate what type of force profile the user may feel with amplitude changes in force, Figure 8 is plotted over a partial trajectory while the haptic device touches the side of an object.



**Figure 8. Force feedback (red line) over a user's exploratory trajectory on an object. The direction of the force is from the penetration point to the surface point.**

## 6. EXPERIMENT SETUP

The performance of the HEMM framework is evaluated based on the results from the three major sub-processes, namely, stereo matching (with ground elimination), mono-stereo matching (with background elimination), and the haptic exploration process. For the first two matching processes, a ground-truth map of the real world the system is observing is created, and the error of the disparity estimation is analyzed. For quantitative analysis, the processing time and the estimation error of the depth are calculated for both stereo and mono-stereo processes. For the qualitative analysis, the final process of haptic exploration is tested with human subjects, both with non-VI students and VI students. We design a set of experiment for human subject testing only with haptic exploration based on the mono-stereo process results because the stereo process deals with a large space volume and the spatial recognition of the VI students will depend on the familiarity of the environment, or *a priori* knowledge of the environment of the student.

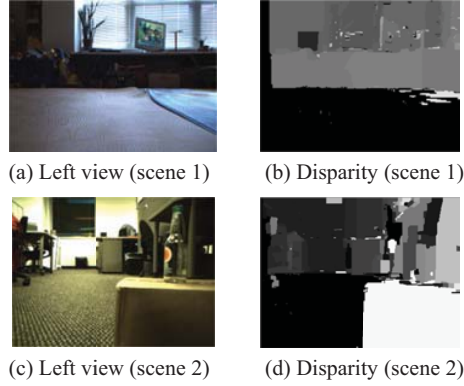
For initial training, the subjects—after providing their written/verbal consent on our IRB (protocol #: H09220)—are given a basic sample shape (a cubic) and given a minute to feel the object with our haptic interface and get accustomed to the concept and feeling of haptic exploration. Then, the subjects are asked to identify objects by haptically feeling the models created from real-world objects, without seeing the object. The non-VI students are provided with a random sequence of three haptic models, along with the images of the three actual objects as depicted in Figure 9. After approximately a minute of exploration time per each object, they are asked which haptic models feel the closest to the objects in the images. The same process is used to test VI students, but this time the actual objects are provided for the participants to select from after feeling the haptic models.



**Figure 9. Images of objects of which the haptically visualized models are provided for haptic exploration to human users.**

## 7. RESULTS

Figure 10 and Table 1 present the results of the stereo-matching algorithm with ground elimination. Two different scenes were achieved, one from an actual household living environment and another from a real office environment. The average processing time for the stereo matching and 3D map generation was 6.01s.

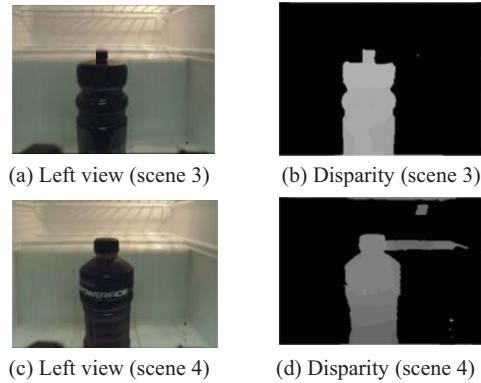


**Figure 10. Results of our stereo matching process.**

**Table 1. Processing Time from Stereo Process**

Stereo Pairs	Scene 1	Scene 2
Processing Time (s)	6.36	5.65

Figure 11 and Table 2 show the results from the mono-stereo matching algorithm with background elimination. Two objects were placed in a small refrigerator and on a table. The disparity map was generated from the mono-stereo algorithm utilizing a moving robotic arm, and the background was automatically eliminated if the number of segments detected in the image reached a threshold. The average processing time for the mono-stereo matching and 3D map generation was 3.26s.



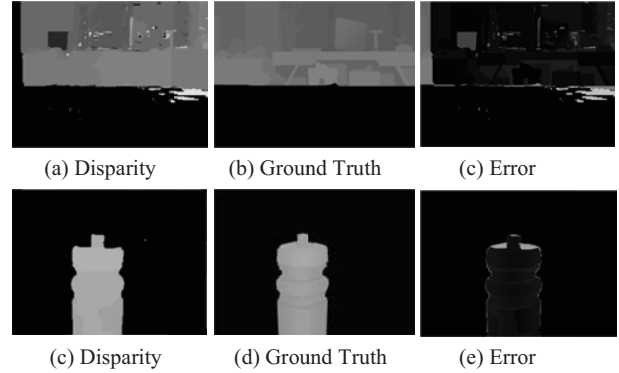
**Figure 11. Results of our mono-stereo matching process.**

**Table 2. Processing Time from Mono-stereo Process**

Mono-stereo Pairs	Scene 3	Scene 4
Processing Time (s)	3.04	3.48

Ground truth data were determined by measuring over the 3D environment and then translated into a disparity map. For equal comparison, the ground planes were also eliminated from the ground truth map by manual segmentation for the stereo process results, and the background was eliminated from the ground truth map for the mono-stereo process. The absolute difference of disparity values over the entire image plane was calculated and the root-mean-squared error was computed for the stereo process. The error term was then calculated only for the foreground part in the mono-stereo process. The error between the algorithm's estimation and the ground truth for the first scene (stereo process) was 5.7%, and the error between the algorithm's estimation and the ground truth for the third scene (mono-stereo process) was 7.9%, showing the accuracy of the process.

The ground truth disparity map and the estimated disparity map from our algorithms, along with the error of depth on the image plane, are shown in Figure 12 and specified in Table 3, respectively. Considering the complexity of the scene (in stereo process) and the low resolution of disparity values for representing detailed 3D shapes in close range (in mono-stereo process), the results are satisfactory.



**Figure 12. Ground-truth disparity maps and estimation errors.**

**Table 3. Disparity Estimation Errors**

Stereo Pairs	Scene 1	Scene 3
Depth Error	5.7 %	7.9 %

Additionally, the average processing times (and percentages from the whole process) for each algorithmic stages are as follows: initial stereo-matching  $\approx 3011\text{ms}$  (52.85%), histogram analysis  $\approx 10\text{ms}$  (0.2%), ground estimation  $\approx 193\text{ms}$  (3.4%), disparity mixture  $\approx 1929\text{ms}$  (33.8%), and 3D map building process  $\approx 546\text{ms}$  (9.5%) in PC environment with a dual-core 2.4GHz processor and 2GB memory. We will discuss our future plans to minimize the processing time in Section 8.

Finally, the human subjects testing results are displayed in Tables 4 and 5, with the confusion matrix listed in Tables 6 and 7. A total of 19 non-VI human subjects participated in the experiment, and their average age was 25. For VI human subjects, 8 middle school

students (4 males and 4 females) participated with their average age 12. Of these, 7 were partially blind and one was fully blind.

**Table 4. Success Rate of Non-VI Human Subjects in Identifying Objects with Haptic Exploration**

Object	#1	#2	#3
Success Rate	84.2 %	78.9 %	84.2 %

**Table 5. Success Rate of VI Human Subjects in Identifying Objects with Haptic Exploration**

Object	#1	#2	#3
Success Rate	87.5 %	87.5 %	87.5 %

Subjects with no visual impairments showed 79% to 84% recognition rate for the three objects, while subjects with visual impairment rated 87.5% for each objects. To understand which objects confused the human users, the confusion matrices for the responses of the participants are listed in Tables 6 and 7. Table 6 reveals that two non-VI subjects became confused between object #2 and object #3 and two other non-VI students had trouble distinguishing object #1 and object #3, mainly because the objects are commonly up-right shaped. For VI subjects, Table 7 shows that one subject became confused between object #2 and object #3, and another subject could not tell the difference between object #1 and object #3, the reason being the same as in the non-VI subjects' case.

**Table 6. Confusion Matrix of Non-VI Human Subjects in Identifying Objects with Haptic Exploration**

Object Answer	#1	#2	#3
#1	16	-	1
#2	1	15	2
#3	2	4	16

**Table 7. Confusion Matrix of VI Human Subjects in Identifying Objects with Haptic Exploration**

Object Answer	#1	#2	#3
#1	7	-	-
#2	1	7	1
#3	-	1	7

## 8. DISCUSSIONS

The objective of this research is to create a linkage between an assistive robotic system and the human user by delivering haptic perceptions of the environment to a person with impairments. More specifically, this research tackles the problem of providing a sense of the world to individuals with visual impairments through a haptic interface based on the environmental data acquired by the perceptual system of a mobile robotic platform. To accomplish this, the user is provided with multi-scale haptic exploration

capability of a real-world environment through a robotic system equipped with vision sensors. The challenges that must be addressed by this system involve 1) recognizing the environment in multi-scale dimensions because real-world objects are of various sizes and 3D world positions, 2) developing real-time processing algorithms to enable real-time interaction with the human, and 3) enabling 3D real-time haptic interaction for smooth tactile representation of objects in the environment.

An extensive implementation of the haptic exploration algorithms using a mobile manipulation robotic system has been achieved, and this paper shows the results of the system working in real indoor-environments. To minimize the processing time and enable more smooth real-time haptic exploration, we plan to utilize the Kinect sensor. Our latest implementation is already showing more than 10x improvement in terms of processing time, although the structure of the sub-modules will be different. Future work will also include sound-source localization and its integration into the haptic feedback for enhanced multi-modal interaction. Methods for multi-modal fusion will be further investigated along with an extended set of real-world experiments and human subject testing.

## 9. ACKNOWLEDGMENTS

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