Tactile Interface Design for Helping Mobility of People with Visual Disabilities

Christian Lykawka
leekafka@gmail.com
School of Informatics
PUCRS University
Brazil

Bruno Konzen Stahl
bkstahl@gmail.com
School of Informatics
PUCRS University
Brazil

Marcia de Borba Campos
marcia.campos@pucrs.br
School of Informatics
PUCRS University
Brazil

Jaime Sanchez
jsanchez@dcc.uchile.cl
Depto. de Ciencias de la Computación, Facultad de Ciencias Físicas y Matemáticas
Universidad de Chile, Santiago, Chile

Márcio Sarroglia Pinho
pinho@pucrs.br
School of Informatics
PUCRS University
Brazil

***Abstract*—This paper aims to study the process of converting the depth information of a real scene captured in a real environment into a tactile representation through a haptic device. We developed a belt-shaped interface with a matrix of 35 (7x5) vibrotactile actuators attached to the users' abdomen. Tests demonstrated that the device can help users to perceive the movement of objects and people, as well as allow them to move in environments containing obstacles without the usage of the vision. The system was tested both with users who are blind and with blindfolded participants. The stages of building and testing the interface as well as the tests applied in this research are described.**

Keywords—Scene Depth; Haptic Device; Sensory Substitution; People with Visual Disabilities; Obstacle Avoidance; Mobility Aids; Visual Navigation

I. Introduction

Increasingly, people with disabilities have resorted to using technology to perform daily tasks. In cases of persons who are blind or have low vision, obtaining information from the environment by artificial sensors, for example, it is becoming more common. Through the usage of them, it is possible to analyze, in real time, the surrounding environment and generate useful information, which contributes to a person who is blind in better understanding the world around them.

The lack of vision is not synonym of having low levels of spatial perception or comprehension. In general, people with visual disabilities, when adequately trained, are capable of orienting themselves, and develop a precise mental representation of the environment. The study by Cattaneo et al [6] indicates that there is no evidence that people who are blind use different cognitive mechanisms of people who have vision and suggest that compensatory mechanisms can overcome the limitations of vision loss. This indicates that visual experience is not strictly a requirement for creating mental representations of space, as other senses can also provide valuable spatial information [13]. In her research, Millar proposes that vision does influence coding and spatial representation, but it is not the only determinant of such skills. Papadopoulos et al [14] also points out that, despite the lack of vision influencing the development of spatial cognition, this does not prevent the development of this competence. Thus, vision alone is neither a necessary nor sufficient condition for spatial encoding.

A person with visual disabilities must be proficient in orientation and mobility (O&M) in order to achieve a good level of navigation, including moving around safely, efficiently and with agility, as well as independently in both familiar and unfamiliar contexts. The learning of O&M skills includes a set of defined techniques that people who are blind or have any visual disabilities must practice stage by stage. However, learning such skills also involves other aspects such as training and refining systems of perception, and the development of both conceptual and motor skills. Such skills are essential prerequisites for learning formal O&M techniques. The primary objective of O&M is to achieve independence and to improve the quality of life for people who are blind or have any visual disabilities. The training for such skills occurs in stages of increasing levels of difficulty according the user's particular characteristics. For people who are blind navigation through unfamiliar spaces can be a complex task compared to a sighted person. According to Legge et al [8], there are two main aspects of mobility: obstacle avoidance and spatial navigation. The first refers to the ability of performing the next step safely, avoiding obstacles. The spatial navigation, sometimes called the wayfinding, refers to the ability of learning layouts and to follow routes while updating the current person's position. In order to achieve orientation & mobility there is a need of using other resources to receive feedback from the environment, such as sounds and textures [10]. For instance, the currently existing technologies can assist people in their mobility by transforming visual information into tactile sensation. The conversion of a human sense into another one by using special devices is called *sensory substitution* [2]. One of the alternative technologies to promote sensory substitution is based on capturing and processing three-dimensional images [16][18]. By using these tools, it is possible to encode the digital representation of a real environment and then convert it into a new representation that can be used to stimulate other human sense, different from vision.

One of the methods available for this new representation is using *haptic devices* to provide the user with a sensation of touch. With this type of device, the user can perceive through the sense

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of touch, the geometry information captured from the environment and shown on the display in real time. This experience with the process of sensory substitution is potentially interesting for users with visual disabilities.

This paper initially presents a review of studies related to the use of haptic devices. After that, it describes the steps for building the prototype. Furthermore, it describes the testing performed with the device and ends with conclusions and suggestions for future research.

II. Related Work

The literature introduces studies that adopt reference models to face navigation problems through either training applications or direct and indirect assistance [8][5][11].

Studies [8][5][11], Sanchez, 2011) highlight five stages to follow to facilitate O&M in people who are blind: perception, that allows the user to perceive the information from the environment through sensory channels; analysis, concerning the organization of the perceived information according to different degrees of confidence and familiarity; selection, to determine what information is more important to meet a navigation need in a certain moment; planning, to make an action plan for an adequate navigation considering the previous stages; and execution, that implies executing an action plan for navigation.

Some spatial concepts are built by the person who is blind in a way he can move from one point to another safely [11][10], according to these studies these concepts are: the concept of body space, the concept of action space, the concept of objects space, the concept of geometric space, and the concept of abstract space. Blind children have difficulty to build spatial concepts, which interferes directly in their orientation and mobility. This implies that it is essential to establish an accurate mental map of a space in order to develop efficient O&M skills. As said, most of the information required to form such mental representation are generally obtained through visual channels [10]. Users who are blind must rely on other sensory channels such as auditory and tactile information, in addition to other strategies for efficient exploration and navigation [13][15].

The use of tactile or auditory feedback as a form of sensory substitution has proven useful to support users in navigation tasks. Some research studies are based on the capture of the user's movement in specific environments with a previously known physical structure in order to support navigation. The research by Amemiya et al [1], for instance, proposes a navigation system that can be used by pedestrians and/or people with visual disabilities in structured environments such as convention centers, where visitors usually depend on visual information from a map or a compass. In order to guide the user, the system adopts a device similar to a small fan, which produces the sensation of pulling the user by the hand through asymmetric oscillations with three degrees of freedom.

With the same goal of helping the user move in structured environments, Ghiani et al [7] presents a system for mobile devices able to guide users during their visit to a museum. The tactile feedback is given with the use of actuators applied to two fingers of the user. The study indicates that tactile feedback is particularly useful to provide dynamic information such as the level of proximity of an obstacle and the distance from the right orientation.

In order to explore unknown environments, Khambadkar et al [9] presents a gestural interface that allows for the analysis of the physical space around the user. In this interface, the user attaches a depth-sensing camera to the neck. The camera allows the user to perform hand gestures that can be used to obtain information from the environment, such as color detection, the presence of a person and the depth of a point or an area. This information is processed and conveyed to the user through an auditory channel. The author concludes that, unlike existing assistive technologies that provide generic information, the gestural interface can assist the user in specific everyday tasks such as picking up an object or approaching a person and provide greater independence to visually impaired users without expensive technologies.

Lorenzo et al [12] also developed techniques to explore unknown environments and aim at investigating the possibility of helping people with visual disabilities learn spatial environment configurations by listening to audio events within a virtual reality experience. In their tests, an individual with visual disabilities used a joystick and headphones with nine channels, containing an orientation sensor equipped with accelerometer and gyroscope to move around in the virtual environment and capture directional audio according to the position of the user's head. The study shows that interactive exploration of virtual acoustical simulations can provide useful information for the construction of coherent mental spatial maps about virtual environments.

The study by Bahadir et al [3] shows a system integrated with the user's clothes, which allows the detection of obstacles for people with visual disabilities. As a proof of concept, they developed a prototype of smart clothing that uses ultrasonic sensors, vibration motors, power supplies, and a microcontroller. The system is based on two major functions: detection of obstacles through a sonar based on ultrasound and user orientation through actuators. Vibration motors with external diameter of 20mm and weighing 2 grams were used as actuators. According to the authors, as it is built in a flexible, light, washable and comfortable material, the prototype can be easily used as garment.

Regarding the place where the sensation of touch is generated, Van Erp et al [17] presented three reasons why the region of the torso is a good place to attach the haptic device for navigation tasks: 1) as it has a large surface, it is neither necessary to reduce the size of actuators nor limit them to a small number; 2) the information presented to the torso does not invalidate actions performed with the hands; 3) as the torso is a volume, it is an interesting region for presenting 2D or 3D information, such as geographical and navigational information.

In the same vein, the work of Barros et al [4] uses a device called TactaBelt, composed by eight tactors placed around the user's waist to measure the performance of different groups to navigate a robot in a virtual environment, with the aim of finding and collecting objects. The purpose of the study was to understand the influence of the tactile information transmitted in a complementary way to users while they were tele-operating a robot, considering that the primary information available was visual. Two implementations were tested: one using only a visual interface and another one using a haptic device. The results showed that the use of haptic devices is efficient to help people perform navigation tasks with waypoints along a route.

As we can see in these studies, the use of haptic interfaces based on vibratory devices can effectively support navigation tasks. In addition, by changing parameters such as frequency, intensity and duration of the vibrations, as well as the amount of actuators, it is possible to further improve the information provided to the user.

Based on these studies, this research evaluated the possibility of using a matrix-shaped haptic device attached to the user's abdomen as a tool to enable the exploration of unknown three-dimensional environments. In order to accomplish this, the real environment is captured by a 3D camera and the distances between the objects and the user, as well as their shapes, are mapped to the haptic device by changing the vibration pattern of the elements that compose the display.

III. THE PROTOTYPE

The prototype developed for this work uses a depth camera to get the scene in front of the user, an image processing unit to detect possible obstacles and a haptic device equipped with vibrating motors attached to the user's abdomen with a belt.

Thus, tactile impulses convey spatial information in a first-person perspective, using his body to determine the location of obstacles in space (egocentric reference system). The user can thus **perceive** nearby objects, stationary or moving, organize the information perceived, select the information that meets his needs for orientation and mobility, plan his movement to reach the goal, avoiding or minimizing collisions, and execute his plan, and may do so while moving.

A. Depth Camera

The depth camera used is embedded in a Microsoft Kinect device. Each pixel acquired by the Kinect sensor represents the distance between the object and the camera plane, in a range between 100 cm and 300 cm. Distances outside this range are reported as "undetermined" by the device.

B. Haptic device

The haptic device developed for this project is composed by a matrix of 7x5 tactors that covers the abdomen area. The region of the abdomen was chosen mainly because of the research from Van Erp et al [17] and the research from Barros et al [4], which demonstrated that it is possible to express distance and direction in this area of the body. The spacing between tactors used to compose the matrix was five centimeters in the horizontal direction and four centimeters in the vertical direction, due to the area available in this region and the size of the available tactors. The main differences from the Barros' work are: (a) our prototype provides information in two dimensions trying to display the obstacles' shape; (b) our scenario is real and (c) the obstacles can move during the experiment.

An odd number of rows and columns in the matrix was selected to ensure a central position in the display. The existence of a central point in the display made it possible to represent the presence of objects exactly in front of the user. The arrangement of the tactors on the waist line was determined to cover the abdomen area to the greatest possible extent, in a tactile area of 30 centimeters wide and 16 centimeters high (Figure 1). Figure 2, on the left, presents a photo of the haptic device developed in this project, composed by (A) microcontroller and (B) belt with tactors. The belt is made of Neoprene, on which a layer of Velcro was sewn in order to facilitate the attachment of the tactors.

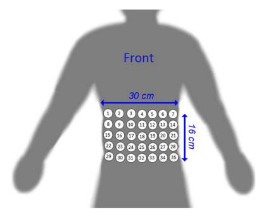


Figure 1 - Position of the Tactors in the Torso Region

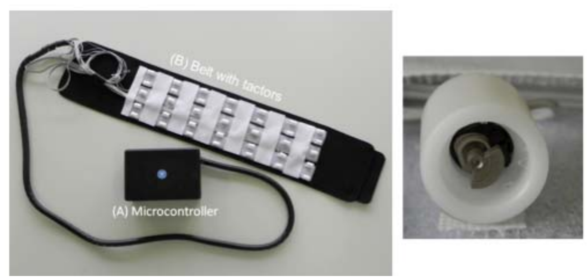


Figure 2 - Haptic device Developed

In the haptic device developed, each tactor is a DC motor that produces vibration through Eccentric Rotating Mass (ERM) technique. The motors used in this project were taken from cell phone devices. Each motor received a Polyacetal (Tecaform) machined encapsulation in order to isolate its axis and eccentric mass from body contact (Figure 2 on the right). This adjustment was necessary due to these motors not having any original shield. The matrix of tactors of the haptic device is controlled by an Arduino microcontroller (http://www.arduino.cc/). An auxiliary electronic circuit was developed to supply the necessary power to the matrix. As the Arduino microcontroller (ATmega1280 model) used does not have enough analog ports to control the 35 motors, the Pulse Width Modulation technique (PWM) was applied, using the digital ports of this microcontroller only. In this technique, a digital signal controls the frequency with which the power of the motor is on or off, over time, rather than the intensity of this power. This produces a controllable variation in speed vibration of the motors.

C. Depth to Haptic Conversion

The process of converting data acquired by the Kinect device into tactile information shown in the haptic device was made by a C++ program running on a portable computer with the Microsoft Windows operating system. The frames containing the scene depth are captured as an image of 320x240 pixels by the Kinect sensor and the conversion resizes them to 7x5 tactors. Figure 3 shows the conversion process in 4x4 matrix.

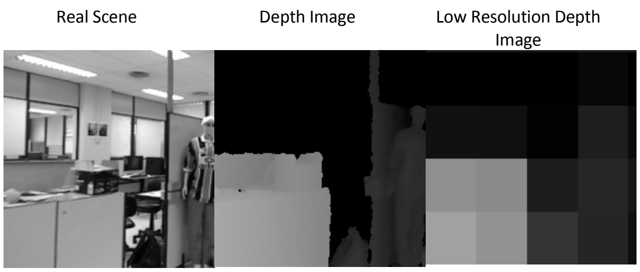


Figure 3 – Depth map downsampling process

Besides the conversion between input and output resolutions, the software maps the distances of the objects to the intensity of each tactor. The developed protocol linearly converts the operating range of Kinect (from 100cm to 300cm) at six levels of intensity for each tactor. To send information to the device, this six levels are encoded by the ASCII characters from "A" to "F". The character "A" represents the highest intensity, "E" represents the lowest intensity, "F" represents the cell turned off and "Z" marks the beginning of the frame. For instance, a frame composed of the sequence of characters "ZAFFFFFAFFFFFFFFFFFAFFFFFFFFFFFAFFFFFA" puts the tactors of the four corners of the matrix and the central tactor at full power, while the others remain off. Figure 4 illustrates the arrangement of this sequence of characters in the haptic device.

A	F	F	F	F	F	A
F	F	F	F	F	F	F
F	F	F	A	F	F	F
F	F	F	F	F	F	F
A	F	F	F	F	F	A

Figure 4 - Example of data pack mapped in the haptic device

IV. PILOT STUDY

During the development of the prototype, a pilot study was performed to support the calibration process. Three specific aspects were addressed separately, since they are related to distinct characteristics in the sensory substitution process: the perception of tactor intensity; the discrimination of points in the matrix; the perception of movement patterns.

The pilot test was important both for the equipment calibration process, with respect to the intensities in which the device is able to individually represent in each tactor, and for verifying if the tactor density in the prototype was appropriate for the abdomen area. At this stage, it was also possible to investigate the ability of the prototype to convey real time information to the participants by showing movement patterns of the display, for instance, and measure the response time.

In order to focus the tests on the haptic device without any interference of possible problems in the depth camera, the display was directly controlled by commands generated by the computer in real time. Thus, the processes of capturing and converting the scene depth were excluded from the set of variables assessed at this stage.

A. Participants

This test was applied in a group of 21 participants: 19 non-blind and two blind users. Each test session in this stage lasted at most 15 minutes. Before taking the test, the participants read and signed an informed consent form. Figure 5 shows a participant wearing the haptic device.

B. Preparation of the user

The sessions of the pilot test took place in a private room with a table and a computer connected to the haptic device. Each participant was asked to wear the haptic device and stoop up during the test. To make sure that the equipment efficiently conveyed the tactile stimuli, the participants were asked to take off heavy clothes, such as jackets or coats. Another instruction given was that they were not allowed to try to feel the tactors by touching the haptic device with their hands.

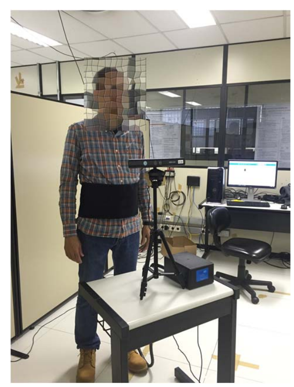


Figure 5 – Participant wearing the belt

C. Perception of Tactor's Intensity Test

The first stage of the pilot study aimed to verify the ability of the prototype to present five different intensities of vibration in the haptic device. The specific goal of this test was to determine whether the haptic device would be able to identify how close or far an object was through five levels of intensity presented to the user. In order to do so, tests measured the time each participant took to notice alterations of intensity in the display.

The participants wearing the haptic device were instructed to push a button when they heard a beep indicating the beginning of the test, and then repeat the process every time they noticed a change in the intensity of the display.

During the tests, the reaction time of each participant was registered both when they identified the first beep and when they recognized a change in intensity. Thus, the time each participant took to recognize the initial beep could be used as a reference value in relation to the time they took to identify the changes in intensity of the haptic device. Five vibration intensities were presented to the user during the tests. The levels were presented in order of decreasing intensity in a random period of time, ranging from four to eight seconds. The results of these tests are shown in Table 1, which describes the mean time (in seconds) the participants took to push the button when the intensity of the stimulus changed.

TABLE 1 - MEAN RESPONSE TIME BY EVENT

Type of event (stimulus)	Mean response time (s)	Standard Deviation (s)
Initial beep	0,914	0,418
Pattern “A” (highest level of intensity)	0,908	0,270
Pattern “B”	0,802	0,182
Pattern “C”	0,837	0,240
Pattern “D”	0,944	0,383
Pattern “E” (lowest level of intensity)	1,160	0,601
Pattern “F” (off)	0,980	0,325

The mean response times to the stimuli related to changes in the intensity of the haptic device, which range from level "A" to "F" (between 802ms and 1160ms), are comparable to the mean response time to the beep (914ms).

In total, 19 non-blind and 2 blind participants were tested. Regarding the response time to the tactile stimuli, it is possible to state that most samples obtained (62%) are within the range between 0.5s and 1s. Table 2 shows the difference between the group of non-blind and the group of blind participants regarding response time (in seconds). The results suggest that the response time to the tactile stimuli is shorter in the group of blind participants than in the group of non-blind subjects. However, it is important to emphasize that these findings are based on only two blind participants. These results show that the prototype developed is able to represent the five intensities of tactile stimuli, as the participants took a similar time to recognize events of intensity alternation than to identify the beep.

D. Discrimination of Points Test

The second stage of the pilot test aimed to verify the ability of the equipment to show simultaneous points that could be discriminated by the user in the haptic device. At this stage, it was possible to test if the resolution of the haptic device developed is suitable for tactile perception in the abdomen area, considering a group of users with no previous training in the use of the prototype.

TABLE 2: COMPARISON BETWEEN NON-BLIND AND BLIND PARTICIPANTS REGARDING RESPONSE TIME

Type of event (stimulus)	Mean response time (s)		Difference in the mean response time (s)
	Non-blind participants	Blind participants	
Initial beep	0.906	0.996	0.090
Pattern “A” (highest level of intensity)	0.924	0.754	0.179
Pattern “B”	0.821	0.618	0.203
Pattern “C”	0.848	0.730	0.118
Pattern “D”	0.972	0.675	0297
Pattern “E” (lowest level of intensity)	1.203	0.750	0.453
Pattern “F” (off)	1.008	0.718	0.290

The ability to display multiple points in the haptic device, which can be perceived by the user, may allow the simultaneous representation of different objects in the scene during the sensory substitution process. Furthermore, the possibility of perceiving different distances between active tactors may be useful to help the user move in an environment with obstacles. The points shown during the tests, also called patterns, should cover both the edges and the center of the matrix. This allows investigating whether users can perceive stimuli in the entire area of haptic device. At the beginning of this test, the participants were informed that they should indicate how many distinct points were turned on at the same time in the haptic device when they heard a beep. A different beep would indicate the end of this test.

Even though the instructions given to the users allowed an unlimited number of answers in relation to how many points were simultaneously shown in the haptic device, the test program only displayed patterns with one or two points.

After the patterns were displayed, they remained at full power until the user indicated how many points he/she was perceiving. Patterns with intensities that differed from the highest one were not shown, in order to reduce the duration of the pilot test. A total of 693 samples were presented, showing thirty-three different patterns: six with only one tactor ON; six with two adjacent tactors ON; and twenty-one patterns with non-adjacent tactors ON. The rate of correct responses, divided by type of pattern, is presented in Table 3. The results of this discrimination test suggest that the distance between the tactors in the prototype is near the threshold of human perception, as the participants were able to describe adjacent tactors properly in a few samples only (17%) when they were shown simultaneously.

The minimum distance between the tactors is 50 mm horizontally and 40 mm vertically in the haptic device. These measures are close to the tactile perception capacity in the abdomen area described in the literature [11], which indicates that the threshold of the ability to distinguish two areas of touch is approximately 37 mm in this region of the body. In addition, it was not possible to find significant differences between the rate of correct answers of non-blind and blind participants in any configuration of patterns.

TABLE 3 - OVERALL RESULT: RATE OF CORRECT ANSWERS IN PATTERN DISCRIMINATION

Types of patterns	Correct Answers	
	Sighted participants (19)	Participants who are blind (2)
Patterns with one tactor on (126 samples)	123 (98%)	100%
Patterns with two adjacent tactors on (126 samples)	22 (17%)	19%
Patterns with two non-adjacent tactors on (441 samples)	274 (62%)	62%
All patterns (693 samples)	419 (60%)	59%

E. Perception of Movement Patterns Test

The third test aimed at verifying if the haptic device could make the participants notice moving patterns. For this purpose, the ability of the device to perform animations and use them as patterns for these tests was investigated. The update rate of the haptic device ranged from 25 to 30 frames per second.

In the process of sensory substitution, the perception of movement by the user may represent situations in which objects or people are moving in the detection field, for instance, or situations in which the device itself is moving or being carried by a user in movement.

In this test, the users should inform when they noticed any movement and, if they did, in which direction they perceived this movement. The participants were informed that the movements could be from left to right, right to left, top to bottom or bottom to top.

Each one of the 21 participants was exposed to the 12 patterns presented in Figure 6, a total of 252 samples. The movements were presented randomly. Each animation lasted 1 second and was repeated until the user indicated the direction of the movement. Immediately after the indication, the next pattern was presented. A beep indicated the end of the test. To avoid very long sessions, movements in diagonal directions were not tested.

Table 4 presents the results for this test, in which more than 96% of the answers were correct. It is important to highlight that a difference of about five percentage points was found in the rates of correct answers in the horizontal patterns in relation to the vertical patterns, when they were analyzed individually.

TABLE 4 – OVERALL RESULT: RATE OF CORRECT ANSWERS IN MOVEMENT PERCEPTION

Types of patterns	Correct Answers	Correct Answers (%)	Standard Deviation
Patterns with horizontal movements only (126 samples)	124	98,41%	0,3
Patterns with vertical movements only (126 samples)	118	93,65%	0,67
All patterns (252 samples)	242	96,03%	0,81

In general, the perception of movements was considered satisfactory due to the percentage of correct answers obtained by the users with little training. It was not possible to find significant differences between the rate of correct answers in the group of non-blind and the group of blind individuals in any category.

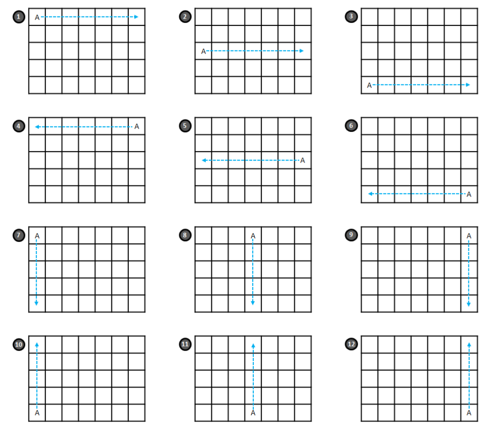


Figure 6 - Animated patterns for the movement perception test

F. Overview of Pilot Study

The pilot test was important both for the equipment calibration process, with respect to the intensities in which the device is able to individually represent in each tactor, and for verifying if the tactor density in the prototype was appropriate for the abdomen area. At this stage, it was also possible to investigate the ability of the prototype to convey real time information to the participants by showing movement patterns of the display, for instance, and measure the response time.

In this research, this stage was essential to make a pre-validation of the prototype before testing it in more complex conditions, like the ones in the evaluation tests.

With regard to the participants, none of them complained about feeling uncomfortable using the haptic device on the waist and all of them considered the duration of the tests suitable in the post-test questionnaire.

The completion of the pilot test also allowed us to discuss some of the usability evaluation of issues, including:

- Device Effectiveness: The belt allowed the user to identify movements?

Regarding the representation of the distances of objects, a good perception of the intensity levels means that the prototype can be calibrated to operate in six different levels, from the highest vibration level, for objects that are really near, to the lowest one (when the tactors are off), for objects that are out of the detection area. If the user is moving, the prototype can inform the proximity of objects through tactile stimuli that are as fast as a beep, according to the data collected in the pilot study. The participants detected the five levels of vibration intensities of each tactor with a response time similar to the one of a beep, as it is shown in Table 1. The density of tactors in the haptic device could also be evaluated in tests to discriminate simultaneous points in the matrix. The results of Table 2 show that it was more difficult for the participants to identify adjacent tactors, due to the minimum distance between them. Interestingly, the results of this test are within the threshold of tactile perception for this region of the body, according to other the research studies [10][11].

- Ease of learning: It was easy to relate the vibration points to the location of obstacles?

Concerning the ability to represent moving patterns in the haptic device, the percentage of correct answers was higher in patterns of horizontal movement than in vertical ones. This result must be further evaluated, but might be related to the fact that there were more tactors distributed horizontally (seven) than tactors distributed vertically (five). In general, the results of the pilot study demonstrated that the prototype could convey both static and dynamic tactile information in the abdomen region.

V. EVALUATION TESTS

The evaluation tests involved the usage of the prototype as a whole, with the haptic device receiving data from the depth of a real scene. The main goal of this stage was to test all parts of the prototype operating together in situations similar to those of an interface to support movement in its everyday use. The group of participants is different from the pilot study group.

Two different tests were applied. In the first one, the Perception Test for People in Movement, 16 users participated (10 male and four female sighted and two visually impaired women) invited by convenience. The ages ranged from 19 to 48.

In this test, the participant using the device stood while people around him/her moved. For capturing the movements, we used the real depth camera, instead of the simulated movements generated during the pilot study.

In the second test, the Navigation Test, four sighted men, one sighted woman, and two blind females participated in this test. They were also invited by convenience. The ages ranged from 22 to 30. For this test, the participants moved and navigated in an environment that simulated corridors surrounded by walls.

A. Prototype Calibration

In order to map the scene depth in different levels of tactor intensity, the device was configured according to the information obtained in the sessions of the pilot study and the technical specifications of the Kinect device.

The Kinectic sensor is able to detect the depth of a real scene within a range from one to three meters away from the device. Based on this, a linear function was used to map the distances detected by the Kinect device and the five levels of tactor intensity, as can be seen in Table 5.

If the depth information did not exist at certain points in the scene due to objects being outside the Kinect range, the corresponding tactors were turned off.

TABLE 5 - MAPPING BETWEEN DISTANCES AND TACTOR INTENSITIES

Distance	Intensity in the display
100-139 cm	A (highest)
140-179 cm	B
180-219 cm	C
220-259 cm	D
260-300 cm	E (lowest)

During the evaluation tests(Perception Test and Navigation Test), the prototype captured scenes using the Kinect device and converted them into tactile stimuli with an average refresh rate of 27 frames per second, the same used in the pilot study for movement perception. Then, the participants received haptic information generated from images continuously captured by the camera in real time. This allowed the application of evaluation tests using moving obstacles and also allowed the user to move with the equipment in the physical space specified for the experiment at about 4 km/h, which is equivalent to walking speed.

B. Perception Test for People in Movement

The aim of this test was to check if the users could notice the position and direction of people moving in front of them while using the prototype.

For this purpose, the prototype was placed on a table (Figure 5) and directed to capture an initially empty space in front of it. The room should be large enough at least to cover the entire area detected by the Kinect sensor. Then, the participant should stand behind the Kinect device, and look at the same direction as the device was capturing the images.

After that, the participants were asked to wear the haptic device and stand up in the same place during the whole test. In this test, sighted participants were blindfolded right after they were in the right position, wearing the haptic device.

Before starting the test, the participants were trained for about one minute to relate the tactile stimulus they were receiving, with the direction of the voice of a person moving at various points in the detection field, in front of the equipment.

After this introduction, a fixed sequence of nine movements of two people walking was performed in front of the prototype for about one minute, while the participant stood up behind the table. This sequence is shown in Figure 7, which is a top view of the movement area. In this figure, the arrows represent user A, and users A and B and the larger circle represents the position of the participant and the Kinect device in this test. The dotted lines represent the detection area of the Kinect sensor.

Figure 8 illustrates some examples of movements used in this test. The pictures show some frames of a recording and their respective depth maps. The speed of the person moving was equivalent to the walking speed of an adult in a normal situation.

In the preparation stage, the participants were instructed to verbally express the direction of movements or point at the movements they perceived during the test.

To avoid the influence of the sound of footsteps on the participants' answers, background music was played during the test, so that the participants could not hear the movements of people walking.

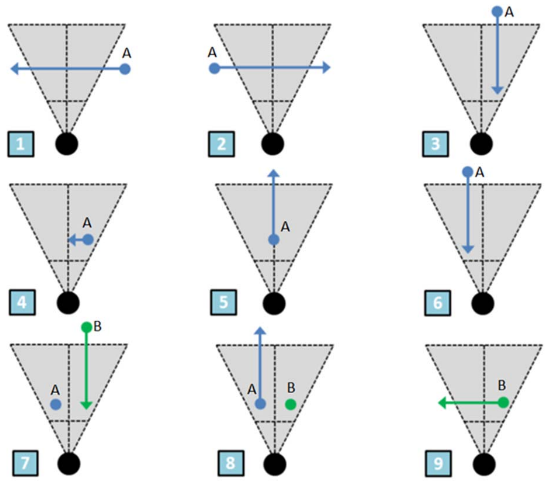


Figure 7: Top view of the walking movements

To be considered correct, the participants' answers should describe exactly the movement in front of them, by using the information from the haptic device only.

Figure 8: Movement of a person during the tests

Answers were considered incorrect when the participants did not describe exactly the movement or did not answer before the next movement was performed. The results, divided by type of movement, are presented in Table 6, which shows the average and standard deviation of the participants' correct answers for each type of movement in the test, according to Figure 7. Movement number 8, which is person A going backwards while person B remains in the right side of the participant, presented the worst results (average of correct answers: 56,3% and standard deviation: 5%) among the different types of movement performed in the test. Even though the participants noticed the presence of two people during movement number 7 (average of correct answers: 87,5% and standard deviation: 3,4%), they had difficulties to describe how person B enter in the scene. Movements number 3, 5 and 6 also presented lower percentage of correct answers because the participants should describe if the movement was on the right, on the left or in the middle and, at the same time, tell if the person was getting closer or further away. For the movements 1, 2 and 9, the average of correct answers is higher because the expected answer was simpler, as the participants should simply describe in which direction the person was moving. It was possible to observe during the tests that the existence of 5 lines of tactors was useful to perceive the distance between the participant and the person in movement. In addition to the fact that vibration intensity is reduced in the representation of distant objects, the mapping of these objects tends to happen in the lower region of the abdomen (tactors number 15 to 35, according to Figure 1). This is the result of the position of the camera at chest height and the perspective of the image obtained, which can be observed in the depth maps of Figure 8. In these tests, the performance of the participants who are blind was 4% better than the sighted ones. However, it is important to emphasize that these findings are based on only two participants who are blind.

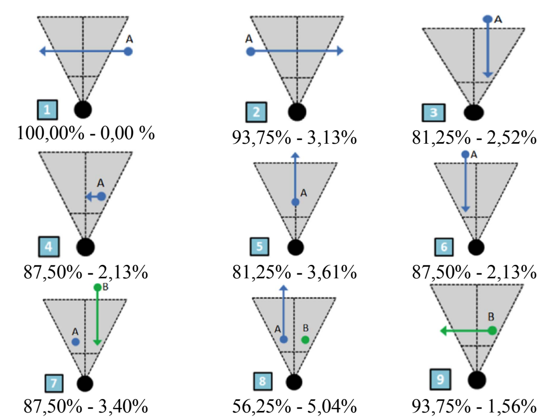
C. Navigation Test

The navigation test aimed at verifying whether the prototype could help the user move in an environment surrounded by corridors. A map of the room where the test was applied is presented in Figure 9, as well as the ideal path represented with a dotted line. Each cell in the figure represents an area of about one square meter.

The prototype was set on a wheel table that could be moved around the environment as a shopping cart and connected to a no-break with enough charge for each test session.

When the participant arrived for the test, the instructor explained that they would wear a belt (the haptic device) and drive a cart in an unknown route. Then, the participants were informed that they would use only tactile information from the haptic device to detect the distance of the walls (obstacles) along the way. If the participant accepted to participate in the test, he/she signed an informed consent form and was led to another room.

TABLE 6 - RESULTS BY TYPE OF MOVEMENT



The numbers bellow the images represent the Average of Correct Answers and its Std Deviation

After these instructions, the participants went to the room with the navigation environment. Sighted participants were blindfolded before going to the room, so that they could not see the route before the test.

As soon as the participants arrived in the navigation room, they were instructed to put on the haptic device and stand up behind the cart containing the prototype, with both hands on the bar used to guide this cart (Figure 10). As in the previous test, the participants faced the same direction as the Kinect device. The cart was placed at the beginning of the route and pointed forward.

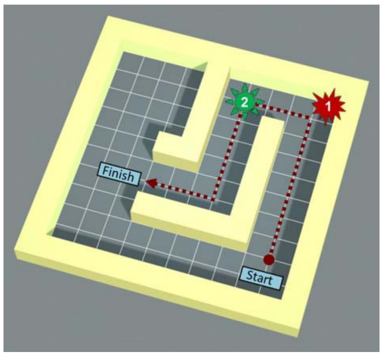


Figure 9: Map of the navigation test environment and collision events

Before starting the route, the participants received training similar to the one in the previous test while they stood at the beginning of the route. At this stage, they should be able to relate the information they were receiving through the tactile stimuli with the distance and direction of the voice of the person who was training them.

After this training, which lasted about 1 minute, the test started as soon as the instructor allowed the participant to move forward and try to follow the route without colliding with the walls. At this stage, the instructor told the participants to rotate the cart smoothly to the left and the right sides whenever they found it necessary to find a way out. Furthermore, the participants were instructed to walk unhurriedly, paying special attention to any strong vibration indicating the presence of an obstacle very close to them.

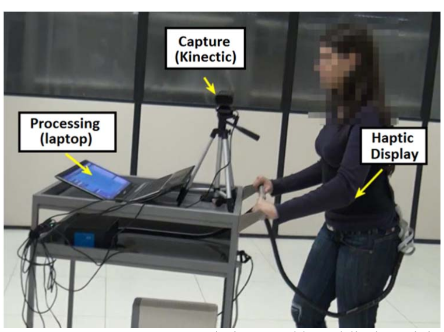


Figure 10: Prototype on a cart being used by a blind participant

D. Overview of Evaluation Tests

The results were evaluated by counting the total time that the participants took to complete the route and by registering collision events and moments at which the participants got confused during the test. Table 7 shows the time spent by each subject to complete the track.

TABLE 7 - RESULTS FOR NAVIGATION EXPERIMENT

Subject	1	2	3	4	5	6(blind)	7(blind)
Time spent(s)	116	122	212	120	50	80	85
Average	124					83	

As can be seen, the blind participants completed the route in a shorter average time (83s) than the sighted ones (124s). Among the reasons for the better performance can be the absence of collisions and confusions, and the higher familiarity in dealing with tactile information, in the group of participants who are blind. However, it is important to mention that this comparison is restricted to a small number of samples obtained in this test. It is important to highlight that all the participants were able arrive at the end of the route and there was only one case of collision(subject 4) and another one with momentary confusion(subject 3) in relation to the right direction to follow. These events occurred with two sighted participants. Figure 9 illustrates the position of the collision event (1) and the moment of confusion (2).

Similar to the Pilot Study, were investigated some issues related to system usability. Effectiveness and efficiency in use: The belt allowed the user to identify obstacles before there was a collision, so it can be considered useful for helping navigation tasks; Safety: the belt identify objects and movements and warn the user in advance, allowing collision avoidance and identification of surrounding movements; Cognitive Overhead: According to the results, it was easy to relate the vibration points to the location of obstacles; Ease of learning: All users of the navigation test were able to relate the vibration points to the location of obstacles, even though not being part of the pilot study.

VI. CONCLUSION

Assistive technology applications in the context of space representation for teaching and developing navigation skills are options for people who are blind to use other senses and perceive the environments such as the use of tactile sensations.

This study focused on the use of haptic devices to develop and test an interface to support the mobility of people with visual disabilities, based on the tactile representation of scene depth information.

The prototype mapped the depth of a real scene to the haptic device as immediately as possible in terms of data conversion, promoting a sensory substitution process from vision to touch in real time. No predetermined sounds or symbols were shown in the haptic device during the navigation.

The results demonstrated positive rates of correct answers in relation to information conveyed by the prototype and in relation to the participants' perceptions, both in the pilot study and in the evaluation test.

The configuration and calibration of the interface developed in this research regarding the dimension of the matrix of tactors, the levels of intensity and the response time were suitable to describe moving objects as big as a person, at different distances and in real time.

The navigation test also shows that this interface can be a tool to help the navigation of people with visual disabilities, based on the conversion from vision to touch. More long-term full testing with a bigger sample is needed to better dimension the real impact of the interface proposed.

It is important to highlight that the participants did not receive any type of extensive training to use the prototype during the tests, which would certainly increase the rates of correct answers. This assumption is based on the fact that human natural senses are continuously developed through a lifetime, so their substitution is also expected to require suitable training.

The ideal device would employ a mapping that is intuitive and requires little to no training.

VII. FUTURE RESEARCH

Future research should focus on improvements of the prototype, such as replacing some of its components by smaller and more efficient ones. During this study, it was not possible to reach a level of ergonomics that allowed the user to wear the equipment and use it more freely, for instance. Thus, the Kinectic sensor may be replaced by a smaller device that could be installed on a cap or on eyeglasses.

We are planning on evaluating in natural environments like outdoors and homes, in order to assess how the belt can be used to help users to better move through these spaces.

Furthermore, the haptic device could be built with special Linear Ressonant Actuator (LRA) tactors, which would take it more comfortable to wear. Any wireless solutions in new version would also help in the ergonomics.

The performance of the equipment should also be analyzed in outdoor environments, as the amount of noise, such as the infrared light from the sun, can interfere in the capturing process.

Future research should include more in-depth usability studies, including a large sample of users who are blind and perhaps comparing performances with similar devices to explore more fully the added value of the haptic interface proposed here and draw final conclusions with more evidence.

Finally, it is relevant to highlight that the users' learning curve can also be the object of further studies. In future research, both participants who are blind and sighted ones could be trained to benefit from additional information during navigation tasks using interfaces similar to the one developed in this study. Users with appropriate training may possibly learn to notice details in haptic devices with higher density of tactors and more intensity levels than the ones used in this research.

VIII. ACKNOWLEDGMENTS

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