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Vibrotactile feedback to aid blind users of mobile guides

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ABSTRACT

In this work, we report on a solution for providing support to the blind using mobile museum guides by exploiting the haptic channel as a complement to the audio/vocal one. The overall goal is to improve the autonomy and social integration of blind visitors. We followed an iterative approach in which the proposed system went through various user evaluations and further refinements. The final solution includes vibrotactile feedback enhancement for orientation and obstacle avoidance obtained through the use of unobtrusive actuators applied to two of the user's fingers combined with an electronic compass and obstacle detector sensors connected wirelessly to the mobile guide. Our study indicates that vibrotactile feedback is particularly useful to provide frequent unobtrusive indications of useful dynamic information, such as the level of proximity of an obstacle or the distance from the right orientation.

1. Introduction

Technological support is increasingly used to provide services and products that are more suitable for a wide variety of users in several different contexts. Technologies also provide new opportunities to allow users with special needs—such as people with disabilities—to access or perform activities previously impossible or particularly difficult to do (e.g. accessing digital information for blind people). There is increasingly enormous potential to harness mobile devices (cells and PDAs) capabilities for use in assistive technologies or in developing supporting tool (see for example [1]). However, to achieve such a result accessibility principles should be applied when developing a product or service.

Accessibility is a general term used to indicate that a product (e.g., device, service, environment) is accessible to as many people as possible, including those with disabilities. This is an important feature of systems to allow users with different abilities to access or use them. In this perspective, a multi-modal approach can represent a valuable way to support various interaction modes, such as speech, gesture and handwriting for input and spoken prompts. Thus, by combining various interaction modalities, it is possible to obtain an interactive interface suitable for users with varying abilities. A well-designed multi-modal application can be used by people with a wide variety of impairments. Visually impaired users rely on the voice modality with some keypad input. Hearing-impaired users rely on the visual modality with some speech input, and so forth.

In this regard, we decided to consider museum environments to investigate how to design and implement a multi-modal mobile application that can be easily used by blind people in this domain [2]. The aim of our study is to provide blind visitors with greater autonomy. Even if the blind cannot view museum items, visiting an exhibition autonomously can represent a good way to integrate the vision-impaired into a group (e.g. family or friends) and is more effective than obtaining cultural information from a Web site or multimedia CD.

In particular, in this work we investigate how the haptic channel, in conjunction with the audio/vocal one, can provide better support for the use of mobile museum guides for blind users. People who are blind or visually

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impaired must rely upon senses other than sight to perceive diverse information (e.g., shape, dimensions, etc.). Haptic interface technology allows building tangible data surfaces to provide an additional modality for data exploration and analysis. Unfortunately, the amount of information that can be perceived through touch is less than that which can be perceived through vision. Consequently, multi-modal approaches should be investigated to enhance the perception of blind and visually impaired people.

In the paper, after discussing some related work, we briefly introduce the key features of our proposal. We then report on the various versions that have been developed and the associated user tests. We indicate how the results of such tests have been considered in the evolution of the work up to the final version. Lastly, some conclusions along with indications for future work are provided.

2. Related work

In general, the use of haptic output for mobile users has already been considered in several studies. For example, an array of nine tactile actuators making up a wearable vibrotactile display was studied in [3]. Brewster and others [4] deal with *Tactons*, structured vibrotactile messages carrying complex information: they studied the use of haptic feedback alone to encode three different parameters (*Rhythm*, *Roughness* and *Spatial Location*) exploiting several vibrotactile actuators. The above-mentioned authors highlight the potential suitability of their proposals with mobile devices such as PDAs, but the reported user tests are limited to stationary environments.

An evaluation of tactile output supporting mobile interaction is provided in [5], which presents the benefits that may be gained from haptic feedback. The tests showed that user performance significantly improves when haptic stimuli are provided to alert users about unwanted operations (e.g. double clicks or slips during text insertion).

The previously cited works mainly focus on the advantages of exploiting the haptic channel as a complement to the visual one and do not regard solutions for blind users.

The literature also contains some proposals for supporting blind users' mobility. For example, in [6] a haptic direction indicator prototype is proposed to support visually impaired users in various emergency situations. User requirement studies indicate that in specific situations (e.g. emergencies) the supporting device should be small so that it can be easily held in the hand. A more general purpose navigation system has been proposed in [7], which adopts tactile perception to inform the blind user about the distance to an obstacle. The authors claim that using multiple sources of vibration to convey information about the environment is more effective than audible feedback. Variable and synchronized vibration pulses have been used to enhance sense of orientation and distance for the user. The navigation system is based on sonar sensors, an embedded micro-controller system and an array of vibrotactile actuators. To convey information to the user exploiting the sensitivity of the hand, the authors tried to combine all three tactile perception parameters: the location of the active vibrotactile actuator, the intensity of the feedback, and pulse duration. However, the proposed hardware seems to be a stand-alone device without any possibility of adapting it to other applications (e.g. customizing the output of a mobile guide).

The recent progress of handheld computers and mobile phones has enabled the development of compact wearable aid systems for the blind, often in combination with RFID or similar technologies. Possible applications are related to indoor solutions to support visually impaired people in mobility and orientation. RadioVirgilio/Sesamonet [8] is a guidance system, based on a cane with embedded RFID reader and a Bluetooth module. Sensed data are sent via Bluetooth to the handheld device (which is also connected to a remote server) that guides the user by means of speech-synthesized instructions. This solution is based on a general purpose handheld device, which requires blind users to follow predefined paths, thus limiting the user's freedom of movement. The RFID-based indoor navigation system for blind people proposed in [9] aims to help them find the shortest path to a destination, as well as to help them if they get lost. The proposed system embeds RFID tags into a footpath that can be detected by an RFID reader with a cane antenna. The dedicated device is portable and equipped with a headphone for navigation where only voice (i.e. mp3 recordings) is used to guide the users. The system however does not include any obstacle detector. Our proposed system combines RFID-based localization, to determine the current user position, with a compass, to provide information on heading; a distance sensor is also used to provide information on the distance from stationary and/or moving obstacles. Another RFID-enabled navigation for the blind has been proposed in [10]. Detected tags provide the coordinates of their location, as well as other information. Orientation is supported by vibrotactile output. An interesting novelty is that the system does not depend on a centralized database. However, like RadioVirgilio/Sesamonet, it focuses on navigation through predefined paths marked by RFID tags. GLIDEO [11] is a different solution for providing blind users with audio information about RFID-tagged objects in their surroundings (such as temperature and weight). The RFID reader is embedded in a glove to let the user freely explore the area.

Coroama [12] also describes an assistive system exploiting electronic markers to provide useful information to the visually impaired. Tagged objects are detectable by a mobile device that provides descriptive information. Tomitsch et al. [13] propose exploiting audio-tactile location markers (ALMs), which use an approach of combined audible signals and tactile identification, for making real-world tags accessible for users. Passive near field communication (NFC) tags are used to mark an object. Since NFC tags are activated at low ranges (below 10 cm), Bluetooth technology is used to locate them from greater distances. An audible signal is used to identify the position of the tag, when a mobile device (i.e. cell phone) is detected in the neighbourhood through

Bluetooth exploration. Although this solution exploits both auditory and tactile feedback, it seems to be somewhat expensive. Ubibus [14] is a proposal for helping blind people in public transportation scenarios. Users rely on a mobile device (PDA or mobile phone) with WLAN or Bluetooth connectivity to activate a stop request or to be informed about the next stop.

While the above reported solutions for the visually impaired provide information about the surrounding environment, they do not offer support to assist users in freely moving towards the tagged objects and, at the same time, to avoid potential obstacles. In particular, our work specifically aims to improve the mobility of blind users in this regard.

3. Key features of our solution

Our solution is based on a combination of various technologies to obtain a multi-modal user interface for supporting blind users. Broadly speaking, the type of context of use addressed is a visit in an indoor environment with various points of interest, such as a museum. In this perspective, the components used in our prototype have been designed to support (1) user movements and orientation, (2) obstacle avoidance along any given path, and (3) access to information and descriptions of items on display (such as artworks). The proposed system is composed of a PDA equipped with technologies that address the goals mentioned above.

Concerning the first goal (i.e. user movements and orientation), our proposed system is based on Active Radio Frequency IDentification (RFID) technology. In order to facilitate object detection in a rather large museum gallery, we decided to apply long-range tags detectable within 5 m. A compact flash (CF) reader has been plugged into the PDA in order to assemble a compact mobile device easy to hold in the hand. To be able to suggest the appropriate direction for moving towards the targeted object (i.e. next artwork or specimens), we used an electronic compass specifically designed for this application. The wireless connection between the PDA and our proposed wearable compass is Bluetooth-enabled. Moreover, the system has been equipped with vibrotactile feedback for supporting the user in orientation. Different intensities and durations of vibration encode the indications to be provided to the user to determine the right direction.

To implement the second aspect, obstacle detection, a distance measuring sensor has been embedded into the electronic compass box. The communication between the system and the distance sensor is also Bluetooth-enabled. Such a sensor allows the mobile application to inform the user when approaching a potential obstacle. The kind of feedback provided to the users has been modified over the various versions we have developed. Both sound and vibrotactile feedback were investigated.

Regarding the audio description of the artworks and the messages provided by the system, we decided not to use MP3 recordings. We preferred a solution based on real-time speech generation. To this purpose, the multilanguage Text-To-Speech (TTS) engine we used offers various advantages, such as requiring less storage space (MP3 files would require a lot of memory) and minimal effort to modify messages and descriptions (no recordings have to be made again in the event of changes, an important aspect especially when dealing with multilanguage applications). Although generating audio messages on the fly is easy, as mentioned above, for some feedback we preferred using vibrotactile output. Such decision is based mainly on the fact that such technology can offer an unobtrusive solution, which might be more appropriate in public places.

4. The first prototype (RFID+electronic compass+audio/vocal feedback)

4.1. RFID-based localization support

The main feature of our first prototype was a localization infrastructure based on a number of RFID tags deployed throughout the exhibition area of the museum: each tag is placed by an artwork [15]. The correspondence between artworks and tags is specified in the museum database. The position of each artwork within the room is stored in the database as well: in our accessible museum guide artwork position is essential for suggesting the right direction to the user. Fig. 1 summarizes the architecture of this first prototype. Bottom-up in the schema:

- *RFID reader* is a hardware module that detects the RFID tags in the environment. It is a compact flash (CF) card plugged into the slot of the handheld device and has been provided by Identec Solutions (http://www.identecsolutions.com). Each tag transmits its ID with a constant power level to enable detection within

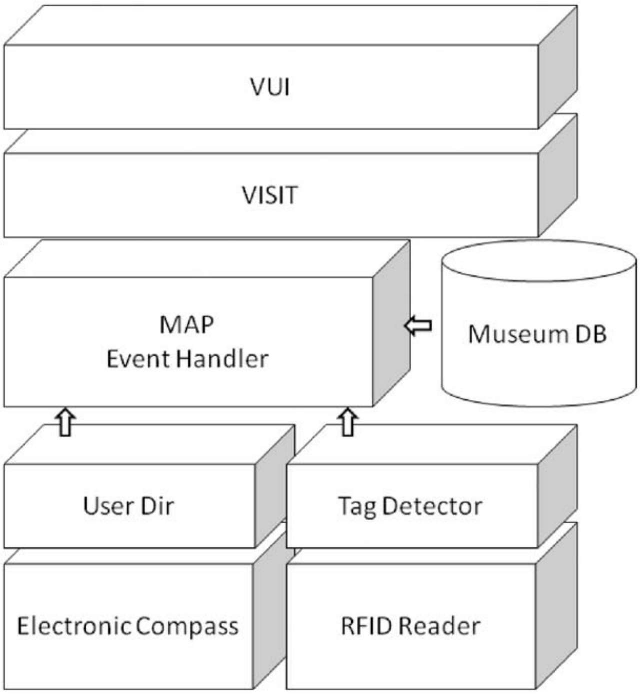


Fig. 1. Architecture schema of our mobile guide system.

about 5 m. For each tag the RFID reader also detects its signal power (that is, the received signal strength indication (RSSI), which depends on how far the tag is), reporting it to the software layer. A location event is triggered when a new RFID tag is detected or when the signal strength of a tag has changed.

- *TagDetector* is the software embedding the RFID monitoring thread that generates location events. It interfaces with the RFID reader through pre-compiled software modules provided by the hardware manufacturer.
- *Electronic Compass* is the device for sensing user direction in absolute orientation degrees. The compass is needed because calculating the user motion vector based on the signals detected from the RFID tag network is rather problematic. Since none of the existing commercial solutions seemed to be suitable for a mobile application, we expressly designed and developed the device to meet our requirements. It consists of an analogue compass sensor and a microcontroller that manages analogue to digital conversion (ADC) and data serialization. The compass device is battery operated, has an embedded Bluetooth interface with serial port profile (SPP) and is detected by the PDA as a wireless peripheral. The small size and low weight of the compass device make it easily wearable. Fig. 2 illustrates a blind user carrying the PDA and wearing the compass as a necklace.
- *UserDir* is the interface software to the compass device. It reads and filters the stream of values and computes the direction three times per second as a value in the interval $[0,359]^\circ$ with respect to the North.
- *Museum DB* is an XML specification of the whole museum: authors, artworks, sections and associations between artworks and RFID tags. These resources make up a simple geographical information system (GIS) that holds enough information (sections geometry and artworks positions) for supporting a blind user. The access to the DB is triggered by the *Map Event Handler*.
- *Map Event Handler* is the module that catches the events triggered by the *TagDetector* and asks the *UserDir* for the direction. This module also queries the *Museum DB* for the environment topology (to compute the paths) and for artwork information (to provide automatic description upon reaching the target artwork).
- *Visit* supports automatic access to museum info such as artworks and section descriptions.
- *Vocal user interface (VUI)* exploits an embedded TTS engine, provided by Loquendo (http://www.loquendo.com), which synthesizes the speech for describing artworks/sections and for giving direction tips on the fly ("… *rotate left*…", "… *carry on in this direction*", "*Please, stop!*").

Fig. 2. A blind user carrying the mobile guide (PDA in the right hand and electronic compass round the neck).

Upon reaching an artwork, the event handler launches a vocal messages that tells the user which item is being visited. If the user accepts, then the description starts, otherwise the path to the next artwork is computed. Input is provided by the user through the keypad of the PDA, which physical buttons are easily distinguishable due to their shape.

The compass information is used in conjunction with RFID detection. When the user requests help to reach the next artwork, the guide computes the line joining the currently visited artwork and the target one. This is possible because the application is aware of the environment topology, which is stored in the DB. Initially, the current user position (detected by RFID) is approximated to the starting point and the direction is sensed in real time by the compass. Thus, the direction is updated many times per second in order to provide the user with indications for keeping the right heading towards the target and not let her stray from the best path.

In the early integration of the compass support we opted to use vocal instructions to guide the user. Depending on the direction change needed to guide the user to a specific location, the application synthesizes speech such as "*turn X degrees left/right*" (with $X \leq 180$). When the right direction is reached the user is asked to move towards the artwork by the instruction: "*slowly approach the artwork continuing in this direction*". When the user enters the destination area (about 5 m around the artwork tag) s/he receives a notification and a "beep" starts to sound repeatedly. The frequency of the beeping depends on the current distance from the destination tag: the faster the beeping, the closer the target artwork. We consider distance monitoring as the only way to ensure the user reaches a point of interest. The compass support is useful to direct the user towards the artwork, but the system has no information about the path taken.

4.2. First prototype evaluation

Before carrying out a user test, we decided to conduct a preliminary test of the first prototype in order to set up the version to be used. In our preliminary evaluation, two blind users were involved to collect useful comments and data while using the system. Initially, they were instructed to reach an artwork by exploiting only the distance support, that is the repetitive sound indicating how far the destination tag was. Both users accomplished the task, but they took quite a long time. Users reported that looking for an artwork placed many meters away from the current one is a too complex task if no direction aid is provided. This is due to the need for scanning almost the entire room before reaching the suggested destination. A second session trial was performed on the guide version enhanced with the compass module. Users were able to discover the proposed artwork location and arrived very near the associated tag. The compass support was judged essential and some improvements were suggested. The first user would have preferred a continuous sound with variable frequency rather than vocal tips: he stated that degrees-based tips are not intuitive. The second user, on the contrary, appreciated the vocal aid but pointed out that not everyone is familiar with measurements in degrees. She suggested indicating the direction by simple sentences such as "*rotate left/right*" or "*turn back*". Therefore, we decided to test these two kinds of audio feedback with a larger group of people in order to evaluate their real impact on the blind. All in all, users found the orientation support to be a reasonable way to help the blind in visiting a museum independently.

4.2.1. *User testing of the first prototype*

Keeping in mind the observations gathered from the two users, we performed a user test involving a larger number of blind users. Two versions of the prototype with the two different audio feedback were used in this evaluation. The main goal of the test was to compare the usability of the two prototype versions with different types of audio feedback. More specifically, the evaluation was targeted at answering the following questions: (1) Can an electronic compass support a museum visit? (2) What is the most appropriate audio feedback for a blind user?

For these purposes, the evaluation regarded a guide prototype, which was provided in two versions differing from that preliminarily tested only in the type of audio feedback. The first version adopted simplified vocal tips such as "*rotate left a bit*" and repetitive "beep" sounds with variable delay to indicate distance. The second version used a continuous sound with variable frequency to suggest direction and repetitive "beeping" sounds with variable frequency to signal the distance. In the latter version, the frequency of the direction sound decreased as the right orientation was achieved. Once aligned, on the contrary, the distance sound frequency increased as the user approached the target.

We recruited five participants: four of them totally blind from the birth and one with a little residual vision. The age ranged from 33 to 69 years. Four of them use a computer with a screen reader in Windows environment daily. None of them had any experience with PDAs.

Users were asked to reach a specific artwork by exploiting the compass-based guide. Since the experiment was also aimed at analyzing the kind of feedback, each user tried to reach different artworks by using the two versions of our guide prototype. In order to avoid a possible bias due to the learning process, three users used the vocal version first and then afterwards the one based only on the sounds; whereas for the others the process was inverted. The task assigned was to start from a specific artwork to reach another one. The artworks to reach were different for the two guide versions. We observed the users as they performed their tasks. The start and finish time was recorded for each user and for each task. At the end of the tests, users were asked to fill in a questionnaire to collect subjective comments and suggestions.

All the users were able to accomplish the assigned tasks. The recorded time for each user for all tasks revealed a significant time saving in localizing the artwork by using the version with both vocal and sound support. Just one user spent more time using the version with vocal feedback. For the other users, the time saved ranged from 50% to 82% ($M = 35.57\%$). Users indicated they encountered some difficulties in carrying out the tasks due to the response times of the system. This referred to the time lag of the direction tips and it has been improved by better filtering the compass event stream.

Concerning subjective opinions, the users could express a value from 1 (the most negative value) to 5 (the most positive value) with respect to various aspects. The users declared that the RFID technology can be a useful support ($M = 3.6$; $\mathrm{SD} = 1.6$) not only for localization, but also for daily activities. However, some of them reported that this methodology should be integrated with other technologies in order to be more precise and reliable. On the other hand, regarding the use of an electronic compass in a museum context, the users reported that such a support would be a useful assistance to allow a blind person to freely move among the artworks ($M = 4$; $\mathrm{SD} = 1.2$). The users were asked to report their preferences regarding the two audio feedback versions. Most users (four out of five) preferred vocal and sound feedback, while one user reported that using only sounds would have been better because sound feedback might be more intuitive and less annoying. This can be easily explained by the fact that he is an expert user in electronic devices. The other users preferred the version with vocal and sound support, declaring that such support is more intuitive especially for a non-expert who is using the system for the first time. In fact, our prototype is designed to be used in a museum context where visitors have no time to learn and become familiar with the guide. However, regarding sounds, one user suggested using different kinds of sounds (e.g. just three types) and well recognizable (i.e., they should have very different frequencies) because very similar sounds could not be easily differentiated. In general users appreciated the support for their autonomy of the application. They provided some hints to improve its efficiency, and one user suggested the addition of tactile feedback, similar to that of mobile phones.

5. The second prototype (vibrotactile orientation feedback)

5.1. *The haptic support*

The second prototype we developed was mainly aimed at evaluating possible benefits coming from the addition of haptic feedback [16]. The main goal was to evaluate whether using multiple sources of vibration to convey information about the environment is more effective than audible feedback alone. The haptic output module, which is an add-on that we specifically designed and tuned, consists of a plastic box (slightly thinner than a packet of cigarettes) fixed to the back of the PDA. The box contains circuitry able to detect infrared signals from the PDA. The photodiode (i.e. infrared receiver) protrudes from the box so that it is aligned to the infrared port of the PDA. The battery-operated circuitry also drives two vibrotactile actuators according to the commands sent by the PDA via the infrared interface. Each motor is attached to a rigid surface of about 1 cm^2 and is connected to the box by a 10 cm wire. The motors can be fixed to the index finger and thumb by Velcro strips to let the rigid surfaces transmit vibrations to the fingertips. We opted for separating the motors from the box to facilitate distinguishing the channels. Otherwise, if motors were attached to the box it would have been very difficult to insulate them and the vibration of a single motor would have propagated to the rest of the device, making harder for the user to distinguish the vibrating side.

The actuators are rotary mass vibrator (RMV) motors like those that enable vibration in many mobile phones (see Fig. 3 top-left). The driver circuitry controls each motor independently. Each command received from the PDA encodes the state of the haptic interface, that is, for each motor, the on/off flag and the vibration intensity value. The flag controls the switch (transistor) while the intensity value, a byte, is passed to a 256-step digital programmable potentiometer (DPP). The haptic module circuitry is managed by a 4 MHz micro-controller whose routine is able to decode a command and to upload the motor states up to 60 times per second.

To change the haptic device state the PDA software application has to generate and send a three-bytes command with the switch flags, the intensity values and some check bits. For example, a haptic message like a short, intense left vibration requires two commands. The first, with left flag = 1, right flag = 0, left speed = 255 (the maximum value) and right speed ignored initiates the left engine fast vibration. The second command, with left flag = 0, right flag = 0, left/right speed ignored stops the motor. The vibration length depends on the delay between the start and the stop commands. A complex haptic feedback such as a left–right fading can be created by repeatedly sending commands where the left speed parameter decreases and the right one increases (or vice versa). Since the latency between the *sendCommand* function call and the new motors configuration is about 15 ms, we assume that even more complex effects may be created, such as the rhythms discussed in [4].

5.1.1. Orientation haptic feedback

One of the aims of our study is to reduce the time and effort required by the blind user to move towards the next artwork. In fact, while localization is ensured by a grid of RFID tags and is provided by messages such as "*you are approaching the artwork x*", orientation (enabled by the electronic compass) is key support for successfully reaching the destination area.

In this application, usability is related to the time needed to reach the next artwork. Even in the smallest museums or exhibitions there are tens of artworks/items. The user should consider the guide as effective, i.e. as an alternative to the human companion. If not, the guide would be perceived as useless, turning the museum visit into a frustrating experience.

As already mentioned, haptic output has been investigated according to the suggestions made by some users of an earlier test. It has been considered as a complementary (rather than alternative) modality for supporting blind users' orientation.

We took into account that the museum visits are usually made just once by visitors and considered that they probably do not want to spend much time familiarizing themselves with the interface. For this reason, and taking into account the suggestions by users in a previous test, we encoded only a small amount of information in the haptic feedback. We actually configured four types of patterns corresponding to the vocal suggestions given by the previous version of the application: "Rotate Left", "Rotate Right", "Rotate Left a bit", and "Rotate Right a bit". Rotation direction (left/right) is given by *Spatial Location* of the activated motor (i.e. which finger is vibrating). Rotation angle is indicated by *Duration* and *Intensity* of the vibration: a strong and long (2 s) impulse or a light and short (700 ms) one to indicate whether rotation must be more or less than 90°, respectively.

Haptic patterns provide an indication of the distance to the target as well: once the user has aligned to the best direction and has reached the destination area, short vibration pulses are activated on both sides. The delay between pulses reduces as the destination tag signal grows (i.e. the user approaches the tag). Feedback on the distance may help the user in reaching the target even if the followed direction is slightly different from the ideal one.

5.1.2. Vibrotactile patterns

Fig. 4 summarises the architecture of our haptic support and shows how it fits within the general one. The mobile application exploits a one-way infrared connection (IrConn) to communicate with the haptic device. Sending a command is a trivial operation since it consists simply of writing bytes on the infrared port stream. As already mentioned, to execute a basic haptic message two commands must be sent to start and end the vibration. The application has to manage the vibration duration as well. As output complexity grows—i.e. many custom vibrating patterns are needed—a mechanism to arrange and execute them is highly desirable. The development of such architectural framework was performed simultaneously with the creation of a tool for editing custom vibrotactile patterns through the PDA touch screen (see Fig. 5). The pattern of the vibrotactile output for each side (left/right) is defined by dragging the curve, which is associated with the vibration intensity over time. By choosing size (number of steps) and delay it is possible to define the pattern granularity.

Fig. 3. One of the actuators used in the experiment (top-left), the PDA fitted with the haptic module (top-right), the mobile equipment fitting on the user's hand (bottom).

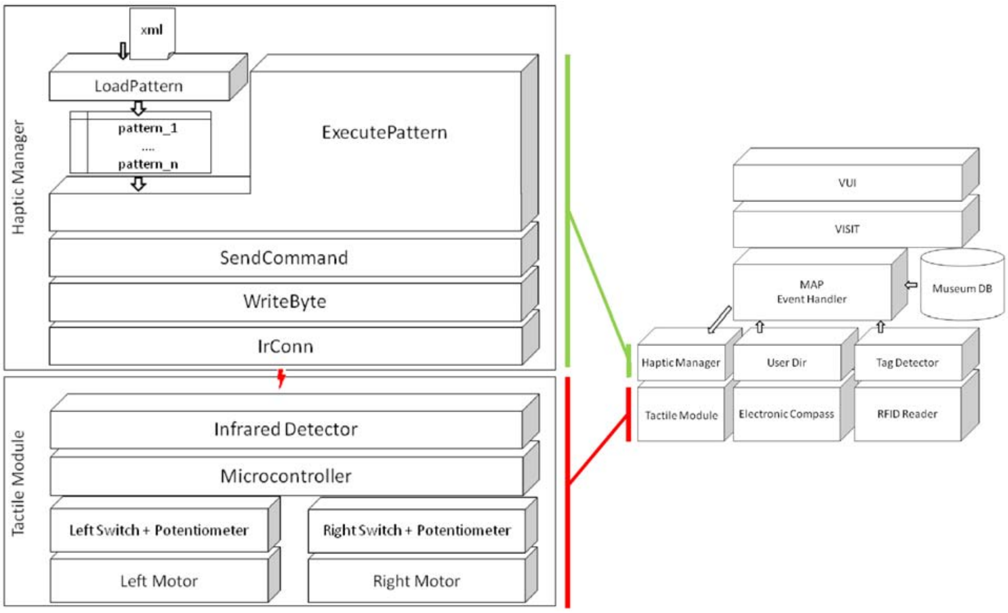


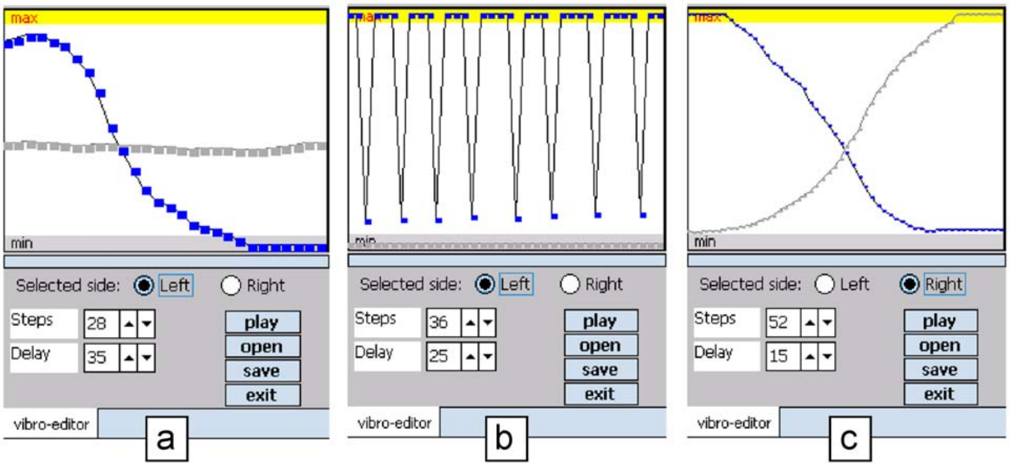
Fig. 4. Hardware and software layers for the haptic framework (left side) and how they fit on the overall architecture (right side).

The *Selected side* radio button indicates which actuator (left or right) is currently active for editing. The curve points of the active actuator are represented by blue squares, while for the inactive one the squares are light-grey.

Steps is the number of points on the curves.

Delay is the pause between each pair of consecutive points on the curve and determines the duration of the vibration impulse. The number of possible intensity values is a fixed value since it depends on the hardware capabilities of the potentiometers.

Fig. 5 shows three patterns that differ in shape as well as in the number of steps (granularity) of the curve. Pattern (a) represents a fading on the left side and a continuous vibration on the right. The pattern is encoded in 28 steps with a delay of 35 ms. Pattern (b) is a high intensity vibration with some roughness only on the left side (right actuator is off). Roughness is generated by



a: Selected side: ● Left ○ Right; Steps 28; Delay 35

b: Selected side: ● Left ○ Right; Steps 36; Delay 25

c: Selected side: ○ Left ● Right; Steps 52; Delay 15

Fig. 5. Three examples of vibrotactile patterns edited through the graphic environment.

lowering the intensity for extremely short periods (the delay is 25 ms). Pattern (c) is a left to right fading in 52 steps with a 15 ms delay. Increasing the steps and decreasing the delay enables refinement of the vibrating pattern.

The vibration intensity values for both sides can be stored in an XML file containing the delay value (which is constant and indicates the pause between consecutive intensity values).

The highest layer of the HapticManager module (see Fig. 4) is able to load vibrotactile patterns defined in XML files. Loading is performed during application initialization.

Loaded patterns can be executed at run time by passing the appropriate index to *ExecutePattern*. Execution consists of a cycle that reads data structures content and sends commands to the device. Such a cycle should be performed in real time to preserve the peculiarity of the curve. One possible strategy is to give high priority to the thread that executes the cycle, but the fundamental requirement is to parse the XML file only once, that is at loading time.

5.2. *Second prototype evaluation*

In order to evaluate this prototype version and particularly the possible benefits coming from the haptic feedback, we conducted another user test with a group of blind people. The evaluation concerned two versions of the guide prototype that differ from that previously tested. The previous evaluation revealed that the vocal version using clear messages was preferred by the users with respect to audio sounds. Furthermore, subjective opinions suggested that a vibrotactile output could have been an appropriate way to convey feedback.

Thus, in evaluating this second prototype, we compared the version based on vocal messages alone with another new one using vibrotactile feedback for orientation. In the solely vocal version, tips such as "rotate left a bit" and repetitive "beep" sounds with variable delays were used to indicate distance and guide the user towards an artwork. The vibrotactile version used right and left vibrotactile feedback to suggest direction and a double vibration corresponding to the repetitive "beeping" sounds with variable frequency to signal the distance. The vocal support provided in the vibrotactile version regarded just the audio descriptions of the artworks. The users had to hold the PDA in the left hand and, for the vibrotactile version, to wear the two motors on the thumb and index finger (see Fig. 3). The choice of the index finger rather than the middle finger is based on the sensitivity level [17].

The goal of our test was to analyze whether there are any differences in terms of user performance between the two different feedbacks. To this end, each user tried both versions to carry out the assigned tasks. An observational method was used to follow the users testing the prototypes. Through the conducted test both quantitative and qualitative data were collected. First, in order to analyze the differences between the two versions, we measured the time taken by each user to carry out the tasks. Secondly, after the test each user was asked to fill in a questionnaire to gather subjective information and possible suggestions. The logged data were used to compare the effectiveness of the two versions. Indeed the time spent to perform each task was used as a quantitative measure to compare the two types of feedback.

Eleven blind participants were recruited for the test: seven women and four men. The age ranged from 27 to 66 years. All of them had used a screen reader in a Windows environment before. Six of them had previously used a PDA.

Users were requested to reach a specific artwork by exploiting the multi-modal guide capabilities. Each user tried to reach different artworks using the two different prototype versions since the experiment was mainly aimed at analyzing the kind of feedback. In order to avoid a possible bias due to the learning process, five users used the version with vibrotactile feedback first and then afterwards the one based only on vocal feedback; whereas for the others the order was inverted. The task assigned was to start from a specific artwork to reach another one. The artworks to reach were different for the two guide versions. All users performed the same tasks. Each test was carried out separately in order to avoid user bias caused by observing other tests. We observed the users while they performed their tasks. As mentioned, the starting and finishing time was recorded in a log file for each user and for each task.

Every user was able to accomplish the assigned tasks and the time log for each task allowed us to compare the time spent by the user in carrying out the task when using the guide with the two different types of feedback. Compared time data revealed time saving in localizing the artwork by using the version with vibrotactile orientation support, though the difference was not statistically significant.

In order to evaluate the effective time saving we examined the data recorded for each user. The analysis was performed taking the users as the statistical unit and considering the time(s) taken by each user to accomplish the task.

Parametric analysis was applied according to two tests: Exact Kolmogorov–Smirnov ($N = 11$; $Z = 0.835$–0.906; $p = \text{ns}$) and Levene's test ($F = 1.179$, $p = \text{ns}$). A Paired T-test ($N = 11$, $t = 0.463$, $\text{df} = 10$, $p = \text{ns}$) revealed a non-significant difference in the time required to complete all tasks by using the two (vocal and vibrotactile) versions. This means that the two versions were similar and more or less equivalent for the purpose. Users declared that they felt more confident with clearer vocal messages, especially about the direction. Probably, in order to become more familiar with the vibrotactile feedback, it is necessary for blind users to experience it for a long period. Unfortunately, this is not the case, because our system is conceived for museum visitors who prefer short time for training.

Concerning subjective opinions, the users rated various aspects on a scale from 1 (the most negative value) to 5 (the most positive value). One aspect regarded the preference level for the two kinds of feedback. The expressed preferences revealed there is no significant difference between the two types of feedback. According to the Exact Kolmogorov–Smirnov ($N = 11$; $Z = 0.780$–0.850; $p = \text{ns}$) and Levene's test ($F = 0.508$, $p = \text{ns}$), we used a Paired T-test, which revealed a non-significant difference ($N = 11$, $t = 1.047$, $\text{df} = 10$, $p = \text{ns}$). This result confirms the quantitative information gathered through the time logging. On average the users rated the vocal feedback well ($M = 3.81$; $\text{SD} = 0.98$) and the vibrotactile version slightly less well ($M = 3.18$; $\text{SD} = 1.47$). Various suggestions on how to improve both versions were expressed through the questionnaires. One user stated that vibration intensity range should be made wider by increasing the motors' peak speed. Another would have preferred different vibration rhythms rather than intensities/durations to signal the angle of rotation. Two suggested increasing the updating frequency of tactile messages, in order to speed up the orientation process. Three users declared that an obstacle detection functionality would allow the avoidance of physical barriers, improving the autonomy of blind visitors.

6. The third prototype (obstacle detection support)

Following the criticisms and suggestions provided by the users that tested the second prototype, we made some modifications to our solution. The detection hardware was enhanced by a distance sensor to alert the user about obstacles on the path. The module was also modified to be carried on a belt rather than through a necklace, because we had noticed that the direction sensing was affected by user's movements when the compass device was carried round the neck.

6.1. Obstacle detection

Obstacle detection was enabled by a Sharp-GP2D12 sensor embedded on the compass device box (see Fig. 6). Obstacles are detected when they are between 10 and 90 cm from the user and within a cone of about 35°. Since the distance (as well as the orientation) is sampled at about 30 Hz, the upload latency is less than 40 ms. Thus, the mobile application is able to warn of approaching obstacles such as walls or other people.

While direction aids are given by left or right side haptic messages with intensity and duration depending on the turning angle, obstacle distance is provided by the same pattern on both sides. We considered two strength levels of feedback for each direction aid and three levels for obstacle alerts. The feedback strength level is given by the intensity of the impulses making up the pattern and the duration of the pattern. Intensity and duration increase as the obstacle distance decreases or as the distance from the right direction increases. The vibrating sequence is made up by reproducing the same pattern with a delay between two consecutive patterns. For obstacle feedback the delay is about 200 ms. Pause time between direction aids is variable and is typically much longer. It depends on when the direction of the user is stable (i.e. when the user stops turning). This is done by the direction aid process that continuously checks for the current user direction and provides the next aid

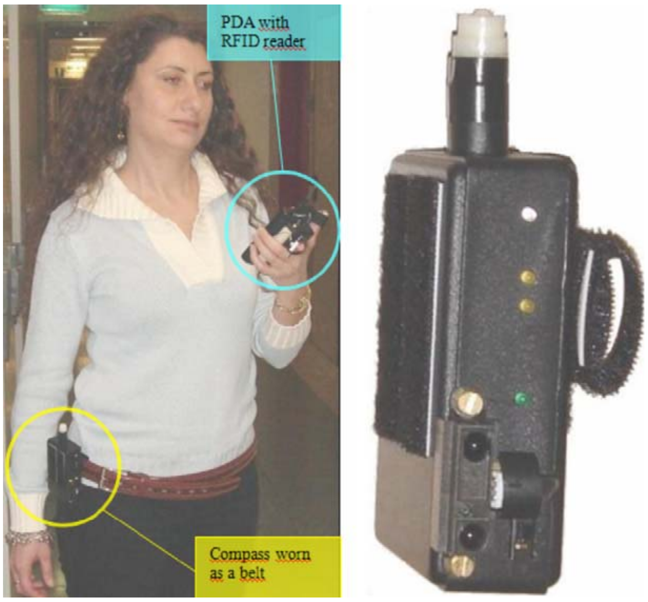


Fig. 6. Left: a blind carrying the mobile guide in the left hand and the orientation/distance detector as a belt. Right: detail of the compass device. The white cylinder on the top is the compass sensor; the distance sensor is located on the bottom-left.

(if needed) when the direction is sufficiently stable (i.e. its variation is under a certain threshold for a while, about 3 s).

In particular, we defined the seven patterns that are briefly explained in Table 1.

Each actuator is characterized by a certain strength in each pattern (see Table 1), which depends on the duration and the structure of the pattern. Note that the vibrotactile direction aids (vocally conveyed by "Rotate left/right…" sentences) only provide vibration on the side to which the user has to turn (Fig. 7).

We tested two versions of the support: one providing continuous obstacle feedback and another one emitting feedback only when the obstacle distance reduces (i.e. when the user moves towards it). Users were also asked for their opinion about the vibration sequences.

6.2. *Third prototype evaluation*

The early investigation on vibrotactile feedback for orientation purposes was dedicated to determining whether users preferred vocal sentences or haptic messages as orientation aids. Although no significant preference emerged, we opted to combine the vocal and haptic channels to indicate the direction to take because their combination seemed to provide more information. According to the observations made by some users we integrated obstacle detection into the system to signal obstacles in front of the user by means of haptic feedback. Custom sequences, with increasing vibration intensity when approaching any obstacle were produced on both fingers.

The latest user test was aimed to evaluate two versions of the vibrotactile feedback for obstacle detection: one with continuous vibration whose intensity depends on the obstacle distance, and the other providing vibration only when the distance to the obstacle decreases.

A group of seven blind users, aged between 25 and 40, was involved. Three of them were women and four men.

Each user tested both versions of the obstacle avoidance feedback. Each of the two trials consisted of reaching a target artwork while coping with some obstacles in the environment. The two target artworks were different. All users wore the obstacle detection in a belt on their left hip, held the PDA in the left hand, and had the vibrating motors attached with Velcro on the same fingers (thumb and index), and started from the same location. However, in order to avoid any bias in the learning process, half of the users tried the continuous feedback version first and then the discontinuous, while the order was inverted for the others.

For each user, we logged the time taken to perform the requested tasks. The time spent serves as an index to compare the effectiveness of the two versions. All the users were able to perform the tasks and at the end of the test they were asked to compile a questionnaire with subjective considerations and possible suggestions. Each version of the haptic support was rated on a scale from 1 (the most negative value) to 5 (the most positive value).

According to the rating, ($\text{mean} = 4.00$–3.28, $\text{SD} = 1.25$–1.15), the version with discontinuous vibration was rated higher, though the difference was not statistically significant. Due to the small sample sizes ($n<10$) we applied nonparametric tests [18]. The normality could not be verified due to the small sample size ($n<10$). We used the exact Wilcoxon sign test to verify the differences in the time to perform the task (by the same users) and in the preference score expressed by each user for the two versions ($k = 2$; $n = 7$).

Users that preferred such support described it as less annoying than the continuous feedback, especially when standing in front of an artwork or an obstacle such as a wall. Since the Exact Wilcoxon test provided $p = 0.12$, we may not assert any trend. Probably this is due to the small size of the sample.

On the other hand, four of the seven users preferred the continuous feedback, indicating a slight preference for such a support overall. This choice was motivated by the "safety" users felt with a continuous indication about an obstacle and is confirmed by the task duration: the mean

Fig. 7. The new layout of the detector module.

Table 1
Summary of the association between patterns and vocal comments.

Pattern vibration strength		Vocal comment	Meaning
Left side	Right side		
Low	Off	"Rotate left a bit"	Rotate left less than 90°
High	Off	"Rotate left"	Rotate left between 90° and 180°
Off	Low	"Rotate right a bit"	Rotate right less than 90°
Off	High	"Rotate right"	Rotate right between 90° and 180°
Low	Low	None	Obstacle distance between 60 and 90 cm
Medium	Medium	None	Obstacle distance between 30 and 60 cm
High	High	None	Obstacle distance less than 30 cm

times taken to reach the targets were 139 ($\mathrm{SD} = 50.95$) s and 155 ($\mathrm{SD} = 54.71$) s for the continuous and discontinuous vibrotactile feedback, respectively. The difference of time spent for performing the task by using the two versions is significant ($p < 0.05$). Users spent less time to achieve the task by using the continuous vibrotactile prototype.

Additional observations were also collected: most users reported that the system latency in providing aids should be reduced. Other suggestions regarded possible improvements in the hardware positioning so as not to obstruct user's movements: the distance sensor line of sight, when carried on the hip, was sometimes obstructed by the users' arms.

7. The final prototype

Based on the user comments gathered, we made some changes both to the wearable hardware and to the user interface. First of all, the compass/distance module has been slightly modified in order to easily attach it on the front side of the belt. Thus, distance detection is not affected by user's arm movements and heading detection is not affected by unwanted shocks. In addition, the distance sensor is now actually pointed forward and provides a more balanced detection of the obstacles. The program embedded on the micro-controller of the detection module has also been improved. While the previous version just continuously transmitted the sensed values (heading and obstacle distance) to the PDA, the current version transmits only as needed. That is to say, whenever the application needs to refresh the parameters' values, it asks the detector for the current ones. This polling strategy has been set up for energy saving purposes: limiting the data transmission over Bluetooth increases battery life (especially for the detection module).

We also upgraded the vibrotactile module: the vibrators have been replaced by two standard electric motors equipped with a small rotary mass. Even if such motors are slightly bigger than the previous ones, they have a very low start-up current that enables them to start and continue running slowly, providing a larger speed range. The extended speed range improves the customizability of the output and facilitates distinguishing the complex vibrotactile tips.

As suggested by the previous test's results, which showed no significant difference between the continuous and discontinuous vibrotactile feedback for obtstacle detection, the customizability of the vibrotactile support has been added to the application. Now, it is possible to choose the vibration intensity level for the direction indications and the obstacle presence alerts through the PDA keys. The perceived intensity of the vibration is related to the structure of the vibrating pattern. At configuration time, several custom patterns can be created through the graphical editor and deployed on the mobile device. Whenever the user changes the vibration intensity level a new subset is loaded from the set of predefined patterns and stored into data structures. The working subset consists of a few vibrating patterns with different intensity. As in the previous version, the pattern is chosen from among the subset depending on the type of suggestion/alert to provide: strong patterns are used for direction changes of over 90° and for alerts about obstacles in the near proximity (30 cm or less).

Another feature added to the final version is the possibility of deactivating the obstacle alert. The user, after approaching the destination item and while listening to its description and/or touching it, may want to switch off the vibration since it would not provide any useful information (the user already knows that s/he is in front of an obstacle).

Thanks to the new demand-response behaviour of the detection module, exclusion of the distance detection results in lower power consumption by the distance sensor (no sampling is required) and the Bluetooth module (30% less data is sent to the PDA) and thus in energy savings in the detection module. An energy conserving strategy has been adopted with respect to direction detection as well: when heading sensing is not needed (i.e. whenever the user does not need the mobility aid), the detection module is not queried for direction.

8. Discussion

Our study is aimed at investigating how haptic feedback can be exploited to improve user interaction as well as to provide additional information for blind users. More precisely, in our work we investigated what type of information can be provided through a vibrotactile feedback compared with that coded through audio and vocal feedback. A mobile guide has been considered as a case study for these purposes. Other studies on comparing both audio and tactile feedback have been conducted. In [19] a study focused on how audio and tactile feedback can be effectively used on mobile devices is discussed. They consider cross-modal feedback in which two modalities are used to provide the same information. The audio and vibrotactile feedback is investigated in a general context, i.e. people with disabilities were not involved. They found that the two modalities can be used in a redundant manner with positive results, while our study shows positive results also using them in a complementary way. In this perspective, our work has provided useful indications about how vibrotactile feedback can be exploited in a multi-modal mobile guide for the blind. The solution is unobtrusive because it does not require wearing cumbersome equipment and involves only two fingers of one hand, which is in any case used to hold the PDA, thus leaving users more freedom of movement. In this way we provide support that allows users to freely move about instead of requiring users to move only along specific paths.

In addition, in our prototype we considered a further important issue for the blind, obstacle detection. We observed in particular—considering also the user comments—that vibrotactile feedback can be a valuable way to provide this kind of information.

Our study indicates that this type of feedback is particularly useful to provide frequent unobtrusive indications of useful dynamic information, such as the proximity of an obstacle or the distance from the right orientation. This is a good complement to the vocal modality, which would become tedious with too many messages and can be better used to point out specific events (such as reaching a given target). In any case, in a mobile guide the vocal channel is also often used to provide relevant content. Therefore, an additional modality for providing other types of information is useful to avoid overloading it. We observed that providing information on target achievement via the haptic channel is quite difficult in comparison with a vocal modality. In fact, the vocal channel can clearly encode a wide variety of messages. Thus, vocal feedback is preferable for various kinds of indications, such as "target reached" or "turn round", and so on. Whereas, for other types of dynamic feedback, a vibrotactile channel can be more effective. For example, informing the user of the obstacle distance via a haptic channel is effective and unobtrusive. Increasing and decreasing the level of vibration can be a good way to code this information. Moreover, using the haptic channel leaves the user free to dedicate the audio channel to social interaction when desired. However, tactile feedback alone is not enough for some specific information. For example, we also tried to provide more complex indications such as "turn round" through the vibrotactile feedback, but this was not appreciated by the users. Becoming familiar with the vibrotactile messages may require some time. Some kinds of feedback are more effective if provided through the haptic channel. This is especially true for repeated short information (e.g. the user approaching an obstacle). One aspect that has been clearly suggested is that the solution for providing the haptic feedback should be customizable by the user, in the sense that users should be allowed to select the type of feedback that they feel more appropriate (e.g., continuous or approach-dependent vibration to indicate obstacle proximity).

Furthermore, different users may have different preferences regarding the feedback intensity: some of them need intense vibration in order to detect the feedback, while others suffer "pins and needles" sensations and thus prefer less intense vibration. For this reason, we have also proposed a vibration pattern editor, which can allow the application developers to prepare various solutions to offer to the end users.

Our solution is original for the approach and the specific solution adopted. Indeed, while those who have worked on haptic feedback for mobile users have not considered solutions for supporting blind users, vice versa those who worked on mobile support for blind users have not considered haptic feedback, at least with the type of unobtrusive solution that we propose. Relevant research on the use of haptics and non-speech sound for supporting blind and visually impaired has been carried out in [20]. However, the experiments reported were limited to stationary situations (conveying graphical information to the blind by means of haptic output solutions). We have instead developed and tested a prototype system that exploits the haptic channel in a mobile configuration for enabling the mobility of the blind.

9. Conclusions and future work

We have presented the design and evaluation of a wearable solution for supporting blind people in moving among tagged objects, such as museum artworks, in particular by providing haptic feedback for user orientation and obstacle avoidance. The final proposal has been obtained after an iterative design process, which has included various tests with visually impaired users. It is a complete solution able to take into account user orientation and position and supports obstacle detection. It is based on the use of vibrotactile feedback in an original manner, which is unintrusive for even crowded indoor environments, easy-to-use, and not annoying when there are many sequential suggestions, as happens with vocal feedback.

We carried out some user tests regarding the vibrotactile feedback for obstacle avoidance. Statistical analyses on the results do not highlight preferences towards a particular feedback mode. However, as users clearly motivated their different preferences (some found the continuous vibration annoying while others felt it was "safer"), we introduced a customizable haptic output to let the user choose the mode.

We plan to set up a context-dependent mode, that is, to signal obstacles (e.g., other people) on the path to the target through continuous vibration and switching to the discontinuous mode when the target is reached (the target item is, implicitly, an obstacle). We are also evaluating the possibility of exploiting other modalities for conveying information, complementarily to the vibration, such as temperature and electricity in addition to carrying out further empirical testing.

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