Integrating Wearable Haptics and Obstacle Avoidance for the Visually Impaired in Indoor Navigation: A User-Centered Approach

Federica Barontini[1,2,3], Manuel G. Catalano[1,3], Lucia Pallottino[1,2] Barbara Leporini[4], and Matteo Bianchi[1,2]

✦

Abstract— Recently, in the attempt to increase blind people autonomy and improve their quality of life, a lot of effort has been devoted to develop technological travel aids. These systems can surrogate spatial information about the environment and deliver it to end-users through sensory substitution (auditory, haptic). However, despite the promising research outcomes, these solutions have met scarce acceptance in real-world. Often, this is also due to the limited involvement of real end users in the conceptual and design phases. In this manuscript, we propose a novel indoor navigation system based on wearable haptic technologies. All the developmental phases were driven by continuous feedback from visually impaired persons. The proposed travel aid system consists of a RGB-D camera, a processing unit to compute visual information for obstacle avoidance, and a wearable device, which can provide normal and tangential force cues for guidance in an unknown indoor environment. Experiments with blindfolded subjects and visually impaired participants show that our system could be an effective support during indoor navigation, and a viable tool for training blind people to the usage of travel aids.

Index Terms—Wearable Haptics; Technological Travel Aids for Blind Users; Indoor Navigation; Obstacle Avoidance

1 INTRODUCTION AND MOTIVATION

All over the world, 285 millions of individuals are estimated to be visually impaired. More specifically, 39 millions are totally blind, while 246 have low visual capabilities [1]. According to the European Forum Against Blindness [2], more than 200,000 Italians are blind and around 6 millions suffer from eye diseases. Blindness dramatically limits the quality of life of these people and their families, especially in terms of autonomous navigation and privacy. Furthermore, it also represents a considerable economic burden for the society: looking at the sole case of Italy, the annual costs related to blindness are over 2 billions Euros [2].

It is not hence surprising that a lot of effort has been dedicated to improve life conditions of blind individuals and their relatives, especially for what concerns the enhancement of blind people autonomy. Under this regard, mobility assistance for visually-impaired people represents a very challenging task, since it requires the reconstruction and intuitive delivery of spatial information on the environment, for enabling a safe navigation.

Specially-trained guide dogs and white canes represent the most widespread systems for navigation and obstacle avoidance. However, they come with important drawbacks due to the extensive training required, the need for occupancy of one user's hand, and the reduced amount of spatial information they can provide to the user (mainly limited e.g. to low obstacles). In recent years, different technological solutions have been proposed to increase blind people walking autonomy. These systems are generally referred to as Electronic Travel Aids (ETAs) [3]. ETAs can surrogate spatial information on position and obstacle location and deliver it to the users via sensory substitution, relying on auditory or haptic cues. ETAs can be portable or wearable, the latter ones are usually preferred since they can be used in conjunction with classical travel aids, e.g the white cane. For a complete review on these topics please refer e.g. to [4], [5]. Looking at the sensory substitution approaches, the practical usability of the acoustical feedback is often limited for mobility applications. This because it might interfere and reduce user's auditory ability – which is usually augmented in blind people, disturbing posture and equilibrium control and severely affecting social interactions [6], [7]. For the reasons above, tactile feedback seems to represent a more natural manner to convey navigational information. This observation has been strenghtened with the avenue of wearable haptic systems (WHSs), which have gained an increasingly important role for the delivery of haptic cues to the human wearers, with special focus on the cutaneous ones (see [8] for a review on this topic). Generally speaking, the haptic exploration mode can be distinguished in two different classes: active and passive [9], [10], [11]. In the active haptic exploration, people actively use their hands to gather haptic information during the interaction with the device. On the contrary, in the passive haptic exploration the hands of the users are still, while the device haptically elicits touch-related perceptions on the fingers, palm or dorsum (or at other body locations in case of wearable systems). Among the different types of portable solutions, which are based on the latter type of exploration, it is worth mentioning guide dog robotic systems and smart canes for indoor and outdoor navigation. The GuideCane [12] is a wheeled system, which can detect the obstacle and steers around it; the user feels this steering action on the hand and follows the robot. In [13] the authors developed a smart rope interactive system connected with the user hand. The NavCane [14] is a smart cane device able to deliver priority information about obstacles in the path. The priority information is transmitted to the user using tactile and auditory communication methods. In [15], [16], [17], the authors developed different smart cane devices that can convey information using tactile stimulation. In [18], [19] the information regarding the environment and the presence of obstacles, which is gathered through different types of sensors, is conveyed to the blind user via vibration or auditory cues. All these devices can be also categorized as portable because

---

*This work was partially supported by the Italian Ministry of Education and Research (MIUR), in the framework of the CrossLab project (Departments of Excellence) and in the framework of PRIN (Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale) 2017, with the project TIGHT: Tactile InteGration for Humans and arTificial systems, grant number 2017SB48FP. This paper was also partially supported by the project "Haptic Assistance in Autonomous Walking for Visually Impaired People" (VI call of the MIT-UNIPI Project).

[1] *Research Center "E. Piaggio", University of Pisa, Largo L. Lazzarino 1, 56126, Pisa, Italy,* (`matteo.bianchi@centropiaggio.unipi.it`)

[2] *Dipartimento di Ingegneria dell'Informazione, University of Pisa, Via G. Caruso 16, 56122, Pisa, Italy.*

[3] *Fondazione Istituto Italiano di Tecnologia, via Morego 30, 16163, Genova, Italy.*

[4] *Human Interfaces In Information Systems Lab, Istituto di Scienza e Tecnologie dell'Informazione (ISTI) "A. Faedo", Area della Ricerca del CNR di Pisa, Via G. Moruzzi, 1, 56124, Pisa, Italy.*

they require the hand of the user to continuously hold them. In addition, wearable haptic solutions have been also developed to convey tactile navigation cues. According to the passive haptic exploration mode, which mainly rely on vibration stimulation [7] and, eventually integrated in gloves designed for haptic feedback delivery, see e.g. [20]. Indeed, vibrotactile stimulation represents the most common tactile modality used in ETAs, which has been also used in wearable belts and devices for the wrist, forearm and torso. For more information see e.g. [21]; for remote guidance [22], or in integration with sensor network technologies (RFID, Bluetooth and Wi-Fi) [23]. In parallel, the effect of different parameters modulating vibrotactile stimulation on skin receptors have been evaluated in several studies, see e.g. [3], [24], [25]. Regarding spatial information, it can be gathered using various sensing modalities [26], [27], which include sonars [28], laser range finders or stereo cameras [29]. Despite the promising results, the effective translation of these technologies in real-world applications is still limited. One of the causes for this scarce acceptance is related to the limited involvement of real users in the conceptual and design phases. Notwithstanding such tendency is changing, we are still far from systems designed for, and hence usable by, real people with real needs.

In this work, we propose a user-centered approach for the development of wearable technological solutions for indoor navigation, which moved from a preliminary investigation of the requirements of visually impaired people. A tight interaction with real end-users informed all the developmental phases of our system, driving us to the definition of the system layout, the cues used for delivering spatial-related information through sensory substitution, the implementation choices for the planning and navigation parts. The wearable travel aid system for indoor navigation proposed in this work consists of: (1) a RGB-D camera that acquires both color and dense depth images from the environment; (2) a processing unit to process the images and perform the needed computations for obstacle avoidance and (3) a wearable fabric-based device, which can convey navigational information at the arm level to avoid the detected obstacles, through normal and tangential force delivery on the user's arm. This device represents a new version of the cutaneous passive haptic interface described in [30], which was specifically re-designed for this work to be more compact and light, and hence to meet users' requirements. The choice of this tactile device was motivated by the fact that the stimuli (i.e. pressure and skin-stretch) it can deliver are similar to the ones that a blind person would experience, if a volunteer would hold the person's arm to guide her/him through the environment. Two different experiments were performed to validate the effectiveness of the presented navigation system: Experiments A (A1 and A2) with blindfolded participants, and Experiments B (B1 and B2) with blind participants. The results showed that our system can be a viable support for navigation, especially for subjects who are not expert users of the white cane.

The paper is organized as follows. In Section 2, users' requirements are described, and in Section 3 and 4 the navigation system is presented, with a focus on the hardware and the software architecture, respectively. Section 5 describes all the experiments we performed to validate the system. In Section 6 the results of the experimental sessions are reported, which are discussed in Section 7. Section 8 discusses the limitations of our work and the implementation plans we envision to overcome them. Finally, Section 9 is devoted to the conclusions we can draw from this work.

2 USERS' REQUIREMENTS

Users' and accessibility requirements are particularly important to inform the design of the hardware and the algorithms for an effective indoor navigation system [3], [31]. The first mandatory step for the development of satisfactory technological travel aids and intuitive User Interfaces (UIs) is to correctly understand how a blind person autonomously moves in an unknown environment.

To collect information on how blind people usually move in unknown environments and which are their needs and requirements, we recruited and interviewed four visually impaired people, who are, respectively: a member of the Omero museum[1] (M, 60 years old hereinafter referred to as S1, congenital blind), a member of "Lega del Filo d'Oro" [2] (F, 70 years old hereinafter referred to as S2, blind since she was 12 years old), and two persons from the "Unione Italiana dei Ciechi ed Ipovedenti ONLUS (UIC)" – Pisa (Italy) [3] (M, 36 years old - hereinafter referred to as S3, congenital blind, and F, 42 years old - hereinafter referred to as S4, congenital blind). S1 and S3 use the white cane to autonomously walk in their everyday life, while S2 uses a guide dog and sometimes a white cane, and S4 relies on an accompanying person in unknown environments. Furthermore, we also interviewed a teacher from "Lega del Filo d'Oro" specialized in training for orientation and mobility of blind people.

All the questions are summarized in table 1. The interviews were designed with the goal of identifying which features and functionalities a navigation system should ideally have, and informing the design of the UI. For these reasons, questions focused on gathering information about: (1) mobility and orientation strategies used by blind people with no travel support or assistance (Questions from 1 to 4); (2) features that an indoor navigation support would be supposed to have (Questions from 5 to 10), and (3) the most suitable kind of stimulation modality to deliver the navigation cues to the end user, while she/he is walking relying only on the ETA support (Questions 11 and 12).

The main outcomes arisen from the interviews are summarized in the following:

Mobility and Orientation strategy

1) *Paths*. Not smoothed but segmented routes are preferable for moving autonomously. Linear routes are usually preferred, since they are more suitable for orientation.

2) *Obstacles and mental map.* In unknown environments, e.g. hotel rooms, blind people usually require to touch everything in an ordered manner to create an internal mental map of the location of the objects. On the other hand, while walking around, e.g. in a corridor, the main goal is to avoid obstacles on the ground; high up obstacles, such as windows or shelves, should be avoided in a safe manner. In other terms, blind persons usually prefer to arrive very close to the object and touch it when they have to use it, otherwise, in case of an obstacle, they just wish to avoid it.

3) *Traditional white cane is a necessary support.* Participants S1, S2, S3 and the specialized teacher confirmed the importance of the traditional cane for a blind person, who usually moves around independently. White cane helps in detecting obstacles, especially in

---

[1] Omero museum is a museum specifically thought for visually impaired visitors, with dedicated and customized exhibition pathways, located in Ancona, Italy http://www.museoomero.it/

[2] The Lega del Filo d'Oro is an Italian ngo, whose mission is to assist, teach and rehabilitate deaf-mutes http://www.legadelfilodoro.it/

[3] Unione Italiana dei Ciechi ed Ipovedenti ONLUS (UIC) – Italian Association for the Blind – is a non-profit organization with legal entity governed by private law, which represents and protects the moral and material interests of the visually impaired people towards public administrations http://www.uici-pisa.it/uic-pisa/

	Question
Q1	What do you commonly use as travel aid among guide dog, white cane and guide volunteer, and why?
Q2	If you walk through a corridor, where do you prefer to walk: in the center well away from possible obstacles close to the walls, or close to the walls?
Q3	If you are in a crowded place, hence with moving obstacles, which type of approach do you use?
Q4	Do you adopt different approaches if you are in an indoor or outdoor environment?
Q5	Which type of directional stimuli do you prefer to receive and where (body location)?
Q6	Do you prefer to experience on the arm a mild-constant cue along the duration of the movement and a more intense cue when there is a change of direction, or a stimulus only when needed?
Q7	In which way do you prefer to avoid obstacles?
Q8	Do you want to arrive as close as possible to the obstacle to understand which obstacle is, or do you want to stay far from it?
Q9	Using a travel aid system endowed with a camera, proximity sensors for obstacle identification and a device that conveys navigational cues in an unknown environment, which information would you like to receive as first and in an immediate way?
Q10	Do you prefer to have immediate indications about the presence of low or high obstacles?
Q11	Have you ever used a different travel aid with respect to the most common ones, for example vibrotactile-based devices?
Q12	Which type of stimulus do you prefer between auditory or tactile, and why?

TABLE 1: Questions proposed during the preliminary interview.

potential dangerous situations, like stairs or unexpected obstacles.

System features

4) *Wearable and hands-free system* While using a traditional white cane, or a guide dog, the hands should be left free. Any type of communication should be provided through another part of the body. This confirms the observations in [3]. The arm represents a good body location for haptic communication.

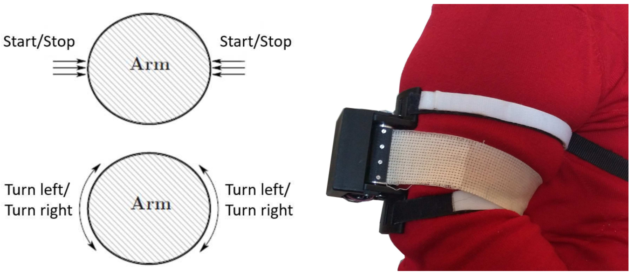
5) *Reliable and able to detect any type of obstacle.* Many obstacles can be encountered when moving autonomously along a path or a route. The white cane is able to detect several obstacles, but unfortunately not all of them. Obstacles located high up but also stairs may be particularly dangerous for a blind person. The system should be able to detect them and inform the users in a clear and unequivocal manner. The user should feel that the system is reliable for obstacle detection.

Feedback and communication with the system

6) *Haptic feedback.* Tactile feedback is preferred with respect to auditory communication, as reported also in [3]. Users motivated this choice with the need of have the auditory channel free while moving autonomously – especially outdoor – to perceive the surrounding environment. The audio feedback could be used for additional information requested on demand.

7) *Simple and instantly recognizable instructions.* Simultaneous delivery of many types of information is not desirable. Clear and unequivocal instructions are needed for important communications. Instantly recognizable indications should be used for crucial indications and important information types. For instance, a clear and single strong pressure to indicate a change of direction (instead of constant stimulation) or obstacle detection are preferable.

3 THE SYSTEM ARCHITECTURE



(a) (b)

Fig. 1: Working modes of the CUFF (a) and overview of the device worn on the subject's arm (b).

The interface represents a fundamental component to manage the interaction between the system and the person. A good and appropriate interaction is one of the major goals of the Human-Computer Interaction (HCI) field, targeting the enhancement of accessibility and usability of a system or application. Therefore, the design of the user interface and interaction features plays a crucial role in system development life cycle. For the navigation system presented in this work, we decided to rely on tactile stimulation – in agreement with the outcomes of the interviews – provided by a wearable system, to leave the hands free. In our case, the interface will hence consist of a wearable haptic device to deliver instructions and information to the user. As emerged from the interviews, important commands and instructions must be given in a clear manner. The translation of these requirements in terms of interface specifications can be summarized as follows:

- Haptic device, which is required to be comfortable and practical;
- Commands and instructions related to *stop*, *proceed*, *turn left/right*;
- Wearable components, which should be easy to use

In the following, we will describe the wearable haptic device and the sensing and processing unit.

3.1 Wearable Haptic Device

The haptic interface on which we focused our attention based on the previously reported requirements is an engineered version of the clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces (CUFF) described in [30]. Briefly, the CUFF consists of two DC motors attached to a band or cuff worn around the user's arm. When the motors spin in opposite directions, they tighten or loosen the band on the arm, thus conveying a normal force. On the contrary, when the motors spin in the same direction, the fabric can slide around the arm, thus conveying tangential force cues and hence directional information, see Fig. 1.

The usage of this type of system for navigation stimulus delivery was motivated by the idea of replicating the stimulation that the hand of an accompanying person provides to the blind person, to inform him/her about the presence of obstacles and on how to avoid them (and eventually to communicate a stop command). This information mainly relies on skin stretch, squeezing and tangential elicitation of the arm, see Fig 1. In this work, we re-engineered this device, to make it more wearable, compact and light and hence to enable a possible employment as travel aid. The device consists of a main frame, which can be fixed to the user's arm through two VELCRO belts, an actuation unit powered by two Maxon DC Motors with a gearbox ratio of 64:1, and a belt used as intersection surface with the human body. The final dimensions of the device result in a reduction of 33% and 56%, respectively for the total dimension and the weight, with respect to those reported in [30]. The CUFF device is endowed with a custom made electronic board (PSoC-based electronic board with

Fig. 2: The proposed navigation system worn by the user. We can see the wearable technological device, the camera and the processing unit (laptop): front view on the right, lateral view on the left.

RS485 communication protocol) [32], which enables controlling the position of the motors, based on the readings of two magnetic encoders AS4550, one for each motor. The actuation unit is powered by a battery pack of 12 V. Due to its high wearability, the CUFF device could be a good solution to fulfill the requirements reported in the previous section, especially for what concerns the need to have the hands free and avoiding acoustical cues.

3.2 RGB-D camera and processing unit

The sensing apparatus of our integrated system mainly leverages the images acquired through a RGB-D camera placed on the user's chest, while a processing unit is placed on the back to process the visual information from the camera and provide commands to the CUFF, based on the obstacle avoidance algorithm described in Section 4, see Fig. 2. It is worth noting that, for this prototype, a light laptop was used as a cheap processing unit. In future developments, an ad–hoc unit will be used to further improve wearability. According to our original idea, the overall system should have included two cameras (to enable a more exhaustive space scanning) and two ultrasonic sensors per leg (placed at the calf level), to detect ground obstacles. Capitalizing upon the interview outcomes described in Section 2, we decided to modify the envisioned final layout of the system, to include the CUFF, only one RGB-D camera, placed on the user's body with a VELCRO belt at the chest level (in order to detect both high and medium-low obstacles), and a laptop to process the images, placed inside a backpack. The usage of additional cameras and sensors on the calf was avoided to reduce the complexity of the system and likely making the assistance more intuitive and comfortable. We chose to use the *Asus Xtion Pro* camera, with a frame rate of 30 Hz at 640x480. However, after some preliminary testing, we realized that in this manner the stimulation provided by the CUFF was delivered at a frequency rate which could have generated confusion in participants. For this reason, we decided to halve the frame rate to 15 Hz, which is still sufficient for enabling a correct image processing. The communication between the different elements was implemented via USB connection.

4 THE SOFTWARE ARCHITECTURE

To enable navigation in the environment, i.e. to reach a target position while simultaneously avoiding obstacles, we implemented an obstacle avoidance algorithm running on the laptop (ASUS UX310U). This algorithm can detect floating obstacles, such as people walking around, and enable the user to move in a safe manner, based on RGB-D data processing. The collision detection algorithm is based on [33], where obstacles were found in images from a camera through corner detection, while the distance was provided by the depth sensor. We chose to implement the techniques in [33] since they were proven to be both efficient and robust in detecting corners and suggesting a safe path to avoid the obstacles in experiments with blindfolded and blind people for indoor navigation. Based on the interview outcomes, reported in Section 2, the navigation strategy was suitably modified as described in the following. The detection algorithm is based on the subdivision of the captured image in three sub areas and a sequential obstacle detection in each area. Once an area is found to be obstacle free, the user is steered toward such area. Based on the interviews outcomes, reported in Section 2, we decided to customize the geometrical segmentation of the areas of interest. Indeed, since end users usually prefer to move straight, and to minimize the obstacle detection time, we identified a bigger central trapezoidal area, hereinafter named as *Safe Area*, and two lateral ones named *Right and Left Areas*, respectively. First, we looked for corners only in the Safe Area preventing the user to receive information on possible lateral obstacles that are negligible for safe navigation purposes. If an obstacle is detected in this area, the algorithm analyzed the corner in the Right and Left area sequentially. In this way we limited the amount of information to the user coherently with the users' requirements we collected. The corner detection is based on the color information of the image, and it implements the OpenCV algorithm *Shi-Tomasi corner detector* reported in [34]. The chosen *ASUS Xtion PRO* sensor provided point clouds with associated color and depth information for each point of the captured image.

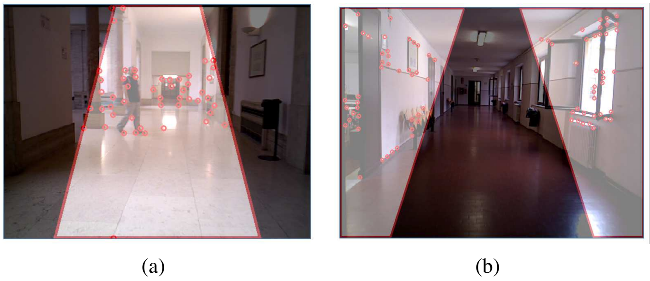

(a)
(b)

Fig. 3: In these pictures it is possible to observe an example of the analysis of the corners inside the three subareas of investigation: central area (a), and lateral ones (b).

Once corners have been extracted, the depth information of the selected points is used to determine the proximity of the potential obstacles with respect to the user. Based on the value extracted from the point cloud, we heuristically chose 3 different thresholds to detect close obstacle. It is worth noticing that since the white cane was selected as a needed tool by most of the interviewed persons, our choice was tailored on the condition that implies the usage of such assistive tool. However, this choice can be safely employed also in other cases of assisted autonomous navigation. The chosen thresholds are:

- If the depth values of all corners are greater than 2 m the corners represent obstacles whose distance from the user is sensibly greater than the length of the white cane. The area is hence classified as obstacle free (F).
- If at least one of the depth values is included in the range 1.2-2 m, the area is classified as occupied by an obstacle (O).
- If at least one of the depth values is less than 1.2 m, the area is classified as critical since there is a potential

obstacle very close to the user (C).

When an obstacle is detected between the range 1.2-2 m the navigation algorithm starts to analyze the image, as described before, finding a free path and giving the command to turn to the right or to the left (R, L). Otherwise when an obstacle is detected closer than 1.2 m, the algorithm gives the STOP signal to the device. Then the user is commanded to rotate toward the area on the right, and if the path is not free, the commanded rotation provided by the CUFF is toward left. Once a free path is found, a start command is given to re-start walking toward the goal direction – straight command (S). The described obstacle detection algorithm (ODA) takes as input one of the three areas (A) and returns as output the classification types of the analyzed area, i.e. free (F), occupied (O) or critical (C), and the commands to be implemented with the wearable devices, accordingly, i.e. straight (S), left (L), right (R), STOP, as described later. After a rotation command, if the path is free, the motors come back to the rest position. The navigation algorithm, based on the obstacle detection one, is shown in the Algorithm 1.

Algorithm 1 Navigation Algorithm (NA)
Input: acquired image (I)
Output: straight (S), left (L), right (R), STOP, commands to be sent to the CUFF

```
if ODA(Safe Area)=F then
    send command S
    acquire new image I and execute NA(I)
else
    if ODA(Safe Area)=O then
        if ODA(Right Area)=F then
            send command R
            acquire new image I and execute NA(I)
        else
            if ODA(Right Area)=O then
                if ODA(Left Area)=F then
                    send command L
                    acquire new image I and execute NA(I)
                else
                    send STOP
                    acquire new image I and execute NA(I)
                end if
            else
                send STOP
                acquire new image I and execute NA(I)
            end if
        end if
    end if
    send STOP
    acquire new image I and execute NA(I)
end if
```

As previously mentioned, the algorithm outcomes are translated into tactile stimuli to be provided by the CUFF device on the user's right arm (see the accompanying video), as follows:

1) Straight walk (S) corresponding to two sequentially squeezing stimuli, which are implemented commanding opposite directions of rotation to the motors of approx 90°;
2) Turn left (L), corresponding to counterclockwise rotation of both motors of approx 180°;
3) Turn right (R), corresponding to clockwise rotation of both motors of approx 180°;
4) Stop, corresponding to a single squeezing stimuli of higher intensity implemented with larger and opposite rotation of the motors of approx 360°.

These values were heuristically chosen as a good trade-off between intuitiveness and clarity of elicited perception and pleasantness. The CUFF device is able to elicit a maximum normal force of approx 25 N. For all the experiments, we chose for the Stop signal a maximum normal force of approx 18 N, and for the Start signal a normal force of approx 10 N. Regarding the Left and Right stimuli, we decided to pre-tension the belt of the CUFF device to provide a normal force approx 3 N, focusing more on the sliding motion elicited on the user's skin. In this case the commanded motor rotation was approximately of approx 4800 ticks. One of the four aforementioned commands is provided to the user, at every algorithm step, i.e. at a frequency of 15 Hz. If the path is free, the CUFF does not provide any stimulation to the user's arm. In this way, we avoid a constant CUFF activation, which may result in an annoying stimulation for the users as it results from the outcomes of our interviews. Furthermore, in agreement with the observations reported in the previous Section, we decided to give stimuli which result in segmented trajectories. It is worth noting that we chose a safe range of 1.2 m because the operating distance of the camera goes from $0.8 - 3.5$ m; from 1.2 m to 0.8 m the algorithm continues to give a STOP signal. If, accidentally, the distance from an obstacle goes under 0.8 m the camera is not able to see anything but the user is close enough to perceive the presence of the obstacle with the cane or hands. Thresholds can obviously be customized based on users' physical characteristics such as age, cognitive abilities and anatomical structure.

5 EXPERIMENTAL VALIDATION

We tested the effectiveness of our system with different participants and end-users, in different environments and navigation conditions. The main goal of these experiments was to verify if the usage of our technological solution could potentially enhance autonomous walking performance in everyday life. For these reasons, in light of the importance of traditional navigation supports – in particular the white cane – for blind people, which emerged from our interviews, we decided to test our system alone, and also in association with the cane, and assess users' performance and impressions in the different cases. To ensure the correct implementation of the validation phase, we first evaluated the safety of our approach with blindfolded participants, gradually increasing the complexity of the path to perform and finally enrolling blind subjects. None of the participants had any physical or mental limitation which could have affected the experimental outcomes.

5.1 Experiments A: Participants

The Experiments A were completed only by blindfolded participants. We performed two different sessions of experiments: a first session where we involved 6 right-handed blindfolded participants – 2 female, mean age 27, hereinafter referred to as Experiment A1; and a second session performed by 10 blindfolded participants – 4 female, mean age 26 years, one left-handed hereinafter referred to as Experiment A2.

5.2 Experiments A: Setup and Procedure

5.2.1 Experiment A1

Experiment A1 was composed of: a discrimination task to evaluate if the directional stimuli provided by the wearable haptic device were clearly interpreted for navigation purposes, and a walking task in an unknown environment, where participants were asked to wear and use our navigation system to walk along a corridor, avoid obstacles (both fixed and moving) and reach a target goal. In both tasks participants were blindfolded.

Discrimination Task

We asked participants to wear the CUFF on the right arm and to recognize the direction of 50 randomized stimuli (50% for each direction). These stimuli were obtained by rotating of approx 180° the CUFF motors in the same direction, clockwise and counter-clockwise to suggest right and left rotation, respectively. The order of rotation direction was randomized. Blindfolded participants comfortably seated wearing the CUFF device, with the forearm placed on a table. They wore headphones with pink noise to prevent the usage of any auditory cue generated by the rotation of CUFF motors. We decided to focus our investigation only on the left and right rotational stimuli because, in our opinion, these two stimuli could have been more challenging to interpret with respect to a strong squeeze on the arm that indicates a stop. Indeed, the interpretation of these rotational stimulations requires a proper association to a change of direction and then a suitable processing in participants' body schema.

Walking task

During this task, each subject was equipped with the CUFF on the right arm, the RGB-D camera on the chest, a laptop in the backpack and a white cane as in Fig.1. The experiment was carried out in the second floor of the School of Engineering of Pisa, see Fig. 4(a). Two different travel aid modalities were considered:

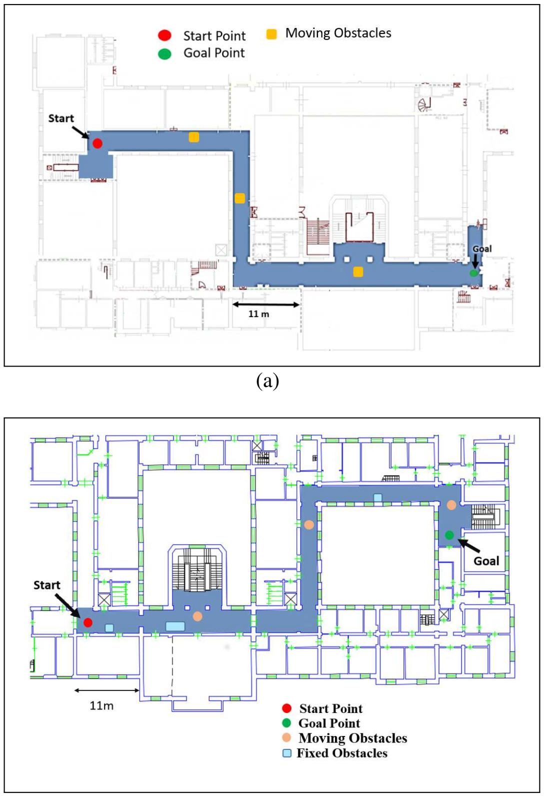
1) walking along the corridor using the white cane together with the CUFF
2) walking along the corridor using the white cane only.

A moving obstacle, i.e. a person walking toward the subject, was presented always in the same positions for both modalities. In Fig. 5 a snapshot sequences of the experiments are reported (see also the accompanying video provided as supplemental material), where the user is able to avoid the obstacle based on the input of our navigation system. Before the experiment, subjects underwent a training period of fifteen minutes to understand the 4 commands delivered by the device, and how the navigation system worked. During this period, participants walked along a different part of the second floor of the building with respect to the one used for the experiments, to avoid any learning effect. After the training, the subject completed the path in both modalities. The order of task execution for the two modalities were randomized and counterbalanced across subjects. A single trial experiment was performed by every participant for each modality in order to avoid learning effects.

5.2.2 Experiment A2

Experiment A2 consisted of a walking task only. It was conducted in the first and second floor of the School of Engineering in Pisa (see Fig. 4 a and b) considering a longer and more complex path , with respect to the one used in Experiment A1, which also included a moving obstacle, i.e. a person walking towards the subjects. The test was divided in two parts:

1) training period to familiarize themselves with the system, as for Experiment A1;
2) walking period along the corridor in three different modalities (CUFF plus white cane, white cane only, CUFF only)



(a)

(b)

Fig. 4: Fig.(a): map of the 2^{nd} floor of School of Engineering of Pisa (Experiment A1, total path length approx 90 m). (b): map of the 1^{nd} floor of School of Engineering of Pisa (Experiments A2, total path length approx 110 m). In blue, the path followed by participants during the experiments. The red and green points are the start and target position, respectively. The yellow points are the moving obstacles set for the modality experiments with the CANE only condition, the orange points are the moving obstacles set for the modality experiments with the CUFF plus CANE; the sky-blue points are the fixed obstacles present for each modality of the experiment. It is worth noting the moving obstacles were in the same locations for all the modalities.

Ten blindfolded subjects wore our system as in Experiment A1. Also in this case a single experimental trial was performed for each condition. The moving obstacle was presented in the same points for all the modalities.

5.3 Experiments A: Data Collection

To evaluate the performance in Experiments A (completed by blindfolded participants), we recorded: the number of correct answers for the discrimination task (Experiment A1), the time for task accomplishment and the results of a subjective quantitative evaluation performed by administrating a Likert scale survey (Experiments A1 and A2). The time for task accomplishment is the time to reach target position as in [35], while the Likert scale consists of questions about the system and the experimental tasks, to which participants had to answer by assigning a score ranging from 1 *totally disagree* to 7 *totally agree*. This represents a common procedure to evaluate devices for assistive robotics and Human-Robot Interaction [36]. The questions delivered to the subjects are listed in Table 2. In particular, questions from Q1 to Q3 referred to the wearability of the CUFF device, questions from Q4 to Q8 investigated the intuitiveness of the sensory substitution, questions Q9 and Q10 were about the performance and questions

	Questions	Mean	Std. Dev.
Q1	It was easy to wear and use the CUFF device	6.06	1.13
Q2	It was easy to wear and use the CANE together with the cutaneous device	6.5	0.77
Q3	I was feeling uncomfortable while using the CANE together with the CUFF device	1.75	1.3
Q4	The haptic suggestions were intuitive	5.9	1.04
Q5	The sound produced by the actuators of the CUFF was hampering	2.68	2.22
Q6	The stimuli produced by the CUFF were easy to distinguish	5.8	1.17
Q7	The stimuli produced by the CUFF were helpful	6.5	0.77
Q8	It was easy to feel the presence of an obstacle receiving the feedback via the CUFF	6.25	0.94
Q9	I had the feeling of performing better while receiving feedback via the CANE only	1.81	1.35
Q10	I had the feeling of performing better while receiving feedback via the CANE and CUFF device	6.68	0.73
Q11	At the end of the experiment with the CUFF and the CANE I felt tired	1.81	1.42
Q12	At the end of the experiment with the CANE I felt tired	3.6	2.7

TABLE 2: These statements, presented in random order, were rated by the blindfolded subjects of Experiments A (A1 and A2) using a 7-point Likert scale (1: Strongly disagree, 7: Strongly agree). Means and standard deviations across all individuals are reported.

	Experiment A1		**Experiment A2 and B1**	
	Mean	Std. Dev.	Mean	Std. Dev.
CUFF plus Cane	162.5	27.5	343	67.34
Cane only	165	42.67	401	170.8
CUFF only	/	/	180	

TABLE 3: The table shows the time in seconds for accomplishing the walking task for Experiment A1 and for the Experiment A2 and B1 (only one blind subject participated in the latter experiment for the CUFF-only condition. The corresponding value is reported in red in the last row of the table.)

Q11 and Q12 dealt with users' fatigue during the experiments.

5.4 Experiments B: Participants

The Experiments B involved only blind participants and it consisted in two parts. The Experiment B1 included one blind subject, a 42-years-old female. Six blind subjects (3 female, mean age 51 years old, all congenitally blind) were involved in the Experiment B2. Four of them were expert users of the white cane; they navigated independently in outdoor and indoor unknown environments and only one of them preferred to use the white cane for outdoor navigation only. The other participants do not use the white cane in their daily life, but a guiding volunteer. Two participants had previous experience with vibrotactile device for navigation and one of them used a vibrotactile feedback for outdoor navigation, i.e. the Miniguide [37]. None of them had experience in the use of force feedback devices as sensory substitution techniques for travel aids. Participants gave their informed consent before the experiments, and none had any previous knowledge of the environment where the experiments were performed.

5.5 Experiments B: Setup and Procedure

5.5.1 Experiment B1

It was completed by a single right-handed subject. She performed the same experimental task and procedures as the blindfolded participants of Experiment A2 (for more information see 5.2 Experiment A2). The subject wore our system as all the other blindfolded participants. Since she does not use the white cane to move in everyday life but only a guiding volunteer, we did not consider the navigation condition with the cane only.

5.5.2 Experiment B2

It was completed by six blind subjects, all of them right-handed. They wore the CUFF on the right arm (only one user preferred to not have the device on the same side, right, of the cane), the RGB-D camera on the chest, a laptop in the backpack, and the white cane only for the expert users. The experiment was divided in three main parts:

- familiarization with the system and the tactile stimulation;
- experiment for recognizing the four stimuli (start, stop, turn left and turn right) provided via the CUFF;
- walking task.

Familiarization

Prior of each experiment, participants went through a training period with the system, of about three minutes, to take confidence with the device. They were comfortably seated with the CUFF placed on their arm and the four commanded stimuli were provided sequentially in this order: start, turn right, stop, turn left. The aim was only to give an idea of which kind of stimulus participants should have experienced via the CUFF, since none of them had previous experience with a force-haptic feedback device. After this part, participants spent 15 min walking along a corridor (first floor of the School of Engineering of the University of Pisa) to better understand the information provided by the CUFF, and the strategy adopted for obstacle avoidance. The paths used for the familiarization were different from the ones used in the experimental tasks to avoid any learning effect.

Commands recognition task

In this task, we asked participants to identify the four commands delivered by the CUFF, while they were walking along a corridor. An operator commanded the CUFF device with a joystick, to deliver navigational cues and suggest the direction to follow. Participants had to recognize 40 randomized stimuli (ten for each of the four main commands). After the analysis of the outcomes of the discrimination task in Experiment A1 (see 5.2.1), although the different stimuli were clearly recognized by participants, we received some comments on the usefulness of increasing the intensity of the stimulation for the navigation commands. For this reason, we decided to rotate the motors of approx 210° instead of approx 180° for the turn right and left commands, and about 360° for the stop and start conditions. During the experiment we video-recorded the task execution to identify when the joystick buttons were pressed by the operator to command the CUFF device and obtain the reaction time of participants. The joystick used for this experiment was a common *PlayStation* joystick.

Navigation task

To assess if our navigation system could be a viable solution not only in big and open spaces like the corridor used in the Experiments A and B1, we tested the system in five small walking tasks in narrow spaces, which included the navigation through a door, and multiple sequential changes of direction. The aim of these tasks was to analyze: (1) the user's perception of the tactile commands, (2) the effectiveness of the system in detecting/avoiding the obstacles and (3) the effectiveness of the system in providing appropriate and precise instructions to guide the user. After a first pilot test, we decided to modulate the corridor of the second floor of the School of Engineering of Pisa with wood panels in order to create customized small paths, with various levels of navigation complexity:

Task 1	to turn left
Task 2	to turn right
Task 3	to walk along a corridor and avoid a fixed obstacle
Task 4	to change three times the direction (turn left, then right and finally turn left)
Task 5	to pass through a door

Tasks 1 and 2 targeted two different direction changes; Task 3 dealt with obstacle avoidance; Task 4 required multiple sequential changes of direction, and Task 5 was related to the navigation through a door. The paths were approx 11 m long (Tasks 1, 2, and 4), and approx 7 m (Tasks 3 and 5), while the width was approx 1.6 m for all the paths.

Since not all the participants were expert users of the white cane, we decided to take in consideration two different modalities of execution. We left the cane to the three expert users so they repeated every task twice: once using the CUFF in conjunction with the cane, and another using only the cane as a travel aid. On the contrary, the other three participants performed the tasks only with the CUFF. It is worth reporting that the expert users of the white cane in Experiment B2 were in total four, but one of them decided to not use the cane during the experimental session, to be completely focused on the CUFF device. The order of task execution for cane users was randomized and counterbalanced across subjects for the two different modalities.

5.6 Experiments B: Data Collection

For the Experiment B1, we recorded the time for task accomplishment and the results of a subjective quantitative evaluation performed by administrating a Likert scale survey (like in Experiments A1 and A2). Since the participant was not an expert user of the cane, the questions focused on the navigation condition with only the CUFF as a support tool, see Table 8 for more details. Furthermore, we asked the participant if she would have preferred the usage of auditory or vibratory cues with respect to forces as a sensory substitution method. Regarding the Experiment B2, to evaluate users' navigation performance related to the clarity and the effectiveness of the commands provided via the device during the recognition task, we decided to record the number of correct and incorrect movements (based on the agreement with the delivered navigational stimulation) and also the reaction time to the stimuli. We defined the reaction time as the time interval between the instant when the joystick button was pressed by the operator and the reaction of the subject as it can be observed from the video (which used a frame rate of 15 Hz). For each navigation experiment (Tasks 1 to 5), we recorded the time for task accomplishment, and the number of collisions with the obstacle in case of failure of the vision system (please note that the camera supports a near field mode at least of 0.8 m). A single trial experiment was performed by subjects for each modality to avoid any learning effect. At the end of the experiment participants underwent through a subjective quantitative evaluation procedure based on a seven point Likert scale, (see Table 9). We divided the questions for the blind subjects based on the modalities of task execution. Questions from Q1 to Q14 were in common to all the subjects. In particular, questions from Q1 to Q11 referred to the wearability of the CUFF, the intuitiveness of sensory substitution and the sensation provided by the device, whereas questions from Q12 to Q14 investigated participants' preferences with respect to other types of sensory substitution cues, like auditory stimuli or vibration. Questions from Q15 to Q18 were delivered to the participants who completed the walking task with the CUFF only, while questions from Q19 to Q28 were delivered to the participants who completed the walking task in both modalities.

Commands	**Subjects**					**Mean**	**Std. Dev**
	S1	S2	S3	S4	S5		
START	2.17	1.44	1.51	1.29	1.62	1.61	0.33
STOP	1.28	1.03	1.03	0.9	1.04	1.1	0.13
RIGHT	0.84	1.66	1.08	1.06	1.39	1.3	0.32
LEFT	0.78	0.67	0.94	1.39	0.99	0.87	0.14

TABLE 4: This table reports the reaction time for each subject and the mean value associated to each CUFF command.

Commands	**Subjects**				
	S1	S2	S3	S4	S5
START	0	0	0	0	0
STOP	0	0	1	0	1
RIGHT	0	0	0	1	1
LEFT	1	0	1	0	2

TABLE 5: This table reports the number of stimuli not correctly understood by the subjects.

6 RESULTS

Starting from Experiments A, we can see that the results of the discrimination task had an average percentage of 97% and a standard deviation of 3.41. Table 2 reports the Likert scale results for the blindfolded subjects in the Experiments A1 and A2. The questions Q1 and Q2 (related to the wearability of the device with and without the use of the cane) were positively rated with a mean of 6.06 and 6.5 and standard deviation of 1.13 and 0.77 respectively. For Q6 and Q7, related to the usefulness of the stimuli, the mean responses were 5.8 and 6.5 with a standard deviation of 1.17 and 0.50. Questions Q9 and Q10,

Commands	**CUFF only**		**CUFF + Cane**		**Cane only**	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Task 1	70	52.32	45	24.33	19.33	1.15
Task 2	64	35.35	50	35.79	16.66	2.3
Task 3	71.5	31.81	24.66	6.5	13.33	1.52
Task 4	73	31.11	38.66	21.54	17.33	2.51
Task 5	72.5	38.89	40	27.49	14	5.56

TABLE 6: The table shows the time (in second), mean and standard deviation to accomplish the five navigation tasks for each different experimental modality.

Commands	**CUFF only**		**CUFF + Cane**		**Global**	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Task 1	1	0	1.5	0.57	1.4	0.54
Task 2	0.5	0.7	0.33	0.57	0.4	0.54
Task 3	0.5	0.7	0.66	6.5	0.6	0.54
Task 4	2.5	0.7	1.33	0.57	1.8	0.83
Task 5	2	0	0.66	1.15	1.2	1.09

TABLE 7: The table reports the number of collisions, mean and standard deviation in each task for the different modalities.

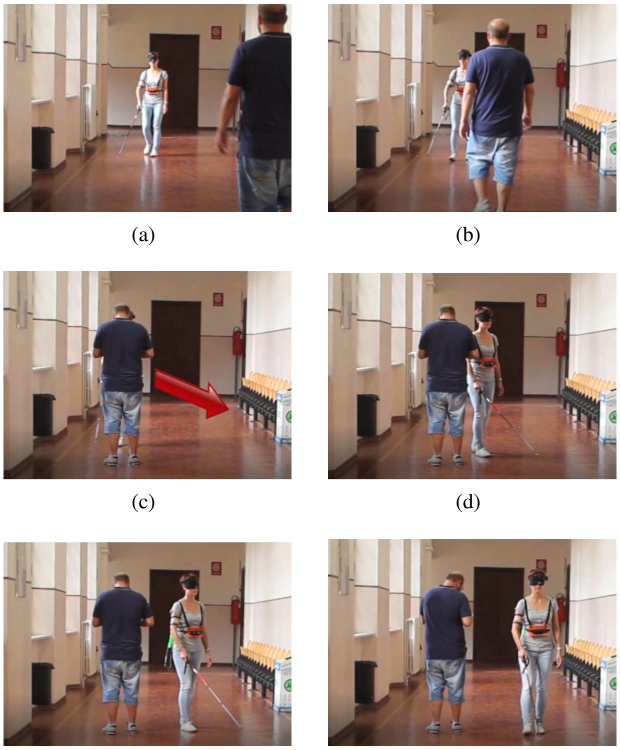
	Questions	Results
Q1	It was easy to wear and use the CUFF device	7
Q2	I was feeling uncomfortable while using the CUFF device	2
Q3	The haptic suggestions were intuitive	7
Q4	The sound produced by the actuators of the CUFF was hampering	1
Q5	The stimuli produced by the CUFF were easy to distinguish	5
Q6	The stimuli produced by the CUFF were helpful	7
Q7	It was easy to feel the presence of an obstacle receiving the feedback by the CUFF	6
Q11	At the end of the experiment with the CUFF I felt tired	1
Q12	Have you ever used a vibrotactile ETA? If yes, you would have preferred it w.r.t the CUFF	Yes; No
Q13	Would you have preferred an auditory cue?	No
Q14	Would you use our system in everyday life?	Yes

TABLE 8: These statements, presented in random order, were rated by the blind subject of Experiment B1 using a 7-point Likert scale (1: Strongly disagree, 7: Strongly agree).

	Questions	All participants		CUFF only users		Cane users	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev
Q1	It was easy to wear and use the CUFF device	5.125	1.80	/	/	/	/
Q2	The haptic suggestions were intuitive	3.87	1.72	/	/	/	/
Q3	I felt hampered by the cutaneous device.	3.25	2.37	/	/	/	/
Q4	The sound produced by the actuators of the CUFF was hampering	1.25	0.46	/	/	/	/
Q5	The stimuli produced by the CUFF were easy to distinguish	4.12	1.72	/	/	/	/
Q6	The stimuli produced by the CUFF were helpful	4.62	2.06	/	/	/	/
Q7	I felt confident using the system.	3.25	2.18	/	/	/	/
Q8	I felt stressed/frustrated using the system.	2.75	1.98	/	/	/	/
Q9	The system gave me an unpleasant feeling	2	1,6	/	/	/	/
Q10	I was able to interact with the environment during the use of CUFF.	5.25	1.9	/	/	/	/
Q11	I had difficult in locating the obstacles during the task.	4.25	1.6	/	/	/	/
Q12	Would you prefer an auditory stimulus?	2 yes only	6 no	/	/	/	/
Q13	Do you ever use a vibrotactile device? If yes would you have preferred a vibrotactile stimulus?	2 yes	6 no	/	/	/	/
Q14	Do you wear the system during the daily life?	4 yes	4 no	/	/	/	/
Q15	I felt relaxed using only the CUFF device during the tasks.	/	/	5.4	2.07	/	/
Q16	I was feeling uncomfortable while using the CUFF device.	/	/	2.2	1.64	/	/
Q17	At the end of experiment with the CUFF only I felt tired.	/	/	3.8	2.77	/	/
Q18	I had difficult in completing the tasks using the CUFF only	/	/	5.6	1.34	/	/
Q19	It was easy to wear and use the CANE together with the CUFF.	/	/	/	/	6.66	0.57
Q20	I was feeling uncomfortable while using the CANE together with the CUFF device	/	/	/	/	1.33	0.57
Q21	At the end of experiment with the CUFF and CANE I felt tired.	/	/	/	/	2.66	2.88
Q22	At the end of experiment with the CANE only I felt tired.	/	/	/	/	1	0
Q23	I had the feeling of performing better while receiving feedback by the CANE only.	/	/	/	/	6	1
Q24	I had feeling of performing better while receiving feedback by the CANE and CUFF device.	/	/	/	/	3.66	1.52
Q25	I had difficult in completing the tasks using the CANE with the CUFF.	/	/	/	/	3.33	2.08
Q26	I had difficult in completing the tasks using the CANE only.	/	/	/	/	1	0
Q27	Using the CUFF with the CANE I was more hampered in completing the task	/	/	/	/	4.66	3.21

TABLE 9: These statements were rated by the subjects of Experiment B2 using a 7-point Likert scale (1: Strongly disagree, 7: Strongly agree). Means and standard deviations across all individuals are reported.

on the performance, showed positive results with a mean of 1.81 and 6.68 and a standard deviation of 1.35 and 0.73. For Q11 (i.e the fatigue at the end of the experiment) the mean was 1.81 and the standard deviation was 1.42. The differences between the time for task accomplishment in the two navigation conditions were studied using a Wilcoxon signed-rank test, due to the non-Gaussianity of the samples. In particular, the p-value from Wilcoxon non-parametric test is associated with the null hypothesis of equal median values. Results show that there is not a significant difference in term of time for task accomplishment in the two navigation conditions ($p > 0.1$, Experiment A1: Time with Cane only seconds: mean standard 165 deviation 42.67; Time with CUFF and Cane: mean 162.5 standard deviation 27.5. Experiment A2: Time with Cane only seconds: mean 401 standard deviation 170.8; Time with CUFF and Cane: mean 343 standard deviation 67.34). Furthermore we performed a Wilcoxon non-parametric test considering scores from Q9 - Q10, and Q11 - Q12, respectively. Statistically significant differences were found in both cases ($p < 0.05$), which suggest that the integration with the CUFF was perceived as effective in improving the navigation performance and reducing the fatigue. Table 8 reports the result for the blind participant of Experiment B1, while table 3 shows the time for task accomplishment for Experiments A and B1. The time for task completion of the blind subject in Experiment 1 was 180 sec. Regarding the Experiment B2, Table 4 and 5 show the time of reaction of the participants to the commands and the mean value across all subjects. As it can be noticed we report data from only five blind subjects; we decided to discard the sixth subject since we experienced some issues during the experimental task due to communication problems from the joystick to the CUFF. What is noticeable is that participants promptly responded to the navigation commands with a mean time of reaction of 1.61 seconds for start command, 1.1 for the stop, 1.3 for turn right and 0.87 for turn left. This result testifies in favor of the intuitiveness of the delivered stimuli. Table 6 reports the execution times for Task 1 to 5 in the different navigation modalities, while Table 7 shows



(a) (b)

(c) (d)

(e) (f)

Fig. 5: In these pictures, it is possible to observe the obstacle avoidance, on the left, performed by the blindfolded individual while walking through the corridor.

the number of times in which the vision system failed, which testifies in favor of the reliability of our solution. The mean time and standard deviation, for the blind participants who were not expert users are: 70, 64, 71.5, 73, 72.5 seconds and 52.32, 35.35, 31.81, 31.11, and 38.89 seconds respectively for Task 1, 2, 3, 4, and 5. The blind participants, who were expert users of the cane completed the tasks in two modalities (CUFF + Cane and Cane only). The mean values and standard deviation are: 45, 50, 24.66, 38.66 and 40 seconds and 24.33, 35.79, 6.5, 21.54, 27.49 seconds for the modality CUFF + Cane. For the Cane only they are 19.33, 16.66, 13.33 17.33 and 14 seconds for the mean values and 1.15, 2.3, 1.52, 2.51 and 5.56 seconds for the standard deviation values. In Table 9 we can find the results of the Likert scale questionnaire provided by all the blind participants of Experiment B2. Questions Q1, Q19 and Q20, are related to the wearability of the CUFF, where we can observe positive scores, with a mean value of 5.12, 6.66 and 1.33, and a standard deviation of 1.80, 0.57 and 0.57, respectively. For Q5 and Q6 (on the sensory substitution) the mean is 4.12 and 4.62, and the standard deviation 1.72 and 2.06. Questions Q15 and Q16, on the sensation during the usage of the device, also comes with a good rate with a mean of 5.4 and 2.2, and standard deviation of 2.07 and 1.64, respectively. For Q25 and Q26, on the task performance, the mean are 3.33 and 1, and the standard deviation 2.08 and 0.

7 DISCUSSION

7.1 Results with Blindfolded Participants

The results of the discrimination task of Experiment A1 showed that participants were able to correctly recognize the direction of the stimuli. Regarding Table 2 we can note that participants had no difficulty wearing and using the CUFF, also in combination with the cane. About the intuitiveness of the proposed sensory substitution approach, users were able to distinguish the stimuli produced by the device and understand the correct direction to follow. The general opinion was that haptic stimuli were helpful for guidance, especially for obstacle avoidance. All the subjects were able to avoid obstacles by following the information provided by the device even though some subjects reported that the sound produced by the actuator of the CUFF was hampering. Since the participants were not expert users of the cane, they had the impression of performing better when they used the cane and the CUFF together, instead of the cane only. Users did not feel tired at the end of experiments with the CUFF and the cane, while on the contrary they had some difficulties to accomplish the experiment with the cane only. In conclusion, the integrated usage of the CUFF and the white cane did not degrade the performance in navigation task accomplishment with respect to the white cane only, but, on the contrary, increases users' confidence in performing in a better manner, especially for obstacle avoidance, as reported in the subjective quantitative evaluation

7.2 Results with Blind Participants

The results of the blind subject in Experiment B1 are reported in Table 8. The subject perceived the CUFF as highly wearable and easy to use (Q1), comfortable (Q2), intuitive (Q3), helpful (Q6, Q7), and at the end of the experiment the participant did not feel tired at all (Q11). The subject reported that the system could be used in her everyday life but portability should be improved. It is important to observe that the blind participant performed the experiment with the CUFF modality only since she was not an expert user of the cane. She confirmed that with the CUFF she felt safer walking through the corridor (Q7); about the sensory substitution, she declared that the haptic stimuli were easy to distinguish and helpful and intuitive (questions from Q3 to Q6).

The results of the experiments conducted with the blind participants, reported in Table 4 and 7, showed that the commands were easy and clear to distinguish. What emerged at the end of the task is that the motor movement back to the reference position can be sometimes misunderstood as an indication to turn left or right. It is reasonable to think that this could make users stop, or just slow down their pace. What we learnt from the experiments was that the participants who are expert users of the cane tended to slow down their pace to be more focused on the stimuli provided by the device. This can be interpreted as a natural adaptation to the new assistive modality, with respect to the one used in everyday life. On the contrary, the non expert users of the white cane walked with their normal pace. This observation testified in favor of the intuitiveness of the sensory substitution we chose. For what concerns the walking task, results reported in Table 6 show that all the subjects were able to complete the tasks with differences in terms of time for task accomplishment; however, due to the reduced number of subjects a statistical analysis cannot be performed. Expert users of the white cane were able to find the free path immediately using only the cane, while they had to spent a few seconds more to understand the indication received from the CUFF and pay attention to the command to follow. On the other hand, participants, who used a volunteer guide in everyday life, were able to complete the task slowly but autonomously.

Regarding Table 9, we can note that in general participants had no difficulty to wear and use the device, neither in conjunction with the cane (Q1, Q19 and Q20). About the intuitiveness of the sensory substitution, the stimuli were helpful and easy to distinguish for the participant who rely on an accompanying person in everyday life, less intuitive and useful for the expert users of the cane (Q5 and Q6); but all of them were able to successfully localize and avoid the obstacles during the tasks. More specifically, the global impression of users of white cane was that the device could be a viable solution for training new blind people in the usage of the cane, but to expert users of the cane the device seems to not give any additional information (Q23 and Q24). Indeed, they liked very much the idea of receiving information about the presence of obstacles, but they preferred to choose the best strategy to avoid it by themselves using the cane. About the non autonomous blind participants, who rely on an accompanying person, all of them liked the device because for the first time they walked alone in an unknown environments. They felt relaxed using the system and understood well the stimuli (Q15 and Q16); although they declared to have some difficulties to accomplish challenging tasks, like passing through the door and double turning (see 7). For this reason at the end of these experiments they felt tired (Q17). Furthermore, we asked the visually impaired users if they would have preferred forces versus vibratory cues: results show that they did not like this type of stimulus, and preferred to have the auditory channel free. Indeed, as said in Section 5.4, some of them had, in other occasions, tried a vibration-based device. Even though most of them had preferred the forces cues, in their opinion the most important thing is related to the fact that the stimulus has to be clearly understood without any possibility of misunderstanding.

8 LIMITATIONS AND FUTURE DEVELOPMENTS

This work reports on the feasibility of the integration of a wearable haptic device, which provides stimulation cues similar to the ones conveyed by the hand of an accompanying person, with an obstacle avoidance systems. The work has followed a user-centered approach, from the definition of the specifications to the validation phase. Despite the positive results, we are aware that the process for translating these outcomes in everyday life is still long and that our approach presents some limitations, which we would like to address in future work. The main aspects we would like to further develop are: (1) the user's requirements - social acceptability of the system, which is also related to its wearability, (2) the hardware architecture, and (3) the algorithm used for the obstacle detection. Regarding the first point, we will explore the possibility of tailoring the navigation instructions on different conditions of the end users, which are based on the travel support used in their daily activities. Indeed, what we learned from the experimental outcomes is that different guidance instructions could be needed for people using the white cane and for those who do not. Furthermore, what emerged from the outcomes of the Likert Scale (see question Q14 in table 9) is that, even if the users appreciate our approach, they would like to have a system with smaller physical dimensions and more visually unnoticeable for an effective usage in their everyday life. This aspect, which is intertwined with the wearability of our architecture, was also highlighted during the informal discussions we had with the participants. This point could be achieved by exploring the exploitation of a processing unit that can be more easily integrated with the user's body, and of other types of sensors with a reduced layout, e.g. depth, proximity sensors. All these investigations and possible changes will be driven by a continuous feedback from visually impaired people. A more in depth analysis of the sensing solutions could represent a strategy to overcome the limitations of the current hardware (point 2), in particular the reduced capacity of the camera to generalize and *see* in different scene illumination conditions. Indeed, the camera and consequently the algorithm used in our system result in robust in environments that are illuminated with artificial light. On the contrary, in natural light settings, the reflection of the sunlight on the floor could lead to the misleading identification of false obstacles. Moreover, the camera is completely blind in a dark environment. Regarding point (3), the major limit of our algorithm is that it is not capable to distinguish between moving or fixed obstacles. This could not guarantee a safe navigation in a crowded place. Also this point could be addressed through a suitable choice of the sensing system. Under this regard, we will evaluate the integration and usage of vision-based and non-vision based sensors and arrays. This evaluation will include the investigation of a multi-sensory approach to increase the robustness of on-line obstacle identification and localization and people detection, for an intuitive spatial map reconstruction [38], [39], [40], [41]. Although multi-sensory integration will be investigated, a minimalistic approach for resource usage will always guide all the phases, to push further system wearability and cost-effectiveness. Furthermore to increase the reliability of the algorithm, we will investigate a new lower level planning strategy based on a learning process on the pace of the users, and create a custom lower level planner. This could also help to increase system acceptability. An integration between the navigation and planning strategy presented in this paper with a higher level planning method for the automatic computation of intermediate target points to drive the user is also envisioned. This could be done through the realization of a database with maps of different places of interest (e. g. hospitals, public offices, etc). The testing of other navigation algorithms coming with a lower computational cost is under investigation, and applications for outdoor navigation will be considered. Finally, future work will include additional experiments with blind people and further investigation and implementation of users' needs, to continuously increase the intuitiveness of the system and its portability, including specific experiments to evaluate the effectiveness of the system for training blind people to use travel aids (such as the white cane).

9 CONCLUSIONS

In this work, we have presented a wearable navigation system of a RGB-D camera, a laptop and a wearable device CUFF, which can provide normal and tangential force cues through the control of a stretching state of a fabric. The target application is blind people guidance in an unknown indoor environment. The final layout of the system and obstacle avoidance techniques was based on the elaboration of requirements and opinions collected from blind individuals and people working in the field of assistance of the visually impaired. We tested the system with blindfolded participants and blind users, in different indoor environments, and verified if it could be a viable solution to increase performance of users with regard to autonomous navigation with and without the white cane usage (see Experiments A,B). Experiments show that our navigation system could be a viable solution to be integrated with classic navigation methods. Interestingly, the visually impaired people, which performed the experiment with the CUFF only (e.g. no cane users) exhibited a good time for task accomplishment and a positive perception of the navigation system and haptic stimuli. On the other hand, according to the blind expert users of the white cane, the device could be a valid aid for training newly blind people to use the white cane. Furthermore the users well recognized the stimuli provided by the CUFF, and they considered them helpful for navigation.

10 ACKNOWLEDGMENT

We would like to thank the association "Unione Italiana dei Ciechi ed Ipovedenti ONLUS (UIC)" for the availability and help in recruiting blind participants for this study. A special thank goes to the visually impaired people who spent their time to test our system. Finally, we would also like to thank Prof. Daniela Rus (MIT), for the inspiring discussions.

REFERENCES

[1] World Health Organization, WHO (2014)., "Visual impairment and blindeness - Fact Sheet N 282," http://http://www.who.int/mediacentre/factsheets/fs282/en//, [Online; accessed 30-Nov-2016].

[2] European Forum Against Blindness, EFAB (September 2013), https://www.euractiv.com/section/health-consumers/news/single-eu-definition-of-blindness-could-help-save-billions-of-euros-study/.

[3] D. Dakopoulos and N. G. Bourbakis, "Wearable obstacle avoidance electronic travel aids for blind: a survey," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 40, no. 1, pp. 25–35, 2010.

[4] R. Velázquez, "Wearable assistive devices for the blind," in *Wearable and autonomous biomedical devices and systems for smart environment*. Springer, 2010, pp. 331–349.

[5] H. SungMin, "Haptic aids for the visually impaired," in *Pervasive Haptics*. Springer, 2016, pp. 221–229.

[6] K. Möller, J. Möller, K. Arras, M. Bach, S. Schumann, and J. Guttmann, "Enhanced perception for visually impaired people evaluated in a real time setting," in *World Congress on Medical Physics and Biomedical Engineering, September 7-12, 2009, Munich, Germany*. Springer, 2009, pp. 283–286.

[7] M. R. Adame, J. Yu, K. Moller, and E. Seemann, "A wearable navigation aid for blind people using a vibrotactile information transfer system," in *2013 ICME International Conference on Complex Medical Engineering*, May 2013, pp. 13–18.

[8] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives," *IEEE transactions on haptics*, vol. 10, no. 4, pp. 580–600, 2017.

[9] C. M. Smith, "Human factors in haptic interfaces," *XRDS: Crossroads, The ACM Magazine for Students*, vol. 3, no. 3, pp. 14–16, 1997.

[10] J.-L. Rodríguez, R. Velázquez, C. Del-Valle-Soto, S. Gutiérrez, J. Varona, and J. Enríquez-Zarate, "Active and passive haptic perception of shape: Passive haptics can support navigation," *Electronics*, vol. 8, no. 3, p. 355, 2019.

[11] J. S. Zelek, "Seeing by touch (haptics) for wayfinding," in *International congress series*, vol. 1282. Elsevier, 2005, pp. 1108–1112.

[12] J. Borenstein and I. Ulrich, "The guidecane-a computerized travel aid for the active guidance of blind pedestrians," in *Proceedings of International Conference on Robotics and Automation*, vol. 2. IEEE, 1997, pp. 1283–1288.

[13] Y. Wei, X. Kou, and M. C. Lee, "A new vision and navigation research for a guide-dog robot system in urban system," in *2014 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 2014, pp. 1290–1295.

[14] V. V. Meshram, K. Patil, V. A. Meshram, and F. C. Shu, "An astute assistive device for mobility and object recognition for visually impaired people," *IEEE Transactions on Human-Machine Systems*, vol. 49, no. 5, pp. 449–460, Oct 2019.

[15] Y. Wang and K. J. Kuchenbecker, "Halo: Haptic alerts for low-hanging obstacles in white cane navigation," in *2012 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2012, pp. 527–532.

[16] B. Andò, S. Baglio, V. Marletta, and A. Valastro, "A haptic solution to assist visually impaired in mobility tasks," *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 5, pp. 641–646, 2015.

[17] M. H. A. Wahab, A. A. Talib, H. A. Kadir, A. Johari, A. Noraziah, R. M. Sidek, and A. A. Mutalib, "Smart cane: Assistive cane for visually-impaired people," *arXiv preprint arXiv:1110.5156*, 2011.

[18] A. Kassim, T. Yasuno, H. Suzuki, H. Jaafar, and M. Aras, "Indoor navigation system based on passive rfid transponder with digital compass for visually impaired people," *Int. J. Adv. Comput. Sci. Appl.*, vol. 7, no. 2, pp. 604–611, 2016.

[19] S. Saegusa, Y. Yasuda, Y. Uratani, E. Tanaka, T. Makino, and J.-Y. Chang, "Development of a guide-dog robot: human–robot interface considering walking conditions for a visually handicapped person," *Microsystem Technologies*, vol. 17, no. 5-7, pp. 1169–1174, 2011.

[20] A. Keyes, M. D'Souza, and A. Postula, "Navigation for the blind using a wireless sensor haptic glove," in *2015 4th Mediterranean Conference on Embedded Computing (MECO)*. IEEE, 2015, pp. 361–364.

[21] J. B. Van Erp, H. A. Van Veen, C. Jansen, and T. Dobbins, "Waypoint navigation with a vibrotactile waist belt," *ACM Transactions on Applied Perception (TAP)*, vol. 2, no. 2, pp. 106–117, 2005.

[22] M. Aggravi, G. Salvietti, and D. Prattichizzo, "Haptic assistive bracelets for blind skier guidance," in *Proceedings of the 7th Augmented Human International Conference 2016*. ACM, 2016, p. 25.

[23] C. Loconsole, M. B. Dehkordi, E. Sotgiu, M. Fontana, M. Bergamasco, and A. Frisoli, *An IMU and RFID-based Navigation System Providing Vibrotactile Feedback for Visually Impaired People*. Cham: Springer International Publishing, 2016, pp. 360–370. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-42321-0_33

[24] M. R. Adame, J. Yu, K. Moller, and E. Seemann, "A wearable navigation aid for blind people using a vibrotactile information transfer system," in *Complex Medical Engineering (CME), 2013 ICME International Conference on*. IEEE, 2013, pp. 13–18.

[25] S. Scheggi, A. Talarico, and D. Prattichizzo, "A remote guidance system for blind and visually impaired people via vibrotactile haptic feedback," in *Control and Automation (MED), 2014 22nd Mediterranean Conference of*. IEEE, 2014, pp. 20–23.

[26] E. E. Pissaloux, R. Velázquez, and F. Maingreaud, "A new framework for cognitive mobility of visually impaired users in using tactile device," *IEEE Transactions on Human-Machine Systems*, vol. 47, no. 6, pp. 1040–1051, 2017.

[27] S. Gay, M.-A. Rivière, and E. Pissaloux, "Towards haptic surface devices with force feedback for visually impaired people," in *International Conference on Computers Helping People with Special Needs*. Springer, 2018, pp. 258–266.

[28] L. H. Villamizar, M. Gualdron, F. Gonzalez, J. Aceros, and C. V. Rizzo-Sierra, "A necklace sonar with adjustable scope range for assisting the visually impaired," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2013, pp. 1450–1453.

[29] S. Pundlik, E. Peli, and G. Luo, "Time to collision and collision risk estimation from local scale and motion," 09 2011, pp. 728–737.

[30] S. Casini, M. Morvidoni, M. Bianchi, M. Catalano, G. Grioli, and A. Bicchi, "Design and realization of the cuff - clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, Sept 2015, pp. 1186–1193.

[31] P. Bach-y Rita and S. W. Kercel, "Sensory substitution and the human–machine interface," *Trends in cognitive sciences*, vol. 7, no. 12, pp. 541–546, 2003.

[32] C. Della Santina, C. Piazza, G. M. Gasparri, M. Bonilla, M. G. Catalano, G. Grioli, M. Garabini, and A. Bicchi, "The quest for natural machine motion: An open platform to fast-prototyping articulated soft robots," *IEEE Robotics & Automation Magazine*, vol. 24, no. 1, pp. 48–56, 2017.

[33] N. Kanwal, E. Bostanci, K. Currie, and A. F. Clark, "A navigation system for the visually impaired: A fusion of vision and depth sensor," *Applied bionics and biomechanics*, vol. 2015, 2015.

[34] J. Shi and C. Tomasi, "Good features to track," in *Computer Vision and Pattern Recognition, 1994. Proceedings CVPR'94., 1994 IEEE Computer Society Conference on*. IEEE, 1994, pp. 593–600.

[35] S. Cardin, D. Thalmann, and F. Vexo, "A wearable system for mobility improvement of visually impaired people," *The Visual Computer*, vol. 23, no. 2, pp. 109–118, 2007. [Online]. Available: http://dx.doi.org/10.1007/s00371-006-0032-4

[36] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback," *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 506–516, 2013.

[37] P. Revuelta Sanz, B. Ruz-Mezcua, and J. Snchez-Pena, *ICTs for orientation and mobility for blind people: A state of the art*, 04 2018, pp. 1177–1203.

[38] H. C. Wang, R. K. Katzschmann, S. Teng, B. Araki, L. Giarr, and D. Rus, "Enabling independent navigation for visually impaired people through a wearable vision-based feedback system," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 6533–6540.

[39] A. Wachaja, P. Agarwal, M. Zink, M. R. Adame, K. Möller, and W. Burgard, "Navigating blind people with a smart walker," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 6014–6019.

[40] A. Carballo, A. Ohya *et al.*, "Fusion of double layered multiple laser range finders for people detection from a mobile robot," in *2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*. IEEE, 2008, pp. 677–682.

[41] A. Cosgun, E. A. Sisbot, and H. I. Christensen, "Guidance for human navigation using a vibro-tactile belt interface and robot-like motion planning," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2014, pp. 6350–6355.