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Augmented White Cane with Multimodal Haptic Feedback

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***Abstract*— This paper proposes an instrumented handle with multimodal augmented haptic feedback, which can be integrated into a conventional white cane to extend the haptic exploration range of visually impaired users. The information extracted from the environment through a hybrid range sensor is conveyed to the user in an intuitive manner over two haptic feedback systems. The first renders impulses that imitate the impact of the real cane with a distant obstacle. In combination with the range sensors, this system allows to "touch" and explore remote objects, thus compensating for the limited range of the conventional white cane without altering its intuitive usage. The impulses are generated by storing kinetic energy in a spinning inertia wheel, which is released by abruptly braking the wheel. Furthermore, a vibrotactile interface integrated into the ergonomic handle conveys the distance to obstacles to the user. Three vibrating motors located along the index finger and hand are activated in different spatiotemporal patterns to induce a sense of distance through apparent movement. The realized augmented white cane not only increases the safety of the user by detecting obstacles from a further distance and alerting about those located at the head level, but also allows the user to build extended spatial mental models by increasing the sensing range, thereby allowing anticipated decision making and thus more natural navigation.**

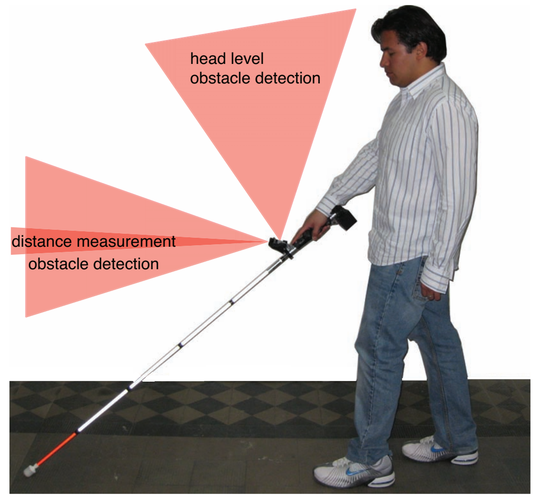

Fig. 1. Subject navigating with the augmented white cane. Hybrid sensing is used to detect walls and obstacles beyond the range of the conventional white cane, and to detect head level obstacles. The extracted information is transmitted to the user in an intuitive manner over two haptic and an auditory interface integrated into the handle.

I. INTRODUCTION

Navigation tasks such as obstacle avoidance, orientation and position awareness as well as the ability to navigate in an unfamiliar environment are highly dependent on our senses. Vision is the sense that allows the best localization of remote obstacles and the mobility of visually impaired persons is thus highly affected. To compensate for the lost sense of vision, blind people rely on their remaining senses such as hearing and the sense of touch.

The white cane as a mobility aid was officially introduced in the 1930's and today is still the most common navigation aid for the visually impaired. It has two main functions:

- It mechanically extends the sensing range of touch of the user, facilitating the exploration of the nearby environment.
- It is an international symbol to identify visually impaired people in the community.

In addition, some users perform semi-active echo-localization by tapping the cane on the ground to identify head level obstacles during navigation. The white cane is a highly reliable, efficient and affordable mean to increase the sensing range of visually impaired people and allows independent navigation. However, the short sensing range of the cane still limits the user, forcing him to apply an "explore first and then decide" navigation strategy in unfamiliar environments, in contrast to the non-impaired, who can make decisions well in advance (e.g. seeing a T-shaped corridor and deciding in advance to turn right at the end). Furthermore, the sensing range of the white cane is too short to build internal representations [1] of large environments such as train stations, malls, places or squares.

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In order to increase the sensing range, Electronic Travel Aids (ETAs) combine various sensors to scan the environment and provide different types of feedback [2][3]. Various approaches are used to represent the spatial information to the user, such as vibrations as used in the Ultracane [4], 3D auditory representations [5][6], transforming the 3D image into a *bas-relief* surface that can be tactily explored [7], etc. Other systems add extra features as the Laser Long Cane [8], which uses an on-board laser system to provide protection against head level obstacles that cannot be detected with a conventional long cane. The Kaspa System [9] and the system developed by Kuc *et al.* [10] mimic animal echolocation to scan the environment and provide auditory or vibrotactile feedback, respectively, to render a map of the surrounding environment. Jacquet *et al.* developed the Teletact, a system that uses a laser telemeter to measure distances to obstacles, and are exploring different strategies

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to represent the information to the user, such as tactile vibrations, musical notes and even semantic information [11].

However, many of the current ETAs still suffer from drawbacks such as:

- overload of the auditory channel, which is crucial for the visually impaired during navigation as it provides vast information about the environment, including approaching vehicles.
- non intuitive or obtrusive feedback requiring extensive training or attention (increased workload and shift of attention)
- low social acceptance of bulky systems or auditory feedback
- high cost compared to the conventional white cane
- unreliable feature classification

For these reasons, most of the visually impaired people still rely on the traditional white cane despite the recent developments. From the limitations of existing ETAs, we derive the requirements for our augmented cane as follows:

- due to the high reliability, efficiency and signaling function, the conventional white cane should not be replaced, and our ETA should be integrated into a white cane in order to augment it's abilities without reducing the initial functionality.
- the ETA should increase the sensing range of the white cane to improve the exploration, planning and navigation abilities of the user.
- the information should be delivered in an intuitive and discrete way and should not overload the auditory sense. An intuitive feedback will have the advantage of requiring little or no training and allow a faster reaction of the user.
- the detection of head level obstacles is an important feature missing on the conventional white cane. The ETA must be able to detect obstacles located in front of the user's trunk and head and warn in an intuitive way.

This paper is organized as follows. Section II discusses suitable feedback methods and justifies the choice of haptics as a communication channel. A brief description of the system elements of the augmented white cane is then presented in section III. Section IV explains the concept, function and implementation of the used feedback systems. Section V presents results from a trial performed with the cane and validates the system performance. Finally, a discussion of the main contributions presented in this work and the next steps concludes the paper.

II. Augmented Haptic and Auditory Feedback

Our ETA is an instrumented handle that replaces the handle part of the conventional white cane, thus allowing the user to continue using his/her white cane with unrestrained functionality when the ETA is turned off or unfunctional. This redundancy is also critical to minimize risks due to malfunction of the ETA. The remote sensing of obstacles and objects is achieved with range sensors. The main challenge is to deliver this information to the user in an efficient, intuitive and discrete way. Auditory feedback is not the most suitable as this modality is already used by the visually impaired person to gather information about the environment, may quickly become disturbing if provided continuously and may be obtrusive. The second drawback is the lack of accuracy when locating an object using auditory feedback. The sense of touch is a promising information channel, especially in situations where either the visual or the auditory system are overloaded or impaired [12]. This modality does not require shifting one's attention to a specific point (as in the case of vision), and can convey a wide range of information intuitively through haptic icons or melodies. Therefore, haptic feedback appeared to be very suitable to guide visually impaired people during navigation tasks.

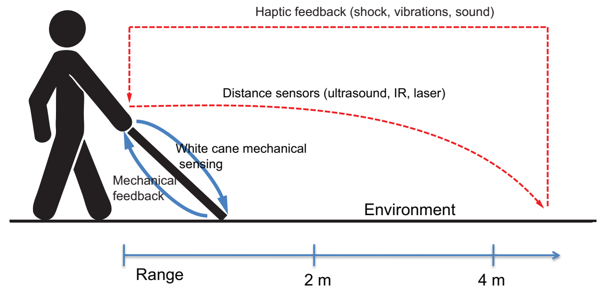

Fig. 2. Augmentation of the conventional white cane through sensing and multi-modal haptic feedback.

The white cane is a mean to extend the user's sense of touch. Our ETA uses the same interaction modality, making it intuitive and easy to use. Our idea is to apply augmented haptics [13] to the white cane, allowing the user to remotely touch and explore objects, as if he/she was holding a much longer white cane. The handling will be similar to manipulating a five meter long cane with the weight and inertia of a conventional cane (Fig.2, typically $1.2-1.5$ m long).

The main challenge for this concept was to generate an external shock force with a portable device. To this end, we propose an embedded shock generation system. The shock system, however, can only indicate the direction to the obstacle. In order to increase the amount of transmittable information, three vibrators integrated into the handle stimulate the index finger and palm by rendering various spatiotemporal patterns. Finally, to avoid collision with head level obstacles, an ultrasonic sensor covering the direct area in front of the trunk and head is added. Because head collision is rare but can lead to severe injury, the user is warned by a loud auditory signal.

III. System Overview

The ETA is integrated into the handle of a conventional white cane and consists of several modules described in the following.

A. Sensing

The augmented cane is equipped with redundant sensors to allow it to extract meaningful features from the environment, which are then conveyed to the user through the multimodal haptic interface. The sensors were selected based on a trade-off of features that can be detected with respect to the amount of data that needs to be processed in real-time, as well as for their size, weight and power consumption. Four types of sensors are used in the proposed concept:

1) Long Range Distance Sensor: The sensor responsible for measuring the distance to obstacles located in front of the user requires a long range of at least 3 m in order to significantly increase the sensing range of the conventional white cane. The beam of at least this sensor needs to be relatively narrow to virtually extend the conventional cane. The IR GP2YO700K infrared range sensor (Sharp, Japan), with its narrow beam and measuring range of up to 5.5 m, mimics the virtual extension of the white cane and detects the distance to walls and other obstacles.

2) Short Range Distance Sensor: The MaxSonar EZ0 (MaxBotix, USA) ultrasonic ranger has a wide beam (up to 50 degrees cone width). It is used to assure that the IR input is not corrupted by external infrared sources or other ambiguous situations. Thanks to its wide beam it is used to delimitate a safe area in the user's direct neighborhood.

3) Head Level Obstacle Sensor: Obstacles at the level of the head are difficult to detect with a conventional blind cane and may result in serious injury. A sensor to detect such obstacles should have a wide adjustable beam and a range varying from 40 cm to 1 m. For these reasons, we used a SRF10 (Devantech, UK) ultrasonic ranger. The beam, a cone with a diameter of 1 m at the height of the user's head, can be adjusted by varying the sensing gain. The module which holds the three selected sensors is illustrated in Fig. 3.

4) Cane Orientation: The instrumented handle will be used with a traditional white cane and, as such, will be subject to constant sweeping during walking. As it is essential to constantly have a global estimation of the cane orientation, an IDG500 dual-axis gyroscope (InvenSense, USA) is used to measure the angular sweeping velocity. The angular position, and thus the orientation of the cane, is obtained by integrating the rotational velocity provided by the gyroscope. The angular position is then filtered through a bandpass filter to reduce artifacts due to small vibrations (i.e the friction of the tip of the cane against the floor) and the drift caused by the slow change in orientation of the user. Further, the bandpass filter eliminates the temperature drift of the gyroscope. This information is used to determine whether the cane is in sweeping mode (user walking; measured angular velocity > 30 deg$/s$) or pointing mode (user standing in place or walking without sweeping). In sweeping mode, the cane indicates the direction to walls and obstacles with the shock module and in the static mode it provides distance information about obstacles in front of the subject over the vibrotactile display.

B. Electronics Board

A dsPIC (dsPIC33FJ128MC710, Microchip Technology Inc., USA) microcontroller was employed to process the measured data and control the haptic displays. The microcontroller provides 16 analog inputs, 85 I/O pins in total, 8 motor control PWM channels, 128 KB of program memory and 16 KB of RAM. The cane is supplied by a pack of six batteries (6×1.2 V, 4200 mAh). The electronics board also holds the gyroscope and a three-axis accelerometer (ADXL 335, Analog Devices, USA), and is integrated into the housing of the shock system (Fig. 3).

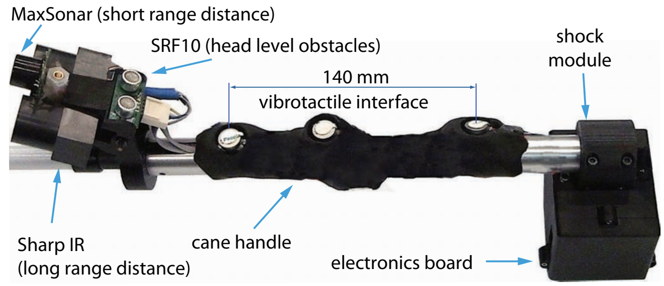

Fig. 3. Realized prototype of the novel ETA with hybrid sensing and multi-modal feedback. The cane is held as show in Fig. 1.

C. Cane Design

This novel ETA system can easily be integrated into a traditional white cane. It is composed of three modules (Fig. 3):

- *Sensor module:* a housing containing the three sensors. It is attached through a clamping ring but is free to rotate, thus allowing adjustment of the sensor's pointing direction.
- *Shock module:* a box containing the shock system and the device electronics. The box is attached to a clamping ring that can be fixed to the cane.
- *Vibrotactile interface:* three coin-type vibrating motors are integrated into an ergonomic handle. They are placed according to the established grip type used to hold a white cane [14] (Fig. 1).

IV. Multimodal Feedback

A. Shock System to Simulate the Behavior of a Long Cane

In order to be realistic, the shock felt by the user must be perceived as an external force. This is difficult to display in a portable mechanism as it should fulfill all the following requirements:

- it should be compact and lightweight
- parasitic forces or torques must be avoided
- the force should be high enough to be perceived as a physical interaction between the cane and an obstacle
- the system should store energy fast enough to produce a shock at each end of the sweeping movement (the sweeping rate is typically below 2 Hz)
- the power consumption should be minimized

These constraints imply that many of the actuation methods used in other shock systems such as a bistable solenoid or a cam compressing a spring to store energy, are not applicable. Both solutions are unable to produce enough shock force. In addition, a solenoid based solution creates an undesired double shock effect when its plunger returns to the initial position, thereby decreasing the realism of the rendered shock. Further, a cam solution may not be able to store the required energy at the required frequency.

1) Concept: To address this issue, we developed a shock mechanism based on two principles. An inertia wheel is used to store kinetic energy and is abruptly stopped in order to create an impulse torque. If the torque required to accelerate the wheel is small enough, the user will not feel it and thus have the impression that the impulse torque was a shock generated by an external collision (Fig. 4). The tip of the cane can either roll on the ground or be tapped during sweeping, while the other end of the cane is held by the user. The impulse momentum is converted into a shock force at the user's hand as illustrated in Fig. 7.

Since no brake could comply with both the size of the motor and the requirements of the system (frequent shocks and sudden braking), we developed a dedicated braking mechanism, which is based on a solenoid that pushes a steel pin into a spoked wheel (Fig. 4).

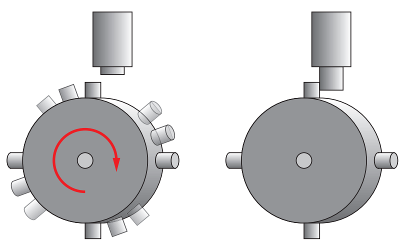

Fig. 4. Impulse generation using an actuated steel shaft to abruptly brake an inertia wheel.

During the shock, the magnitude of the peak force is very high and is transmitted through the entire mechanism, potentially damaging weaker parts. In order to limit the propagation of the peak force into the mechanism, a torque limiter and an axial force limiter were added between the inertia wheel and the motor. The torque limiter decreases the stress in the motor shaft connection during each shock, while the axial force limiter is only engaged if the stopper pin directly hits one of the wheel's spokes, thus displacing the wheel axially (Fig. 5).

2) Shock Generation Rate: Table I presents the characteristics of the shock module, which will determine the minimum interval time between two consecutive shocks.

TABLE I

SHOCK MODULE CHARACTERISTICS

Motor	RE 13 (3 W)
Torque constant (K_m)	5.04 mNm/A
Rotor Inertia (I_r)	0.484 gcm^2
Terminal Resistance (R)	3.53 Ω
Wheel Inertia (I_d)	60 gcm^2

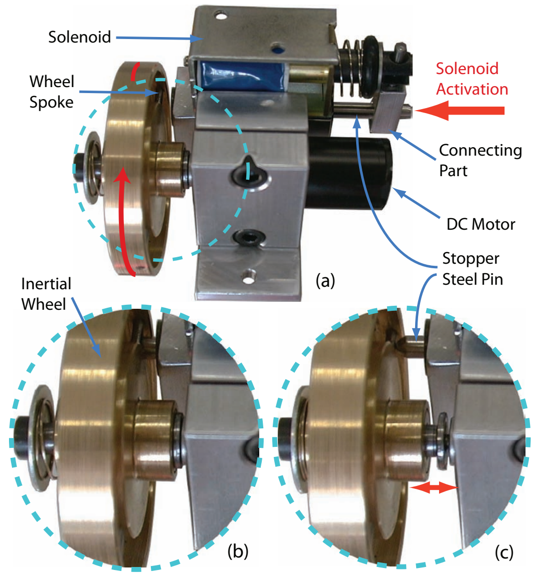

Fig. 5. a) Impulse generation using a spinning inertia wheel and an actuated steel shaft. A brushed DC motor accelerates the inertia wheel, which is abruptly braked by a steel pin actuated by a modified bistable TDS-K06B solenoid (TDS, Japan). b) When the steel pin is extended and collides radially with a spoke of the inertia wheel, the wheel is abruptly stopped. c) If the steel pin interferes with a spoke of the inertia wheel during extension, the wheel can deviate axially by compressing a spring, which then pushes it back, thereby preventing axial load on the motor shaft. A torque limiter allows the inertia wheel to slip on the motor shaft when stopped, further limiting excess load on the motor shaft and reducing the necessary time to accelerate the wheel for the next shock.

The voltage on a DC motor is determined by the following equation:

$$u = R \cdot i + K_m \cdot \omega \tag{1}$$

Where u is the motor voltage, R the motor resistance, i the current, K_m the torque constant and ω the rotor velocity. Furthermore, the equation of motion of the inertia wheel connected to the motor is defined by:

$$(I_r + I_d) \cdot \dot{\omega} = K_m \cdot i \tag{2}$$

The system time constant (τ) is obtained after integration by inserting (1) into (2)

$$\tau = \frac{R}{K_m^2}(I_r + I_d) \tag{3}$$

The time required to accelerate the inertia wheel to the desired velocity n_b is expressed as [15]:

$$\Delta T = \tau \cdot \ln\left(\frac{(1 - \frac{M_b + M_r}{M_h})n_0}{(1 - \frac{M_b + M_r}{M_h})n_0 - n_b}\right) \tag{4}$$

Where M_b, M_r *and* M_h are the working torque, the frictional torque and the stall torque, respectively, while n_0 is the maximum no load speed.

Inertia Wheel Velocity, Acceleration Time and Collision Force:

The steady state velocity of the inertia wheel and the input current of the DC motor were measured for different motor input voltages and are reported in Fig. 6.

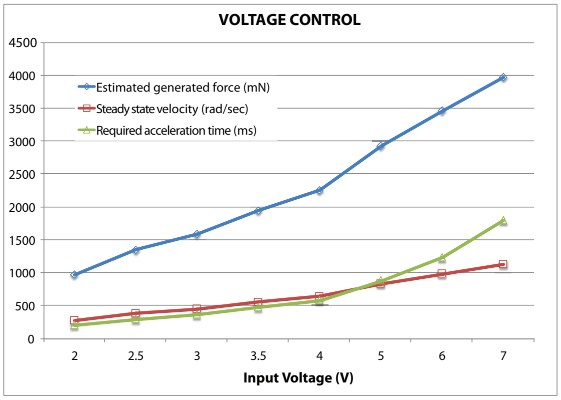

Fig. 6. Estimated shock force on the hand, steady state velocity and required acceleration time of the inertia wheel-motor system in function of the input voltage.

3) Impulse Magnitude: In order to estimate the impulse force on the handle, two assumptions were made:

- The impact between the shaft and the spokes is entirely elastic
- The user is considered as an infinite mass and thus assumed to remain immobile when the impulse is generated.

The law of conservation of momentum states:

$$\sum_i I_i \omega_i(t_e) = \sum_i I_i \omega_i(t_i) \tag{5}$$

where I_i is the inertia of the element i, ω_i its angular velocity, t_e and t_i the times after and before the collision respectively. In our system there are two elements, the user holding the cane and the inertia wheel. Both have an inertia I_c, I_w, and a before and after collision angular velocity, $\omega_{ci/e}, \omega_{wi/e}$. Thus, Eqn.(5) becomes:

$$I_w \omega_{wi} + I_c \omega_{ci} = I_w \omega_{we} + I_c \omega_{ce} \tag{6}$$

We assumed that ω_c equals zero. Therefore, the change in momentum is $\Delta P = 2 I_w \omega_w$. The second law of Newton relates the change in momentum to the generated impulse:

$$p_{t_w} = \int_t t_w(t) dt = \Delta P \tag{7}$$

Where t_w is the shock torque of the inertia wheel. The result of the shock is an impulsive torque applied to the user and the cane. We assumed the cane tip to be sweeping constantly over the ground with negligible friction. The system thus behaves as illustrated in Fig. 7.

Applying force and torque equilibrium laws to this system, we obtain the impulse force:

$$p_{f_{hand}} = \frac{p_{t_w}}{L cos\alpha} \tag{8}$$

The magnitude of the rendered impulse depends on the shock duration Δt_{shock}. The shorter the impact the stronger the impulse:

$$f_{hand} = \frac{p_{f_{hand}}}{\Delta t_{shock}} \tag{9}$$

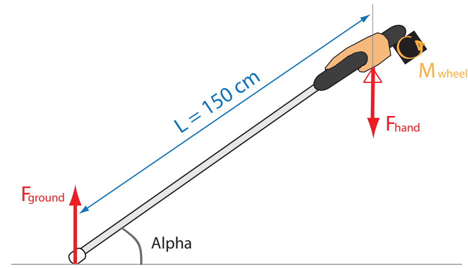

Fig. 7. Force and torque equilibrium as the user sweeps the cane over the ground.

Measurement: By measuring the impact time with the accelerometer and directly transmitting the output to an oscilloscope, we found an impact time of approximately $5ms$. Using equation (9), with the angle in between the cane and the floor (8) arbitrarily set to 45 degrees, we obtained the force curve presented in Fig. 6.

The system was found to generate a satisfactory impulse with the inertia wheel spinning at 480 rad/sec. The shock system generates an impulse of 5.4 mNs every 0.3sec (Eqn.8) delivering an estimated force f_{hand} of 1.1 N.

An experiment was performed to measure this impulse force on the handle. The device, mounted on a white cane, was placed on a 6-axis force/torque load cell (Nano 17, ATI, USA) fixed to a table. The cane had an angle of 43 deg with the floor. The peak shock force was measured to be $2.4 \pm 0.9N$.

B. Vibrotactile Interface to Display Obstacle Distance Information

The shock system is only meant to warn the user about the presence of obstacles or walls while sweeping the cane. The intensity of the shock being constant, it is mainly used to guide the user by indicating the direction to obstacles, but can not provide distance information. For this reason, a second haptic display is implemented on the cane, providing range information on distant obstacles. Three vibrators are used to stimulate the hand at different locations, allowing an increased number of spatiotemporal vibration patterns and thus increasing the amount of information that can be provided to the user.

1) Apparent Movement: This secondary haptic feedback is based on the concept of *Vibrotactile Apparent Movement*. Research on this phenomenon has been going on for decades [16]. It consists of a sequential stimulation at different locations of a body part. For example, Niwa and Yanagida [17] locally stimulated the lower and upper arm sequentially. The result was an impression of apparent movement of the vibration from the lower arm to the upper arm.

The vibrotactile handle exploits the same concept, using three aligned vibrators to create an apparent movement from the bottom of the palm to the tip of the index finger. As illustrated in Fig. 8, there are two important periods that characterize the stimulation [17]. First, the time period between the beginning of two distinct stimulations, the Stimulus Onset Asynchrony (SOA), and second the time during which a

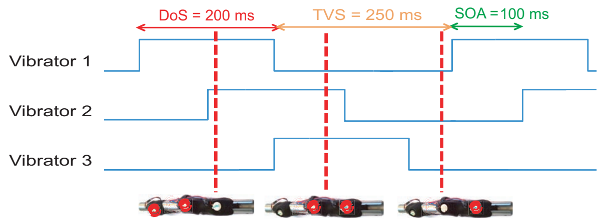

Fig. 8. Apparent Movement created by activating coin-type vibrating motors sequentially.

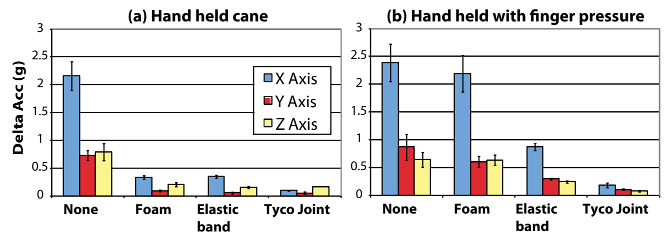

Fig. 9. Transmitted vibration amplitude for different damping materials and for two different setups: (a) The cane is held in the hand (b)The cane is held in the hand and the index finger is pressed against the vibrator.

vibrator stimulates the user (Duration of Stimulus, DoS). The desired movement impression was obtained with a DoS of 200 *ms* and an SOA of 100 *ms*. By repeating this apparent movement, the user will have an impression similar to the tip of a pencil stroking the hand repetitively. Five different tactile patterns were displayed depending on the distance to the obstacle ($1-1.5\ m$, $1.5-2\ m$, $2-3\ m$, $3-4\ m$ and $4-5\ m$) by changing the time between vibration sequences (TVS) proportional to the distance. When the obstacle distance is below 1 *m*, all the vibrators are activated continuously to alarm the user before the imminent collision.

2) Implementation: The handle skeleton consists of a hollow aluminum cylinder. FIMO paste, a modeling thermosetting paste, was applied on the aluminum cylinder to realize an ergonomic grip. The vibrotactile interface was integrated into the handle. The coin-type vibrating motors consist of an embedded DC motor spinning an eccentric mass fitted on shaft. The fast rotation of the eccentric mass, at approximately 13000 *rpm*, generates the vibration. For this device, three FM34F DC motors from TPC corp. were placed on the handle. They are aligned as illustrated in Fig. 8, with a distance of 140 *mm* between the first and the last vibrator. The placement of these vibrators was based on the established grip type used to hold a white cane (Fig. 1), and anthropometric data of the hand [18].

In order to allow for the rendering of localizable spatiotemporal patterns, the vibrations need to be adequately isolated in order to avoid transmission through the entire handle. In order to compare the efficiency of different vibrator supports, we measured the transmitted vibration into the entire device with an accelerometer as illustrated in Fig. 9. It was found that hollow rubber Superseal Joints (Tyco electronics, USA), were most efficient due to their large compliance in the horizontal plane, and relative stiffness in the vertical plane, allowing localized stimulation on the user's finger without transmitting the vibration to the rest of the handle, and thereby the hand.

3) Preliminary Tests: Preliminary tests were performed to determine the optimal range of TVS values to render the apparent movement. As it was found in [17], when the TVS is reduced the speed of the apparent movement increases. Using higher speed to represent approaching objects was found to be the most intuitive method. The TVS threshold that should be overcome to allow the user to perceive the sense of the apparent movement was determined at 100 *ms*. Therefore, the stimulation TVS ranges used in this system range from 300 *ms* to 700 *ms* for an obstacle distance range from 1 *m* to 5 *m*.

C. Auditory Alarm System for Head Level Obstacles

Obstacles above the ground or with protrusions such as tree branches are extremely dangerous for the visually impaired person. For this reason, an ultrasonic sensor constantly monitors for the presence of obstacles in front of the user's upper body and head. When an obstacle is detected, a *Digisound F/UCW 03* sound emitter delivers a loud alarm (2300 *Hz* at over 85 *dB*) that will warn the user and allow a fast reaction. The use of an auditory feedback is justified by the rarity and emergency of this situation requiring a clear signal and a rapid reaction from the user.

V. Usability Analysis: Trial Results

The augmented white cane can detect the walls in a hallway and generate a shock depending on the distance to the wall or obstacle. The orientation of the cane as well as its distance to the obstacle are constantly updated and the system is capable of deducing if the user is still pointing towards the same wall or if a new wall was detected. Only one shock will be generated for each detected wall to avoid misinterpretations.

A trial was carried out to evaluate the performance of the overall system. The user walked along a 15 *m* long and 2 *m* wide hallway while sweeping the cane regularly. The status of the obstacle detection, shock generation and angular orientation data were wirelessly transmitted to a PC via Bluethooth transmission. Fig. 10 presents data from one of the five subjects who participated in the study. The angular position represents the pointing direction of the cane. The square signal indicates the detection of an obstacle. Obstacles lying outside a cone of $\pm 60°$ around the movement direction and closer than 4.5 *m* are considered as walls and indicated by a shock, whereas objects located within the cone and closer than 3.5 *m* are considered as obstacles and indicated by vibration. The *shock generation* signal illustrates the short powering of the solenoid for a duration of around 10 *ms*, necessary to generate the impulse.

One can notice that the solenoid is activated almost immediately after the wall is detected. The delay between the obstacle detection and the physical impulse generation is under 15*ms*. Furthermore, even though the time period during

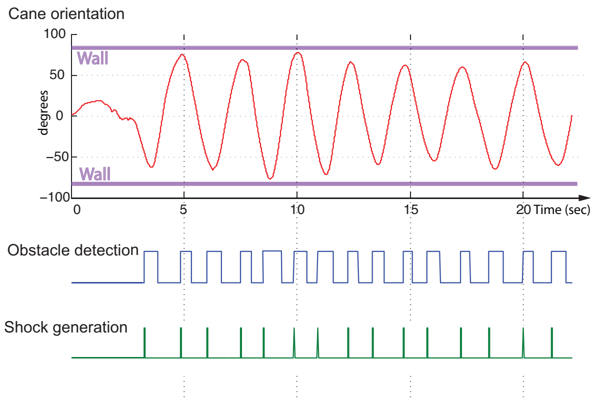

Fig. 10. Cane behavior when walking through a hallway.

which an obstacle is detected varies, the system generates a single shock for each newly detected obstacle.

According to feedback from the users, the indication of walls and the distance to obstacles represented by apparent movement was a very intuitive approach and thus easy to understand. However, in order to be able to estimate the exact distance to the obstacle from this feedback, users should go through a training period.

VI. Conclusion

Conventional white canes are a widely accepted, intuitive and reliable navigation aid for the visually impaired. However, the obstacle detection and haptic exploration range is restricted to the length of the cane. The main purpose of this work is to overcome this limitation by proposing a new augmented white cane concept that integrates sensors to detect distant objects and informs the user though a multimodal haptic feedback handle. The proposed solution combines the measurements of infrared and ultrasonic sensors to improve the reliability of the obstacle detection. When a distant obstacle is detected, the device informs the user by imitating the impact of the white cane with the object, thereby successfully providing the sensation of handling a much longer cane. This feedback is generated by a shock-generation module that stores kinetic energy in a spinning wheel and then releases it in a controlled impact. Furthermore, the proposed augmented white cane provides additional distance information when users stop sweeping and point the cane towards an obstacle for several seconds. This distance information is conveyed through a vibrotactile interface that stimulates the user's hand. The spatiotemporal vibration pattern creates the sensation of an apparent movement, with increasing speed as the obstacle approaches. The usability of the device and the intuitiveness of the multimodal feedback were assessed by a visually impaired cane user and five unimpaired subjects in a practical test.

Future work will focus on more advanced data analysis and feature extraction to increase the reliability of the augmented white cane in unstructured environments and extract further features which are helpful for navigation. Further, psychophysical studies with impaired and unimpaired subjects will be performed to evaluate the potential of haptics as a communication channel in assistive devices. These psychophysical studies will be conducted to assess if users can easily extract the distance information represented by the vibrotactile patterns. Navigation performance using our prototype and a conventional cane will be compared. Further, we will question user to determine the acceptance of this novel concept.

VII. Acknowledgments

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