Advanced Augmented White Cane with Obstacle Height and Distance Feedback

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***Abstract*—The white cane is a widely used mobility aid that helps visually impaired people navigate the surroundings. While it reliably and intuitively extends the detection range of ground-level obstacles and drop-offs to about 1.2 m, it lacks the ability to detect trunk and head-level obstacles. Electronic Travel Aids (ETAs) have been proposed to overcome these limitations, but have found minimal adoption due to limitations such as low information content and low reliability thereof. Although existing ETAs extend the sensing range beyond that of the conventional white cane, most of them do not detect head-level obstacles and drop-offs, nor can they identify the vertical extent of obstacles. Furthermore, some ETAs work independent of the white cane, and thus reliable detection of surface textures and drop-offs is not provided. This paper introduces a novel ETA, the Advanced Augmented White Cane, which detects obstacles at four vertical levels and provides multi-sensory feedback. We evaluated the device in five blindfolded subjects through reaction time measurements following the detection of an obstacle, as well as through the reliability of drop-off detection. The results showed that our aid could help the user successfully detect an obstacle and identify its height, with an average reaction time of 410 msec. Drop-offs were reliably detected with an intraclass correlation > 0.95. This work is a first step towards a low-cost ETA to complement the functionality of the conventional white cane.**

Keywords—Electronic Travel Aid (ETA), ultrasonic sensor, infrared sensor, vibrotactile display, head-level obstacle, drop-off detection

I. INTRODUCTION

Currently, about 314 million people worldwide suffer from visual disabilities [1]. One of the greatest challenges that visually impaired people face in their daily life is navigating in unknown environments. The conventional white cane is a common tool that blind and visually impaired people use to independently navigate and detect obstacles at the leg level. The main strengths of the white cane compared to other types of assistance such as a guide dog are its simplicity, low cost, important signaling effect as well as the direct physical interaction with surroundings. However, the conventional white cane also suffers from several limitations: it has a short sensing range and cannot detect obstacles above the ground level such as hanging objects at the head or trunk level, which are frequent causes of injuries. According to a survey by Manduchi and Kurniawan [2], 13% of 307 visually impaired participants experienced head level injuries during navigation more than once per month. Twenty-three percent of head injuries required medical attention. Following such accidents, 43% of the cane users changed their walking habits. They raised their arms whenever possible and navigated more slowly to prevent head level collisions [2]. Furthermore, the conventional white cane only transmits direct collisions with obstacles, without any information about approaching obstacles. Similarly, drop-offs are only detected within the reach of the cane. The user may fall if he/she is unprepared and unable to stop before the drop-off. In order to overcome these limitations, Electronic Travel Aids (ETAs) were introduced in the 1970s. ETAs incorporate sensors to extend the obstacle detection range, and inform the user via sensory feedback (e.g. auditory or vibrotactile).

ETAs can be classified into two categories depending on whether they are used in combination with or independent of the conventional white cane. The Miniguide, the Virtual White Cane, and the electronic white cane based on light detection and proximity sensors [3-5] were designed such that they can be used independent of the conventional white cane. They display obstacle information in the direction in which the user points the ETA, but lack the essential functions of the conventional white cane, including the ability to perform semi-active echolocation to probe the environment by tapping the cane tip on the ground. In the case of previously explored paths, white cane users can combine their mental representation of the environment with tactile and auditory information to improve navigation [6]. Hence, ETAs used independently of the conventional white cane may seem less practical, especially when navigating in an unknown environment, as the existing devices do not interact with the ground and may be less robust than the white cane.

On the other hand, many ETAs that attach to or integrate with the white cane have been developed. The HALO system, the

Teletact, the Tom Pouce, the Ultracane, the C-5 Laser Cane, and the iSONIC [7-11] all combine a white cane with proximity sensors and provide haptic or auditory feedback to help the user navigate the surroundings. We previously developed the Augmented White Cane (AWC, [12]), which incorporates two ultrasonic sensors and an infrared sensor mounted on the conventional white cane, and provides feedback to the user via a vibrotactile display. The infrared sensor operates with one of the ultrasonic sensors to detect obstacles in front of the user, and the other ultrasonic sensor is used to detect head level obstacles. However, the AWC along with most of the previous ETAs cannot detect drop-offs nor identify the height level of the obstacles. Early detection of drop-offs is directly related to the safety of users, and it is an important function to overcome one major limitation of the conventional white cane. The Virtual White Cane and the C-5 Laser Cane support drop-off detection, but the evaluation of this function has not been reported [4, 10]. Furthermore, most of the devices do not present information about the vertical location and extent of obstacles. Therefore, we integrated additional sensors into the AWC [12] and implemented an improved obstacle detection algorithm resulting in the Advanced Augmented White Cane (AAWC, Fig. 1).

The AAWC detects obstacles in front of the user over the full vertical range, along with drop-off detection. This is achieved through a combination of three ultrasonic sensors and an infrared sensor. Obstacles can be detected up to a distance of 3.5 m in front of the user, and are indicated via auditory and different patterns of vibrotactile feedback so that the user can extract the distance to an obstacle along with its rough height profile. This paper describes the requirements and presents the design of the AAWC. We further report the obstacle detection algorithm and evaluation of the device, and discuss the limitations of the AAWC along with future developments.

II. System Overview

A. Requirements

The design requirements for the AAWC are mainly related to the functionality of the device. It should be capable of detecting obstacles over the full height of the user with three vertical levels, and also drop-offs. After the detection of obstacles in the walking direction, it should deliver the distance information to the user in an intuitive way such that the cognitive demand for the interpretation is low. The AAWC displays the distance information through a vibrotactile feedback. Auditory feedback, whilst also a valid solution, was avoided for the continuous obstacle feedback, as it could be disturbing for the user and others, and mask auditory feedback from the environment that is crucial for navigation. Auditory feedback is used for the less frequent but more imminently dangerous drop-off alerts. The AAWC should have different operation modes such that the user can change the sensing range to avoid unnecessary feedback: a long range mode for outdoor usage, and a short range mode for indoor usage or in crowded environments. In addition, the user may choose to only receive head-level obstacle and drop-off alerts to limit feedback to imminent dangers (i.e. head and drop-off mode). The device should provide simple feedback during navigation (i.e. sweeping mode), but could transmit more detailed information if the user stops (i.e. scanning mode).

In addition to the functional requirements, the device should be integrated with the white cane to maintain the important features of the latter, such as the direct physical interaction with the environment. Moreover, the robust white cane is necessary in case of malfunction of the electronics or misinterpretation of the ETA feedback by the user. The AAWC should be easily attachable to the white cane to allow independent use of the cane.

The vibrotactile display should be separated from the sensing module to allow flexible placement and assure good contact with the body. Through this separation, the assembly with the white cane becomes easier, as the handle (i.e. the interface between the cane and body) of the white cane does not require modification. The ETA can be mounted on the body of the white cane, and the vibrotactile display can be attached to the handle or even directly to the user's body, depending on the preference of the user.

B. Electronic Components

The AAWC comprises four sensors: three ultrasonic sensors and an infrared sensor. The ultrasonic sensors (srf-05, Devantech, USA) are used to detect the closest obstacle within 3.5 m in front of the user. The infrared sensor (2Y0A710, Sharp, Japan) is used to detect drop-offs. A microcontroller (ATmega 128, Atmel, USA) processes the sensor signals and controls the vibration motors (DMJBRK30CU, Samsung Electro-Mechanics, South Korea) and other electronics along with the buzzer for auditory feedback. The vibration motors encode the obstacle distance information, and the buzzer alerts the user of drop-offs. Three switches are integrated into the system in order to turn the device on and off, and to switch between the different modes. A rechargeable lithium-ion battery is used to power the electronics. Light emitting diodes (LEDs) were used to visualize the sensor values, and a Bluetooth module was integrated to wirelessly stream sensor data to a PC for development and evaluation purposes.

C. Prototype Design

The two modular parts of the AAWC are shown in Fig. 1. The instrumented cane part contains all the sensors and electronics except for the vibration motors. The separate vibrotactile display comprises four vibration motors.

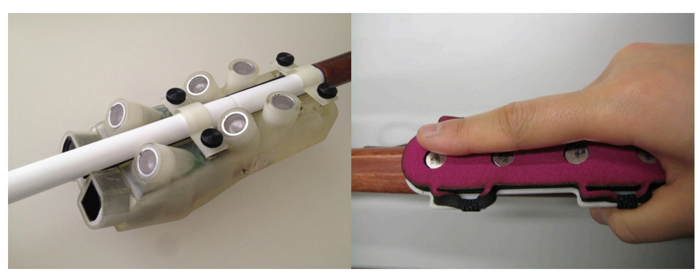

Fig. 1. Instrumented cane (left) and vibrotactile display attached to the cane handle (right).

The instrumented cane part was designed based on the sensor characterization tests performed in a realistic environment in previous work [13]. The optimal angles for the ultrasonic sensors were determined as 38, 58, and 85 degrees with respect to the white cane, and the angle for the infrared sensor was fixed at 27 degrees as shown in Fig. 2. With a cane tilt angle of 43 degrees, drop-offs should be detected approximately 3.2 m in front of the user.

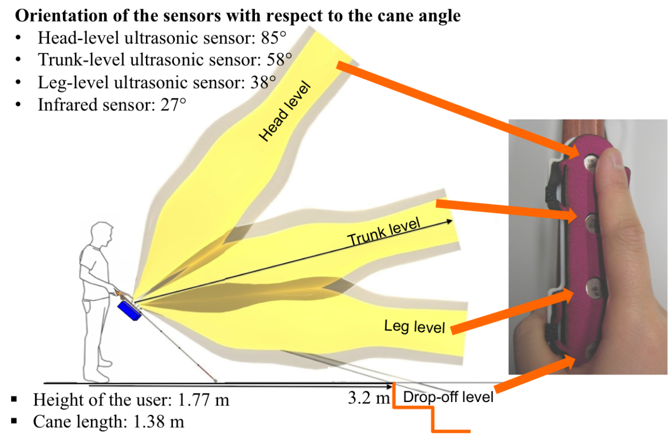

Fig. 2. Optimal sensor arrangement based on a reconstruction of the beam shape of the ultrasonic sensors with respect to a human user [13].

The emitter and receiver of the ultrasonic sensor were separated from each other in order to create space for the cane to be inserted in between and at the same time allow for a compact overall design (see Fig. 1). Furthermore, this concentrates the weight below the cane, and assures that the sensors point upward at all times.

D. Functionalities

The AAWC performs an initial calibration of the infrared sensor at the beginning of each use. When the calibration button is pressed for the first time after turning on the device, it collects 100 data points from the infrared sensor. During the calibration only the infrared sensor is triggered. The data, which depend on the angle between the ground and cane as well as the length of the cane, are averaged to determine the threshold for drop-off detection. This procedure should be performed on flat ground. As the user navigates through the environment, the infrared data are compared with the initial data from the flat surface to detect any change in distance resulting from a drop-off. After the calibration, the ultrasonic sensors are triggered sequentially with 50 msec delay between each sensor to avoid any interference between the ultrasonic waves. The infrared sensor is then triggered again to measure the distance to the ground at the current position. First, feedback from the drop-off detection is given to the user through the buzzer. A drop-off is detected when the three most recent infrared data points are below the threshold for drop-off detection, which indicates that the distance between the sensor and the ground is significantly greater than in the case of a flat surface.

The AAWC has three sensing modes as shown in Fig. 3: a long-range mode, a short-range mode, and a head and drop-off mode. The long-range mode detects obstacles up to a distance of 3.5 m, while the short-range mode limits this distance to 1.5 m, slightly beyond the range of the conventional white cane. The long-range mode and short-range mode are ideal for outdoor and indoor use, respectively. Using the short-range mode would also allow to avoid continuous feedback in crowded environments. All of these modes provide vertical level information. However, the user may select the head and drop-off mode when he/she desires feedback only in case of dangerous situations such as an imminent head-level obstacle or a drop-off. This mode does not provide feedback on trunk-level and leg-level obstacles. Each of the three different modes has two additional feedback modes (i.e. a sweeping and a scanning mode). The sweeping mode is the default mode, and provides feedback of the distance to the closest obstacle in any vertical level. Depending on the distance, four different vibration patterns are generated. The scanning mode is only activated while the scanning trigger button is pressed, the same button used to initialize the calibration in the beginning. It provides independent distance information for the head, trunk, and leg levels as well as for drop-off detection. Each vibration motor corresponds to a height level, and the vibration intensity is inversely proportional to the obstacle distance. After providing vibrotactile feedback according to the selected mode, the sensors are triggered again to collect a new set of data. The sampling frequency was set to 4 Hz.

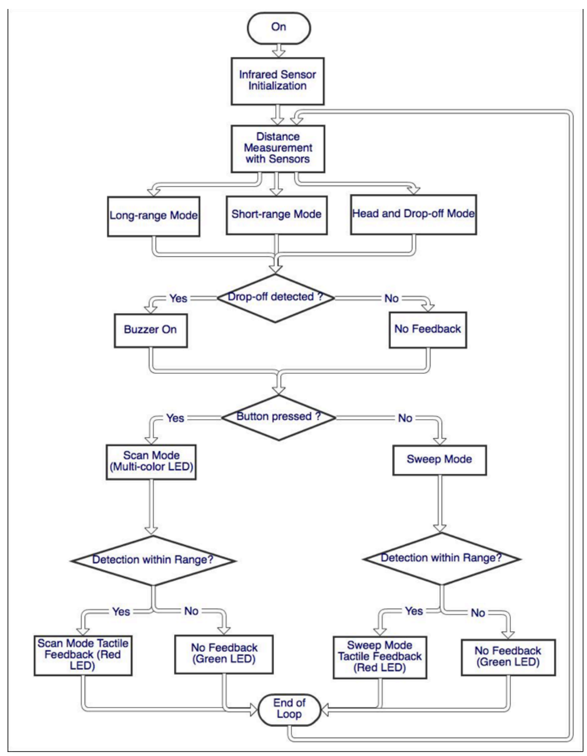

Fig. 3. Flowchart of the AAWC functionalities.

III. EVALUATION

A. Methods

a) Sweep Mode: In order to evaluate the sweep mode, a 2.5 m high and 0.3 m wide obstacle was placed in an open space. The AAWC was pointed in three different directions for data collection. The device was pointed to the right of, to the center of and to the left of the obstacle. For the left and right directions, the sensor detected free space while it correctly detected an obstacle at the center. The measurements were performed at four different distances; i.e. 1.31 m, 2.18 m, 3.06 m, and 4.00 m.

b) Reaction Time: In order to determine the reaction time of the user to the haptic feedback, the elapsed time from the detection of an obstacle by the ultrasonic sensor to the user's reaction to the feedback was measured. A stack of boxes with 1.5 m height and 0.3 m width was placed as an obstacle. The green LED was turned on when the sensor was triggered, and the red LED was lit when the user pressed a switch. Five-sighted subjects were instructed to sweep the device naturally. While they performed constant sweeping movements, the power switch was randomly turned on. Before the evaluation, they were blindfolded and wore earphones with music in order to prevent them from hearing the power switch click. As soon as the subjects started to feel the haptic feedback, they were asked to press the switch to turn on the red LED. The elapsed time between the activation of the green LED and the red LED was recorded by a video camera. The experiment was also filmed with a second video camera in front of the subjects to determine the sweeping frequency. Ten sweeps were measured and averaged for each subject.

2) Height Levels: To evaluate if the device can successfully detect obstacles at different height levels, three experiments were performed. For head-level detection, a sheet of paper was attached to the top sill of a door, and data were collected with the distance between the cane tip and the door fixed at 30 cm (Fig. 4). Head level obstacle detection was evaluated in the sweeping mode. For the trunk and leg levels, the scanning mode was used to evaluate the system, and a trashcan and stone bench were used as obstacles (Fig. 4).

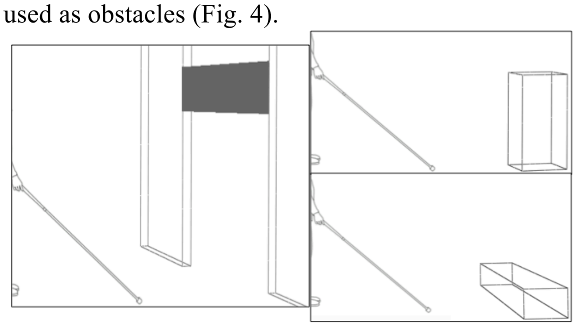

Fig. 4. Head-level (left), trunk-level (right-top), and leg-level (right-bottom) obstacle detection evaluation set-up; a sheet of paper, a trashcan and a stone bench were used as obstacles, respectively.

a) Ascending Stairs: The detection of ascending stairs was evaluated at various distances. The distance information was collected and compared in order to verify if the device can differentiate ascending stairs from tall obstacles.

3) Descending Stairs: To demonstrate the detection of drop-offs with the device, infrared sensor data was collected while walking straight toward descending stairs without sweeping the cane. Disparities between the new infrared sensor data and the initial data on the flat surface were plotted over time.

4) Drop-off Detection Reliability: In order to assess the reliability of the drop-off detection, eight sighted subjects (three females and five males) performed ten trials of approaching a drop-off (i.e. descending stairs) by walking along a straight line in two conditions: with and without sweeping movements of the cane. The average height of subjects was 174.69 ± 9.53 cm, and the mean tilt angle (angle between the cane and ground) was $39.63 \pm 3.76°$. The angle between the cane and the infrared sensor was approximately 25°.

The subjects held the cane, as they would during sweeping, and initialized the device on a flat surface to calibrate the infrared sensor, confirmed by a short beeping sound. Then, subjects were instructed to walk straight towards the drop-off by following a straight line drawn on the ground (without blindfold). When the sensor detected the drop-off, the ETA presented a beep sound along with haptic feedback. The subjects were instructed to stop when they received the feedback. The distance between the tip of the cane and the drop-off was measured. For the walking without sweeping trials, subjects were allowed to move back and forth to find the exact position where the drop-off was initially detected.

B. Results

1) Sweep Mode: The distance to the obstacle measured by the three ultrasonic sensors while sweeping to the center of the obstacle, are presented in Table I. For an obstacle at 131 cm distance, all three sensors returned similar values. At a distance of 306 cm, the head level sensor could not detect the obstacle anymore. When the device was pointed to the right of and to the left of the obstacle, all sensor readings were greater than 5 m, indicating that no obstacle was detected.

TABLE I. SWEEPING MODE DETECTION AT THE CENTER OF THE OBSTACLE

Distance (cm)	**Effective Distance to Obstacle**		
	From Head-level Ultrasonic Sensor (cm)	**From Trunk-level Ultrasonic Sensor (cm)**	**From Leg-level Ultrasonic Sensor (cm)**
131	128.35	124.58	121.79
218	349.67	212.14	232.70
306	532.00	295.46	386.48
400	532.00	404.60	385.02

2) Reaction Time: The average reaction time of the five subjects was 410 ms (Table II). The average of the reaction time to sweeping time ratio was 26.07% with a standard deviation of 9.94%.

TABLE II. REACTION TIME RESULT

Subject	Sweep period (sec)	Reaction time (msec)	Reaction time to sweeping time ratio (%)
1	2.31	303.33	13.11
2	1.31	511.11	38.92
3	1.57	400.00	25.48
4	1.41	396.67	28.07
5	1.27	443.33	34.91
Average ± SD	1.58 ± 0.43	410.89 ± 75.81	26.07 ± 9.94

3) Height Levels: The distance measured by the ultrasonic sensors for head-, trunk-, and leg-level obstacles are reported in Table III. The head-level sensor successfully detected the head-level obstacle, i.e. the paper attached to the doorway, while the other sensors detected the next closest obstacle (i.e. a wall outside the doorway). For the trunk-level obstacle, the head-level sensor detected the wall behind the trashcan, and the trunk- and leg-level sensors detected the obstacle. At the leg-level, only the leg-level ultrasonic sensor detected an obstacle.

TABLE III. HEAD LEVEL, TRUNK LEVEL AND LEG LEVEL OBSTACLE MEASURED BY ULTRASONIC SENSORS

Sensor	Head-level Obstacle: Distance (cm)	Trunk-level Obstacle: Distance (cm)	Leg-level Obstacle: Distance (cm)
Head-level	131.09	198.00	532.00
Trunk-level	218.30	125.00	520.16
Leg-level	263.74	122.00	280.23

4) Ascending Stairs: To examine the device behavior in front of ascending stairs, sensor measurement were performed at a distance of 140 cm, 200 cm, 260 cm, and 320 cm from the stairs (Table IV). When the user was close to the stairs, e.g. 140 cm from the sensors to the stairs, the trunk-level and leg-level distance indicated a difference of 24.63 cm, while the other distance measurements showed only small differences.

TABLE IV. ASCENDING STAIR DETECTION ACCURACY RESULT

Effective Distance (cm)	Measured Distance for Head-level (cm)	Measured Distance for Trunk-level (cm)	Measured Distance for Leg-level (cm)
140	502.48	203.75	179.12
200	532.00	240.61	235.89
260	532.00	293.56	287.11
320	532.00	354.09	346.76

5) Descending Stairs: To illustrate the behavior of the infrared sensor for drop-off detection, the change in distance between the infrared sensor and the ground while walking on a flat surface towards the drop-off was measured. The calibration value was subtracted from the current distance value to detect the drop-off (Fig. 5). During the first 8 s, the infrared sensor detected a flat surface, and fluctuated within a range of about 190 cm change in distance, which is set as the threshold in order to alert the user. This threshold corresponds to approximately 52 cm drop-off depth. When the sensor detected the descending stairs, the change in distance increased dramatically to 467 cm.

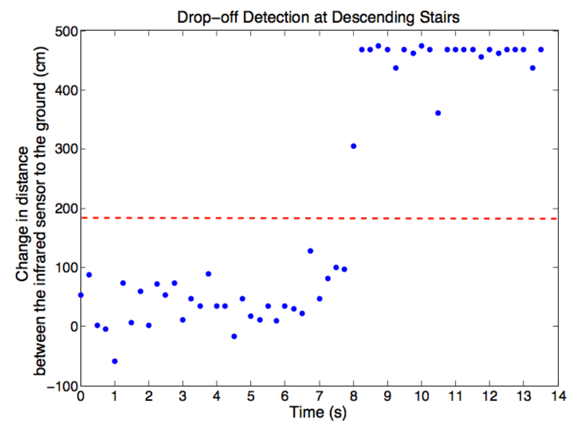

Fig. 5. Change in distance from the infrared sensor to the ground. Data were acquired while walking on a flat surface towards a descending staircase.

6) Drop-off Detection Reliability: The mean distance from the cane tip to the stairs was 1.02 m (SD: 0.20 m) and that from the subjects' heel to the stair 2.29 m (SD: 0. 27m) for trials without sweeping. During the trials with sweeping motion, the drop-off was detected later than in the prior condition. The distance between the cane tip and the stair was 0.83 m (SD: 0. 24m) and that between the heel and the stair was 2.09 m (SD: 0.31 m). Drop-off detection reliability was assessed through the intra-class correlation coefficient (ICC) calculated with IBM SPSS Statistics 19 (IBM Corporation, USA). The ICC is a quantitative rating to evaluate how much measurements correspond to each other within a group. An ICC of 0.984 and 0.976 was found for the distance between the cane tip and the stairs in the no-sweeping and sweeping conditions, respectively.

IV. DISCUSSION AND CONCLUSIONS

We developed and evaluated a prototype of a new ETA, the AAWC, comprising three ultrasonic sensors to detect obstacles at different height levels, i.e. head, trunk and leg-level, as well as an infrared sensor for drop-off detection. The sweeping function was validated by pointing to the right of, the center of, and the left of an obstacle at different distances. The head, trunk, and leg-level detection were tested with different types of obstacles. For trunk and leg-level obstacles, the scanning function was operated. All the measurement corresponded to the expected distance values.

Also, the highest percentage of the reaction time to sweeping time ratio, 38.92 %, indicates that the users were able to respond to the haptic feedback before they finished the next half-sweep after a sensor detected an obstacle.

Sensor measurements were also performed at ascending stairs and descending stairs. For the ascending stairs, the sensor data did not show distinct distance information. Thus, the AAWC was not able to distinguish ascending stairs from tall obstacles. In the case of descending stairs, the change in distance between the infrared sensor and the ground was acquired by walking on a flat surface towards the descending stairs. The change in distance varied below the threshold while walking on the flat surface, and then exceeded the threshold significantly before the drop-off.

We further investigated the reliability of the ETA in detecting drop-offs. The distance between the drop-off and the cane tip was influenced by the user's height, the tilt angle, the stride, walking speed, sweeping range, and the reaction time. This was also reflected in the different calibration values of the infrared sensor for each subject. The ICC for both experimental cases of the test were above 0.97, indicating reliable detection.

Though most of the evaluation of the device was successful, several limitations were identified, some of which can be indicated to the user and others requiring correction in a future version. Although the wide sensing field of the ultrasonic sensor could be an advantage in terms of obstacle detection, it could be problematic in narrow hallways. The sensor could detect the walls due to the wide field, and the vibrotacile display would constantly give wrong feedback to the user.

A major drawback of the infrared sensor is false drop-off detection in the case of reflective surfaces. Also, the sensor is sensitive to the light conditions in the environment, and the sensitivity to drop-offs can vary if the luminance in the environment changes. Therefore, further investigations on the sensor behavior for different types and colors of material and luminance levels should be performed to fully understand the behavior of the sensor. Possibly another sensor such as a brightness sensor to detect the luminance of the surroundings should be added to make the drop-off detection more reliable. Also, an ultrasonic sensor with narrow angle beam could replace the infrared sensor, which suffers from the reflective surface.

In the case of an inclined upward road, the distance between the infrared sensor and the ground increases and the tilt angle between the cane and the ground decreases, resulting in the infrared sensor pointing upwards and false drop-off detection. This could be resolved by including an accelerometer in the cane to detect changes in the vertical orientation of the cane.

The drop-off detection is also highly dependent on where and how the device was calibrated. When the tilt angle changes slightly, the distance between the infrared sensor and the ground may change significantly, and false alerts may occur. Therefore, the current prototype is implemented with an alert threshold of approximately 190 cm if the tilt angle is at 43 degrees. This reduces false alerts caused by small changes of the tilt angle; however, small dips or drop-offs are not detected. Therefore, further investigations are required to derive methods to compensate for the inherent drawbacks of the sensors and possibly detect smaller drop-offs.

While the battery operation time was not evaluated, an estimation based on the power requirements of the individual electronic components indicated in the datasheets points to a continuous (i.e. minimal) operation time of 37h. To evaluate this aspect and the functionalities of the AAWC in daily use, an in-depth evaluation with visually impaired people must be performed, which is the focus of future work.

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