# ’SMART’ CANE FOR THE VISUALLY IMPAIRED: DESIGN AND CONTROLLED FIELD TESTING OF AN AFFORDABLE OBSTACLE DETECTION SYSTEM

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**SUMMARY**

Visually challenged persons face great difficulty in independent mobility and use the white cane as a mobility aid to detect close-by obstacles on the ground. However, the cane has two major limitations:

- It can only detect obstacles up to knee-level. Hence, the user cannot detect raised obstacles like elevated bars and frequently collides with them.
- The cane can only detect obstacles within 1m from the user. Also, obstacles like moving vehicles cannot be detected until dangerously close to the person.

Almost 90% of the blind persons live in developing countries, with a majority below poverty line [1]. Current devices available internationally are unaffordable. In this work we present the design and usability features of a low-cost knee-above obstacle detection system and report results from controlled field experiments.

**Approach**

- Use of directional ultrasound based ranging to enhance the horizontal and vertical range of the cane. System designed for ease of use at an affordable cost.
- To assess reduction in collision-risk and improvement in personal safety with the unit, controlled trials with 28 users was performed.

**System Design**

A light weight, detachable unit comprising of an ultrasonic ranger and vibrator was developed which offers an increased range of 3m and detects obstacles above knee-level. Distance information is conveyed to the user through vibratory patterns that vary incrementally with changing obstacle distance. The projected cost of the device is **under 35 USD** making it affordable for users in developing countries. The initial prototype and design was discussed in an earlier publication [2,8].

**Field Experiments**

In controlled trials, 28 users underwent training in device usage and then negotiated 4 obstacle courses (randomized: two using the device and two with the white cane. The following metrics were studied: (i) **Obstacle Awareness**, (ii) **Collision rate** and (iii) **Distance** at which each obstacle is detected.

Smart Cane usage increased obstacle awareness by 57%, decreased obstacle collision-rate by 91% and increased the mean distance of detection by 2.6 folds and hence improved safe mobility for the blind users. Two users using the device for three months reported successful detection of railings, raised bars, raised sides of trucks and presence of a gate, people, trees etc.

**Conclusions**

We have devised an affordable obstacle detection system to improve independent mobility for the visually challenged. User feedback has been positive from field experiments and suggests applicability in real life scenarios.

**Key Words:** Visually impaired; obstacle-detection; mobility; way-finding; Smart Cane

## PURPOSE OF THE STUDY

Safe mobility is among the greatest challenges faced by the visually challenged in day-to-day life. They use the white cane as a mobility aid to detect close-by obstacles on the ground. However, the white cane has two major shortcomings:

- The cane can only detect obstacles up to knee-level. Hence, the user **cannot detect raised obstacles** like protruding windows, scaffoldings and portable ladders and frequently collides with them.
- The cane can only detect obstacles **less than 1m**, giving them little time to take any preventive actions. Additionally, obstacles like moving vehicles cannot be detected until dangerously close to the person.

To ameliorate the problem, researchers have developed Electronic Travel Aids (ETA) to enhance obstacle detection. However, they possess limitations that have restricted their wide-spread acceptance amongst the visually impaired. The K-Sonar gives the output in the form of auditory cues which mask other important environmental sounds e.g. sound of moving vehicles on road and of fellow pedestrians [3]. Mini-Guide is a vibration feedback based obstacle detection system but cannot be attached to the white cane, resulting in occupation of both hands [4]. Laser Cane, apart from being prohibitively expensive also requires consistent movement of the user to comprehend the small cone of obstacle detection [5]. The Ultra Cane transmits the vibration feedback through two buttons, forcing the user to modify their grip [6]. Present day systems available internationally cost more than 450 USD. WHO estimates show that there are 45 million blind people in the world of which 90% live in developing countries [1] where such devices are unaffordable. India has 13 million visually challenged persons (largest for any country in the world), with a vast majority with no access to an affordable and effective mobility aid.

*Hence, there is a need for a knee-above obstacle detection and warning system with a user-friendly design, available at an affordable cost to users in low-income countries who presently have very limited access to electronic navigation aids.*

Additionally, research and user experience regarding ETAs reported in the literature highlights the difficulty in demonstrating their effectiveness in enhancing safe mobility [7]. The complication arises in formulating realistic, practical and objective experiments that (i) capture the complexity of navigation in the unstructured real-word, (ii) incorporate feedback for a representative use group and (iii) provide a quantitative measure for improvement in mobility.

*Hence, once a novel mobility is developed, there is a need for formal controlled trials to assess improvement in mobility encompassing (i) realistic use cases, (ii) assimilating experience from a representative user group and (iii) providing a quantitative measure for performance improvement.*

<u>The twin aims of this project are:</u>

- To develop an **affordable knee-above obstacle-detection and warning system** for the visually impaired employing ultrasound based ranging to enhance the horizontal and vertical range of the cane.
- To conduct a **controlled trial** with 28 visually challenged users on 4 randomized obstacle courses, quantitatively assessing the improvement in personal safety with the Smart Cane employing the following metrics: (i) obstacle awareness (perception), (ii) obstacle collision-rate and (iii) distance of obstacle detection.

## MATERIALS AND METHODS

### 1. System Description

We developed a novel navigation aid called the Smart Cane that detects hazardous raised obstacles and increases detection range to 3m, thereby improving safety for the blind user. Initial design and implementation details were presented in [2, 8]. Next, we summarize the key design and usability features of the device.

The Smart Cane employs directional ultrasound based ranging to detect obstacles in front or above knee-height within a range of 3m. Distance information is conveyed through patterns of vibration that vary incrementally with changing obstacle distance; hence the Smart Cane can also be used by deaf-blind individuals.

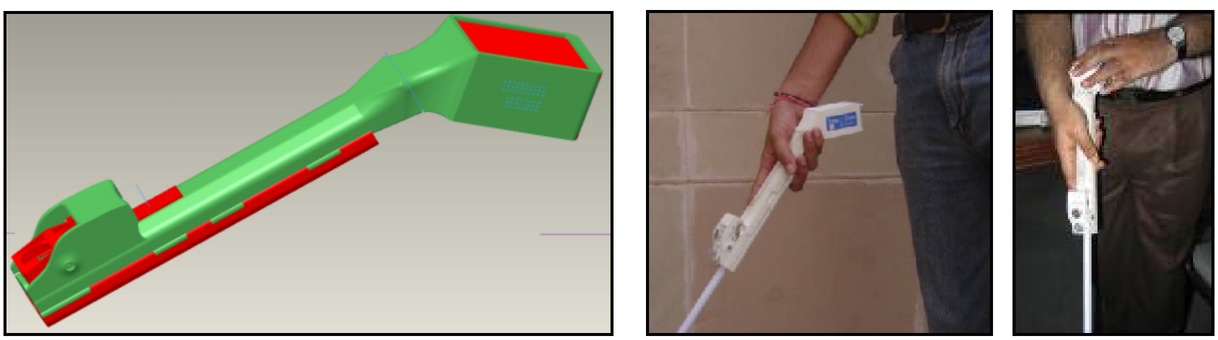


**Figure 1: Smart Cane CAD model (left) and close-up view of the device being used by volunteers.**

The device operates in two user-selectable modes: (i) *Short Range Mode (<1m)*: Useful while navigating within a room and (ii) *Long Range Mode (<3m):* Used outdoors e.g. roads, parks etc. Detection and warning of fast-approaching obstacles, like vehicles, within 3m allowing time for a reflex action instead of being hit unwarned.

The system is powered by rechargeable Li-ion battery which can be charged like a cell phone. This eliminates the inconvenience of opening the battery pack to replace batteries and dependence on others to procure batteries from a store. Once fully charged, the batteries last at least 4 days of device usage after which a recharge is indicated through a beep pattern.

The system is designed as a detachable unit that a user can mount on his/her white cane. It complements and enhances the functionality of the traditional cane. The device is user-detachable, light-weight and possesses Braille markings. An ergonomic design allows the user to hold the Smart Cane with a variety of personalized grips.

A crucial design objective was cost. The device employs innovative use of low-cost and mass produced electronic components manufactured in a durable yet inexpensive plastic material. The projected cost of the device is under 35 USD making it affordable for users in developing countries.

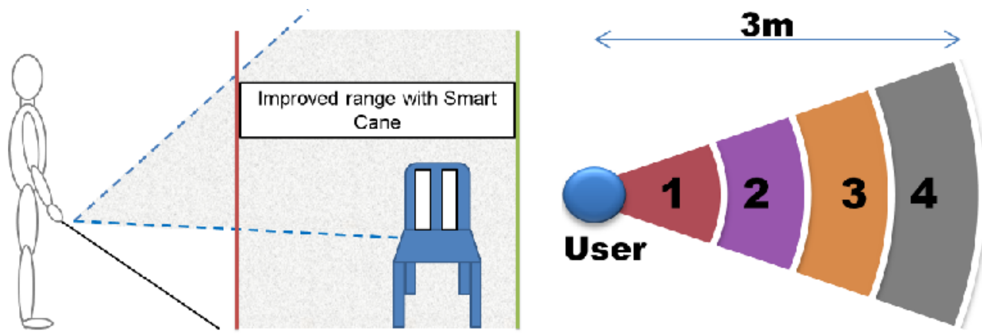



**Figure 2: (a) Detection of knee-above obstacles and increase in detection range with the Smart Cane. (The red and green lines compare the typical range of normal cane and Smart Cane, respectively. The dotted lines illustrate the detection cone of the ultrasonic transducer.) (b) Top view of detection cone showing the horizontal and angular coverage.**

**(a)** **(b)**

**Figure 3: Smart Cane utility (a) detection of the raised side of a truck and (c) finding a clear path without colliding with randomly positioned observers.**

## 2. Controlled Trials

To quantitatively assess reduction in collision-risk and improvement in personal safety with the Smart Cane, a controlled trial was conducted with 28 users on 4 artificial obstacle courses to test reliable detection of commonly encountered obstacles. Users were enrolled from varied backgrounds (age, gender, experience in cane usage etc.) and were given standardized training in Smart Cane usage. During experiments, users negotiated two obstacle courses with the traditional cane and two others with the Smart Cane. The experiment design is discussed in the subsequent sub-sections.

*2.1 Experiment Site*

Experiments were conducted in a corridor (17m x 4m) with 14 laid out obstacles commonly encountered obstacles in indoor and outdoor environments. Seven obstacles were perceptible with the traditional cane (e.g. flower pots, chairs, ladder, card-board boxes) and the remaining were knee-above obstacles (e.g., railing, horizontal bars, table edge, inclined ladder, elevated bar) that are difficult to detect using the traditional cane. Four different courses were created by randomizing the obstacle positions. This eliminates the effect of spatial map learning by the users during the trial. The obstacle course area was regularly tiled. This allowed (a) determination of obstacle detection distance and (b) accurate positioning of obstacles during multiple runs for different users.

*2.2 User Enrolment*

Twenty eight visually challenged cane users were enrolled in the trials from 5 blind schools and associations in New Delhi. There were 20 male and 8 female cane-users from an age group of 10-35 years with experience in white-cane usage varying between 1-25 years. All the volunteers consented to participate in the trials. Figure 4 illustrates the composition of users according to age and number of years of cane usage. Please note that an ideal trial necessitates stratified random sampling with equal number of users within each age and gender group. However, this was not possible due to practical issues. We found that male volunteers aged between 20-25 years were most willing to visit the controlled trial site and participate in the experiment. Also, organizations were less willing to allow female volunteers to participate in the trial, probably due to the need to travel to the site or other cultural reasons.

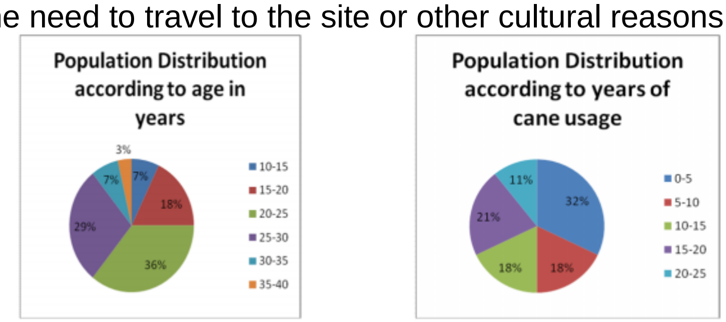



**Figure 4: Background of users enrolled in controlled trials.**

*2.3 Training in Smart Cane Usage*

Volunteers were trained in Smart Cane usage for three consecutive days (two hours per day). The first day introduced the Smart Cane and focussed on understanding the following: (a) *Form:* shape, structure, location of buttons, sensor etc. (b) *Operations:* Switching the device on, familiarization with varying vibratory patterns (c) *Additional Features:* Mode selection and adjustment of sensor orientation (d) *Usability:* Walking towards obstacles like walls, chairs, people in the immediate surroundings. The training sessions were conducted on consecutive days to ensure retention and accurate learning.

The second day began with a revision of the vibratory patterns and their correlation with obstacle distance. The session proceeded in a *learn-and-test* manner. Six objects (a minimum of three knee-above obstacles) were identified and the user was requested to walk towards the obstacle till they registered a change in the perceived vibratory pattern. This was reinforced by (a) repeatedly walking towards and then walking away from the obstacle and (b) a practice exercise in which the trainer positioned himself/herself at a random distance in front of the user and the user was asked to infer the distance from the vibratory patterns. The detection of knee-above obstacles was particularly challenging for the users as such an obstacle induces a distance-correlated vibratory pattern in the device but remains undetectable with the tip of the white cane. Perception without physical contact was a novel experience for the blind person and required special emphasis during training. Additionally, users were trained to actively turn the sensor left and right for scanning the presence of obstacles in any desired direction while ambulating.

In the final session, volunteers employed the device for navigation in common indoor and outdoor environments. This provided a refinement period for the user to internalize the vibratory information complimenting the tapping action with the cane.

*2.4 Trial Phase*

The test phase involved users negotiating two obstacle courses with their own white cane and two others with the Smart Cane. Initially, the users were positioned at a starting location and were asked to walk forward, encountering obstacles, till they reached a wall at the end of the course. The experimentation area had regular tiles which allowed the determination of distance of obstacle detection. The user's movement was videotaped and analyzed later to generate an observation table. The training concluded with an interaction session in which the users shared their views on the utility, merits, demerits, ease of learning and further improvements for the device.

*2.5 Key Performance Indicators*

To compare the Smart cane performance over the baseline performance with the traditional cane the following performance indicators were studied:

- **Obstacle Awareness:** Proportion of the obstacles on the experimental course detected by the blind user. A higher number indicates increased awareness (perception) of the environment while navigating.
- **Collision rate:** Proportion of obstacle-collisions per number of obstacles encountered. A lower collision rate indicates increased safety for the user.
- **Distance of obstacle detection:** Detection of a majority of the obstacles at larger distances indicates greater safety for the blind user by providing time to take corrective action without coming in physical contact.

For performance indicators listed above, the terms *obstacle detection* and *obstacle collision* are formalized as follows. Considering the traditional cane, an obstacle is considered *detected* if the user comes in contact with it either through the cane (generally for low lying obstacles), the upper portion of the cane or the user's body (for raised obstacles). Unexpected obstacle detections characterized by a sudden precautionary action by the user are considered *collisions*. The definitions are analogous for the Smart Cane with the exception that obstacles can be *detected* through vibrations without physical contact with the cane portrayed through an obstacle avoidance behavior by the user.

## RESULTS

### 1. Increase in Obstacle Awareness

Table 1 compares obstacle-awareness for the Smart Cane and the traditional cane. The Smart Cane increases obstacle awareness by 57.2 ± 4.1% thereby giving a wider perception of the environment while navigating. For knee-above obstacles, obstacle-awareness increases considerably by 73.5 ± 4.95%, emphasizing the significant advantage of the Smart Cane in detecting elevated obstacles.

Please note that all reported numerical results are averaged for 28 users. The p-values were less than 0.0001 for all hypotheses implying greater than 99.99% confidence. Since the same users tested the traditional cane and the smart cane, pair wise t-test was employed for computing p-values.

| | **Normal Cane** | **Smart Cane** | **Percentage increase in obstacle awareness** |
|---|---|---|---|
| All obstacles | 28.2 ± 1.8 % | 65.9 ± 2.3 % | 57.2 ± 4.1 % |
| Knee-above obstacles | 20.0 ± 2.25 % | 75.6 ± 2.7 % | 73.5 ± 4.95 % |

**Table 1: Percentage of Obstacle course perceived**

### 2. Reduction in Collision Rate

Using the traditional cane, the users collided with 40.4 ± 2.8% obstacles on an average, compared to the 63.3 ± 3.9% collisions in the case of knee-above obstacles which are difficult to detect with the white cane. The Smart Cane reduced the collision rate to only 3.4 ± 0.9% (considering all obstacles), a drastic reduction of 91.6 ± 3.7%.

For knee-above obstacles the collision rate declined by 91.8 ± 5.3% to 5.2 ± 1.4% thereby lowering the injury risk significantly and improving the safety. As discussed in the section detailing user training, learning the detection of raised obstacles with the Smart Cane, characterized by perceived vibrations without physical contact with the cane, was particularly challenging for the users and needed special emphasis during training. This could possibly be a factor for the higher collision rate observed for knee-above obstacles and can potentially be lowered by an improved training methodology.

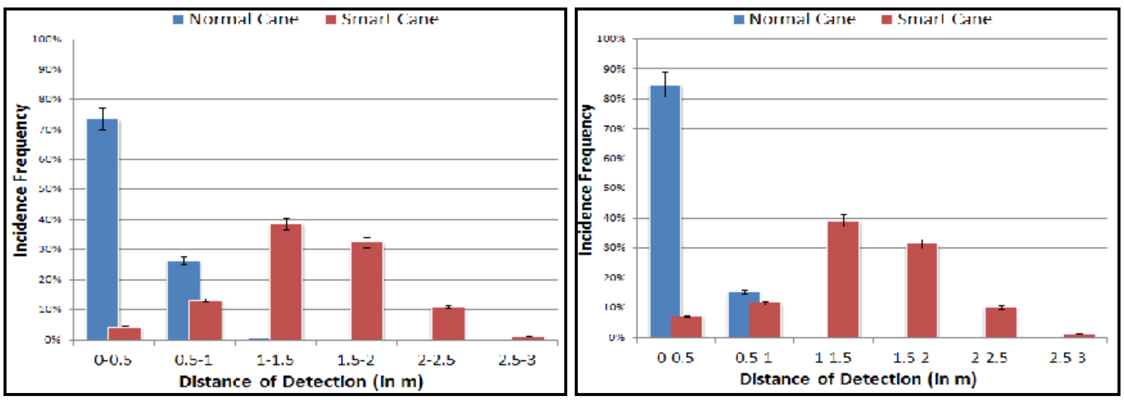
| | **Normal Cane** | **Smart Cane** | **Percentage reduction in collision rate** |
|---|---|---|---|
| All obstacles | 40.4 ± 2.8 % | 3.4 ± 0.9 % | 91.6 ± 3.7 % |
| Knee-above obstacles | 63.3 ± 3.9 % | 5.2 ± 1.4 % | 91.8 ± 5.3 % |

**Table 2: Collision Rate (Number of Collisions per detections)**

### 3. Obstacle Detection distance

Figure 5 illustrates the percentage distribution of distances at which obstacles were detected by the visually challenged users. The limited range of the traditional cane leads to a lower mean distance of obstacle detection 0.39 ± 0.18m, see Table 3. Overall, 72% of all obstacles and 84% of all knee-above obstacles are detected within a close range of 0.5m from the user (Figure 5a).

The Smart cane significantly increased the average of obstacle detection distances to 1.41 ± 0.25 m (a 2.61 fold improvement). The incidence of collisions with raised obstacles declined significantly from 63% to 5.2%. A significant majority of obstacles (81%) were detected at a safe distance of more than 1m (Figure 5b). Hence, the user becomes aware of an obstacle much before colliding with it and gets enough time to avoid it.




**(a)** **(b)**

**Figure 5: Histograms illustrating distance of obstacle detection with the traditional cane (blue) and the Smart Cane (red) (a) Distribution considering all obstacles and (b) considering only knee-above obstacles.**

| | Normal Cane (in meters) | Smart Cane (in meters) | Percentage increase in mean distance of detection |
|---|---|---|---|
| All obstacles | 0.39 ± 0.18 | 1.41 ± 0.25 | 261.5 ± 0.43 % |
| Knee-above obstacles | 0.33 ± 0.09 | 1.38 ± 0.30 | 318.2 ± 0.39 % |

**Table 3: Mean distance of obstacle detection**

### 4. Other Observations on Smart Cane Usage

The time duration for course completion was longer for the Smart Cane compared to the traditional cane. Observers noticed that on some occasions, users felt very surprised to detect an obstacle through vibrations without a physical contact with the cane. Hence, they took longer to internalize the *new* sensory channel through vibrations. In a small number of cases, users did not register a change in the vibration patterns and collided with the obstacle. Subsequently, the users paid greater attention to the changing vibratory patterns and were able to successfully negotiate obstacles. As the experiment progressed, users became more confident and frequently pointed the device to the left or right to obtain obstacle distance. In these experiments, users received only 6 hours of training. With long term use, users should be able to negotiate obstacles more naturally as they would become more accustomed to the new information channel.

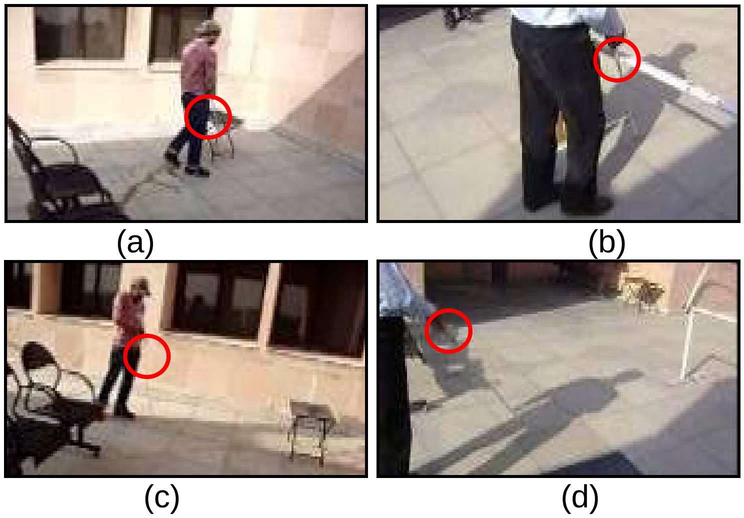


**Figure 6: Detection of Knee above obstacles. With the traditional cane the user collided with the (a) raised Iron stool and (b) railing (*circled in red*). The Smart Cane detected both the obstacles from a distance of 2m (c and d) allowing the user to find a clear path without colliding.**

During the experiment, users were asked to walk forward, negotiating the course, from the starting position and not given an explicit reference like a continuous wall. On a few rare occasions, users did not maintain the forward direction of movement while moving and went on a sideways trajectory and hence required an auditory cue from the trial coordinator to indicate the target direction.

## 5. Post-experiment User Feedback

After completing trials, users were interviewed about the overall utility and usability of the device. All 28 users believed that the device is useful for day-to-day living. 57.14% perceived Smart Cane as *very easy to learn* with the rest saying that it is *moderate* and none voting for *difficult to learn*. 82% said that the current additional weight of the module was *just right*.

## 6. Special use cases (Indoor navigation and gate detection)

Additional experiments were conducted to assess the indoor mode of operation with a shorter detection range (1m). Blind users were positioned randomly in a medium sized room (typical office workspace) and were asked to navigate without colliding with obstacles. Figure 7a shows a user colliding with the raised edge of a table, the wall and the cupboard while finding his path. Using the Smart Cane (Figure 7b), the person could find a clear path without coming in contact with the obstacles. The user was also able to detect open windows protruding into the walking area in the adjoining corridor. The user walked with the sensor predominantly facing forward to detect raised/protruding obstacles and occasionally tilted the device sideways to re-align along to the wall while moving along the corridor.

A common mobility task for the visually challenged is detection of a gate. This is accomplished by using the cane to tap sideways against the wall while moving alongside till a gap is detected. This approach is challenging as the user must be very close to the wall while moving thereby increasing his chances of colliding with protrusions like open window panes. The device allows the user to detect the presence of a wall by pointing it sideways. The vibratory pattern indicates the wall distance. Once the gate is encountered, a sudden change in the vibration pattern is felt (Figure 8). Note the presence of a letter box close to the wall (Figures 8a and 8b). In the absence of the cane, the user is forced to walk very close to the wall and eventually collides with an obstacle like the letter box standing next to the wall.

**(a)**

**(b)**

**Figure 7: Indoor Navigation Experiment**
**(a) Without the unit mounted on the cane, the user collides with the edge of the table, walls and the cupboard. (b) With the device mounted on the cane the user gets prior warning of the obstacles through vibratory feedback before coming in contact with the obstacle. This information is used to negotiate obstacles.**


**(a) (b) (c) (d)**

**Figure 8: Gate Detection Experiment**
**(a, b) User detects the wall and follows alongside feeling a particular vibratory pattern. (c) Once the gate is encountered, the pattern of vibrations changes to a distant mode. (d) The user realizes the presence of the gate and then enters it.**

## CONCLUSIONS

In this work we presented a novel knee-above obstacle-detection and warning system for the visually impaired to enhance personal mobility for the visually impaired. Formal quantitative controlled trials with 28 users on 4 challenging obstacle courses possessing commonly encountered obstacles demonstrate (a) a 57.2 ± 4.1% increase in obstacle awareness, (b) a 91.6 ± 4.1% reduction in collision-risk and (c) a 2.61 fold increase in the average of obstacle detection distances with the Smart Cane over the traditional cane. An innovative electrical and mechanical design enabled us to keep the projected cost of the device under 35 USD. The system reduces dependence on sighted assistance, improves independent mobility and paves the way for affordable electronic travel aids for the visually challenged particularly in developing countries.

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