Design, Development, and Clinical Evaluation of the Electronic Mobility Cane for Vision Rehabilitation

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***Abstract*—This paper proposes a new electronic mobility cane (EMC) for providing obstacle detection and way-finding assistance to the visually impaired people. The main feature of this cane is that it constructs the logical map of the surrounding environment to deduce the priority information. It provides a simplified representation of the surrounding environment without causing any information overload. It conveys this priority information to the subject by using intuitive vibration, audio or voice feedback. The other novel features of the EMC are staircase detection and nonformal distance scaling scheme. It also provides information about the floor status. It consists of a low power embedded system with ultrasonic sensors and safety indicators. The EMC was subjected to series of clinical evaluations in order to verify its design and to assess its ability to assist the subjects in their daily-life mobility. Clinical evaluations were performed with 16 totally blind and four low vision subjects. All subjects walked controlled and the real-world test environments with the EMC and the traditional white cane. The evaluation results and significant scores of subjective measurements have shown the usefulness of the EMC in vision rehabilitation services.**

***Index Terms*—Electronic travel aid, ultrasonic obstacle detector, vision rehabilitation, visually impaired.**

I. Introduction

VISION is the prime sensory modality among the human senses to gain knowledge about the surrounding world. It provides a feedback mechanism for balanced interaction with the environment and plays a vital role in sensory integration. Vision loss brings a major challenge for living a normal daily life. It can adversely affect one's quality of life in terms of social, psychological, physical and independent performance. According to World Health Organization, there are 285 million visually impaired people worldwide of whom 39 million are blind [1]. Most visually impaired people prefer a long white cane or guide dog as an assistive tool to attend their daily-life mobility activities. A white cane is the most basic, versatile and low maintenance assistive option. Situations that require broad route planning are little difficult to serve with a white cane, as it provides tactile information of things confined to its length [2]. A guide dog is helpful for detecting and avoiding obstacles as well as dangerous situations in the travel path [3]. However, both white cane and guide dog provide short range information and cannot detect overhanging obstructions [4]. A qualitative and quantitative research is being persuaded since last 60 years for the rehabilitation of visually impaired people. Many electronic travel aids (ETAs) are now available for assisting their mobility difficulties. These ETAs provide spatial feedback to the subject via nonvisual senses, primarily hearing and touch [5]. As per guidelines of National Research Council, these ETAs should assist to detect floor-level to head-level obstacles in the travel path, understand travel surface information and deliver information for mental mapping of an environment. These aids should comply ergonomic issues and have minimum interface with the natural sensory channels [6]. Majority of available ETAs are consistent with some of these guidelines. In the following paragraphs, we present a brief review of the existing ETAs.

Laser Cane [7], Teletact [8], and Minitact [9] are laser augmented canes. These canes are useful for detecting floor-level to head-level obstacles in front of them. A subject needs to continuously scan the surrounding environment as these canes use very narrow beam laser devices. The distance measurement in these devices is susceptible to interference due to natural light. Laser cannot detect transparent glass as its beam traverses through the glass without being reflected. Furthermore, the high cost and the significant expertise required to operate these devices is a major concern. Pouce [8] and RecognizeCane [10] refer the augmentation of a cane with infra-red sensors. The applicability of these canes in the outdoor environment is limited due to their infra-red sensors.

K-Sonar Cane [11], Ultracane [12], and GuideCane [13] are ultrasonic sensor augmented canes. K-Sonar Cane uses low-pitch and high pitch sounds to convey the distance of obstacles. It requires good scanning and sound interpretation skills. Ultracane assists to detect floor-level to head-level obstacles in the travel path. These two canes require arching techniques for their systematic usage similar to a traditional white cane. GuideCane is a robotic guiding cane rolled on passive wheels that support its weight while walking. It can detect floor level front-way and sideways obstacles. This cane is large in size and has limited scanning area [6]. CyARM [14], miniguide [6], [15], the sonic torch [16], and kaspa system [17], [18] are echolocation based handhold obstacle detection devices. A user needs to continuously move his/her hand in multi-direction for consistent usage of these devices.

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Navbelt [19], ultrasonic waist-belt [20], and electronic bracelet [21] are wearable assistive aids that are implemented in the shape of belts and bracelet. These aids are limited in detecting floor-level obstacles. Echolocation system for the blind (ESB) uses a phase beamforming approach to perceive the surrounding environment [22]. It is a promising system, but its complexity can be a major concern. Binaural sonar ETA [23] is a small wearable device that can be used for landmark recognition, obstacle motion perception and texture recognition. The field evaluation details of this prototype aid are not provided. A navigation system for the blind [18] is a multisensory system for augmenting blind navigation. The information content of this system is less and it works under the condition of low noise surroundings only.

The vOICe is a video guided assistive system that translates visual information into different sound patterns [24]. The learning curve for these sound patterns is quite steep [6]. The BrainPort vision device uses tongue display unit to assist the subject to navigate around obstacles [25]. It translates visual information acquired from a camera into an electrical stimulation pattern and displays this pattern on the tongue of the subject via a 20×20 electrode array. Clinical evaluation study of this promising device has been scheduled. A stereo vision aid [26] is multisensory system that employs disparity measurement for obstacle detection, and uses motion estimation and inclinometer for overall understanding of surrounding environment. This system is expensive and large in size.

The advent of technology has contributed such several ETAs with their independent advantages in terms of functions, size, shape, and cost. However, a very few ETAs have succeeded to attract potential users. This does not mean that visually impaired people are not interested in technology aids; rather it highlights the need of research to improve their usability and acceptability. Usable functions, user interface and information overload are major concerns for majority of ETAs. Most of the existing ETAs exclusively use variable frequency sound patterns to represent surrounding environment. The learning curve for these sound patterns is quite steep. Most of the ETAs either pass majority of the cognitive and perceptual load to the subject, or they completely relieve him/her from it [4]. Multisensory ETAs are equipped with very good functions, but are too complex to use, large in size, and heavy in weight. Some ETAs are portable and have simple user interface, but they are limited in functions. These ETAs have short detection range and demand continuous scanning of the surrounding environment [27], [28]. This continuous usage and increased perceptual effort may cause tiredness and fatigue [3], [27], [29]. Furthermore, these ETA provide less reaction time, and subsequently demand faster response. Elder visually impaired subjects may find difficulty while using such short range devices [27], [30]. Some ETAs are good in functions as well as in user interface but have inappropriate aesthetics. These above discussed usability issues of ETAs persisted may be because of inadequate communication between ETA developers and the potential users [4].

Therefore, we conducted a survey to determine subjects' requirement and expectations from an ETA. We interviewed 57 visually impaired subjects, their care takers, and rehabilitation professionals. We asked them about their preferred usable functions, user interface, physical interface, carry method, and aesthetic aspects for an ETA. We also asked them about mobility difficulties and suitability of their current aid. These participants expressed diverse requirements from an ETA. However, they showed common agreement on issues namely 1) adequate information of the surrounding environment, 2) simple user interface, 3) cosmetic acceptability, 4) light weight, 5) easy carry method, 6) safety, and 7) cost effectiveness. Amongst subjects 73.68% admitted usefulness of a white cane, but also acknowledged its inadequate information. Of the participants, 28.07% expressed anxiety of collision with above knee-level obstacle or unintended object. Close to 37% participants stated perceptual efforts while using a white cane. Over to 8% subjects reported injuries because of floor plates, metal barricades, and manhole cover. Of the participants, 22.80% experienced slipping resulted accidents on account of wet floor at least once in two months. A total of 59.64% participants preferred augmented cane type of assistive aid for attending their mobility needs. Further, this survey was extended to study the real-world indoor and outdoor environments. We analyzed different types of frequently observed obstacles in these environments and their possible distribution on the travel path.

The limitations of existing ETAs and mobility difficulties of visually impaired subjects motivated us to research into assistive technology. The objective of this research is to develop an ETA that is able to 1) construct a logical map of the surrounding environment, 2) interpret, categorize, and prioritize situation specific details of the environment to reduce the information overload, and 3) simplify representation of the priority information. Addressing limitations of existing ETAs and requirements of visually impaired subjects we developed a novel aid called electronic mobility cane (EMC) at Indian Institute of Technology (IIT) Kharagpur, India. It was named VENUCANE [31]. The EMC has remarkable distinctions to serve the mobility requirements of visually impaired people. It constructs the logical map of the surrounding environment and interprets the distribution of obstacles by relevance of their distances from each other. It simultaneously detect multiple obstructions namely sideway obstacle, front-way obstacle and the information about the floor status without user's additional perceptual effort. It assists to proactively detect ascending staircase, floor-level obstacles, knee-level obstacles, waist-level obstacles, trunk-level obstacles, head-level obstacles, blocked front-way, left turn, right turn, and blocked all-sides situations. It categorizes detected obstacle situations and deduces the priority information from them. It represents the distance of obstacle in terms number of walking steps of the subject and maintains a safety margin distance to negotiate nearby obstacles. It conveys a simplified representation of the perceived information to the subject by using intuitive vibration, audio or voice feedback. The EMC system is available in both wired and wireless mode of operation. The wireless configuration is proposed to further minimize the physical interface of the EMC with the natural sensory channels of the subject. This paper covers design, development, and clinical evaluation of the EMC. Within this we present design in Section II. Implementation and functional assessment of the EMC is described in Section III. Usability study design and clinical evaluation

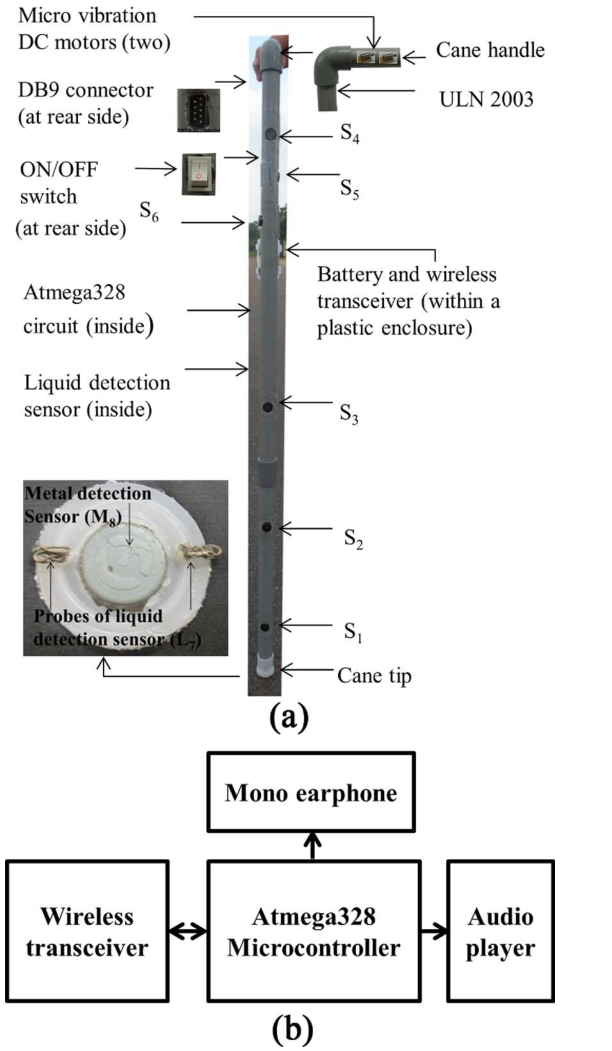

Fig. 1. Completely assembled electronic mobility cane: (a) DADM module showing the placement of system components and (b) CM. Wired and wireless connectivity configurations are available for communication between DADM and CM modules.

are reported in Section IV. Results of clinical evaluation are reported in Section V. Section VI is about discussion and conclusions are drawn in Section VII.

II. Design of the Electronic Mobility Cane

The EMC is a real-time embedded system that provides obstacle detection and way-finding assistance to the visually impaired subject. It consists of six ultrasonic sensors, a liquid detection sensor, a metal detection sensor, wireless transceivers, microcontroller circuits, and a battery for power supply, as shown in Fig. 1. Amongst six ultrasonic sensors, three are wide beam width (S_4, S_5, and S_6) and other three are narrow beam width (S_1, S_2, and S_3) sensors. Of these six sensors, S_1, S_2, S_3, as well as S_4 face toward the front-way and are used to detect the floor-level to head-level obstacles in front of the EMC. The remaining two sensors S_5 as well as S_6 face toward sideways (i.e., leftward and rightward directions) and are applied to detect knee-level to waist-level sideway obstacles. Liquid detection sensor (L_7) and metal detection sensor (M_8) are employed to acquire information about the floor (i.e., whether it is wet, metallic, or both). A novel algorithm named *way-finding with reduced information overload* (WRIO) is proposed in the EMC to control this multisensory system. This algorithm samples the environment information by using above mentioned sensors and constructs the logical map of the surrounding environment. It interprets the distribution of obstacles in the surrounding of size 200 cm $\times$ 400 cm by applying relevance of their distance from each other. This comprehensive logical map is constructed by building two sub-maps for the sideway obstacles and the front-way obstacles, respectively. The sub-map of the sideway obstacles (SMSO) is built by investigating three categories of obstacle situations namely, leftward obstacle, rightward obstacle, and simultaneous presence of both. According to our study of the real-world environments, there can be ten categories of front-way obstacle situations as per their shape and size. These situations are staircase, floor-level obstacles, knee-level obstacles, waist-level obstacles, trunk-level obstacles, head-level obstacles, blocked front-way, simultaneously blocked left-way and front-way, simultaneously blocked right-way and front-way, and blocked all-sides.

The sub-map of the front-way obstacles (SMFO) is made by inquiring these obstacle situations. The distance of some of obstacle situations in the SMFO are represented in terms of number of walking steps of the subject. This scheme is named *nonformal distance scaling* (NFDS). This approach is proposed to provide a simplified understanding of the obstacle distance. The WRIO algorithm maintains a safety margin of 200 cm distance for its front-way obstacle situations. This algorithm interprets SMSO as well as SMFO and shortlists one nearest obstacle situation from each of them. It conveys this shortlisted information to the subject in terms of intuitive vibration, audio, or voice feedback cues. The outputs of L_7 and M_8 sensors are connected to the external interrupts of the microcontroller. This interrupt driven information of the floor status (IFS) assumes highest priority and is conveyed instantly by using a voice message. The audio and voice messages are played by using an audio player that is controlled by the microcontroller. The EMC uses a mono earphone to convey audio and voice feedback to the subject. Obstacle situations detected in the safety region are conveyed by generating strong vibrations (at the handle of the EMC) along with relevant voice messages. These particular features are proposed in the EMC in order to provide a simplified understanding of the surrounding environment to reduce the cognitive as well as perceptual effort of the subject.

1) Construction of Logical Map of the Surrounding Environment: The arrangement of eight sensors in the EMC is resolved based on the general layout of the real-world indoor and outdoor environments. The specific placement of ultrasonic sensors is presented in the Table I. These six ultrasonic sensors are ranged consistently in two groups. Sensors S_1, S_3, and S_5 are in group 1 whereas sensors S_2, S_4, and S_6 are in group 2. Three ultrasonic sensors in each group are ranged simultaneously. These two groups are made according to their positions to reduce the possibility of sensor crosstalk because of simultaneous ranging. The

TABLE I
PLACEMENT DETAILS OF SIX ULTRASONIC SENSORS FIXED ON (INSIDE) ELECTRONIC MOBILITY CANE

Location name*	Sensor's face direction	Height (distance) of sensor from floor (cm)
S_1	front way	8.5
S_2	front way	28
S_3	front way	48
S_4	front way	88
S_5	left sideway	83
S_6	right sideway	78

*S_j = location name of j^{th} ultrasonic sensor

symmetric ranging of these sensors is termed as sensor cycle $\psi(t)$.

The environmental information is sampled twice by executing two consecutive sensor cycles $\psi(t)$ and $\psi(t+1)$. The duration of the two sensor cycles is same, and each of them performs following four operations.

i) Ranging group 1 sensors simultaneously.
ii) Recording range readings of group 1 sensors after a time interval of 100 ms.
iii) Ranging group 2 sensors simultaneously.
iv) Recording range readings of group 2 sensors after a time interval of 100 ms.

After two consecutive sensor cycles the mean distance of the obstacle detected by all six ultrasonic sensors are computed by using

$$ds_j = \frac{ds_{j(t)} + ds_{j(t+1)}}{2} \tag{1}$$

where ds_j is the mean distance of the obstacle detected by the sensor s_j in sensor cycles $\psi(t)$ and $\psi(t+1)$.

The ds_j of each ultrasonic sensor s_j is correlated to construct SMSO and SMFO.

A. Construction of Sub-Map of Sideway Obstacles (SMSO)

This sub-map is built by investigating three categories of obstacle situations namely leftward obstacle, rightward obstacle, and simultaneous presence of both. The resolved obstacle situations are indexed in a virtual table that is stored in the memory of the microcontroller. This virtual table is referred as the SMSO table.

1) Leftward Obstacle Situation: The presence of an obstacle up to 100 cm distance to the cane's leftward direction (i.e., $ds_5 \leq 100$ cm) and absence of an obstacle up to 100 cm to its rightward direction (i.e., $ds_6 > 100$ cm) is considered as *leftward obstacle situation*. This situation is indexed in the SMSO virtual table with the ds_5.

2) Rightward Obstacle Situation: This situation indicates the presence of an obstacle up to 100 cm distance to the right of the cane (i.e., $ds_6 \leq 100$ cm) and absence of an obstacle up to 100 cm to its leftward direction (i.e., $ds_5 > 100$ cm). This situation is indexed in the SMSO virtual table with the ds_6.

3) Simultaneous Presence of Leftward and Rightward Obstacles: This situation is resolved when leftward as well as rightward directions are obstructed up to 100 cm distance (i.e., $ds_5 \leq 100$ cm and $ds_6 \leq 100$ cm) and obstacle is not detected up to 200 cm distance in front of the EMC. This situation is indexed in the SMSO virtual table with the distance $(ds_5+ds_6)/2$.

The entries in the SMSO virtual table are sorted according to their distance from the EMC and the entry with minimum distance is assigned highest rank.

B. Construction of Sub-Map of Front-Way Obstacles (SMFO)

The front-way obstacle situations are classified according to their distance from the EMC. Obstacle situations detected up to 320 cm distance are termed as *alert* situations and that are found between 321 to 400 cm distance are considered as *warning* situations. The *alert* category obstacle situations are ascending staircase, floor-level obstacle, knee-level obstacle, waist-level obstacle, blocked front-way, simultaneously blocked right-way and front-way, simultaneously blocked left-way and front-way, and blocked all-sides. The SMFO is built by investigating both *alert* and *warning* category obstacle situations. The resolved obstacle situations are indexed in a SMFO virtual table.

1) Ascending Staircase Situation: The specific arrangement of four ultrasonic sensors S_1, S_2, S_3, and S_4 is linked with International Residential Code (IRC) for staircase building [32]. The part of the staircase that is stepped on is called tread depth and vertical portion between each tread on the stair is called riser height. As per IRC, dimensions for stair width, tread depth, and riser height are 91.4 cm, 25 cm, and 19.6 cm respectively. The presence of the ascending staircase is deduced when an ordered and structured pattern of an approximate difference of tread depth is observed amongst the ds_1, ds_2, ds_3, and ds_4. The correlation among the values of ds_1 to ds_4 is investigated by using (2). The possible numbers of steps (n) in between S_1, S_2, S_3, and S_4 are computed by applying (3). The value of n is rounded off based on the value of e that is computed from

$$ds_j \cong ds_{j-1} + xn_{j-1} \tag{2}$$

$$n_{j-1} = \frac{ds_j - x}{ds_{j-1}} \tag{3}$$

$$e_{j-1} = (ds_j - x)\mathrm{mod}(ds_{j-1}) \tag{4}$$

j ranges from 2 to 4, x *is tread depth (25 cm),* n *is* number of steps between ds_j and ds_{j-1} and e *is* the remainder of modular division. Ascending staircase is derived when $n_1 = 1, n_2 = 1$, $n_3 = 2$ and values of e_1, e_2, as well as e_3 are insignificant. The resolved ascending staircase situation is indexed in the SMFO virtual table with the ds_1.

2) Floor-Level Obstacle Situation: The obstacle that exclusively detected below knee-level height (tibialis anterior region) is considered as *floor-level obstacle* situation. This situation is confirmed if the following stipulations in (5) and (6) are satisfied. These two conditions verify the relevance of this situation with the remaining *alert* category situations

$$\begin{aligned}&[(((ds_3 - ds_1) > (2x + \alpha))|| \\ &\quad ((ds_3 - ds_1) \leq (2x - \alpha)))\&\&(ds_4 > (ds_1 + x))]\end{aligned} \tag{5}$$

$$\begin{aligned}&[(((ds_4 - ds_1) > (4x + \alpha))|| \\ &\quad ((ds_4 - ds_1) \leq (4x - \alpha)))\&\&(ds_3 > (ds_1 + x))]\end{aligned} \tag{6}$$

x *is tread depth* (25 cm) and α *is constant offset value* (8 cm). Resolved *floor-level obstacle* situation is indexed in the SMFO virtual table with the ds_1.

3) Knee-Level Obstacle Situation: This situation is confirmed when an obstacle is entirely detected at knee-level height. This situation is resolved if the following conditions in (7) and (8) are fulfilled

$$[(ds_1 > (ds_3 + x))\&\&(ds_4 > (ds_3 + x))] \quad (7)$$

$$[(((ds_4 - ds_3) > (2x + \alpha))|| \\ ((ds_4 - ds_3) \leq (2x - \alpha)))\&\&(ds_1 > (ds_3 + x))]. \quad (8)$$

These two conditions verify the relevance of this situation with the remaining *alert* situations. This situation is indexed in the SMFO virtual table with the ds_3.

4) Waist-Level Obstacle: The obstacle that exclusively detected at waist-level height is called *waist-level obstacle* situation. This situation is confirmed if the following stipulation in (9) is satisfied:

$$[(ds_1 > (ds_4 + x))\&\&(ds_3 > (ds_4 + x))]. \quad (9)$$

This situation is indexed in the SMFO virtual table with the ds_4.

5) Blocked Front-Way Situation: This situation is determined when $[\max(ds_1, ds_2, ds_3, ds_4) \leq 200 \text{ cm}]$ and the values of ds_1, ds_2, ds_3, and ds_4 are nearly identical as per condition in

$$([\max(ds_1, ds_2, ds_3, ds_4)] - [\min(ds_1, ds_2, ds_3, ds_4)] \\ \leq x - \alpha). \quad (10)$$

It indicates that more than two front-way sensors are consistently detecting the same obstacle. This situation is indexed in the SMFO virtual table with the distance $(ds_1 + ds_2 + ds_3 + ds_4)/4$. The distance of above five obstacle situations (i.e., ascending staircase, floor-level obstacle, knee-level obstacle, waist-level obstacle, and blocked front-way situation) from the EMC are represented by using NFDS approach. The NFDS scheme is discussed in Section II-C.

6) Simultaneously Blocked Right-Way and Front-Way (Left Turn) Situation: The situation having an obstacle up to 200 cm distance to the right as well as in front of the EMC and absence of an obstacle up to 200 cm to the left of it is considered as a *left turn* situation. This situation is resolved when SMFO situation (v) and condition in (11) are fulfilled

$$[(ds_6 \leq 200 \text{ cm})\&\&(ds_5 > 200 \text{ cm})]. \quad (11)$$

This situation is indexed in the SMFO virtual table with the distance $(ds_3 + ds_4 + ds_6)/3$.

7) Simultaneously Blocked Left-Way and Front-Way (Right Turn) Situation: Right turn indicates unobstructed rightward direction up to 200 cm distance and simultaneous presence of obstacles up to 200 cm toward front-way as well as leftward directions. This situation is affirmed when SMFO situation (v) and condition in (12) are satisfied. This situation is indexed in the SMFO virtual table with the distance $(ds_3 + ds_4 + ds_5)/3$

$$[(ds_5 \leq 200 \text{ cm})\&\&(ds_6 > 200 \text{ cm})]. \quad (12)$$

TABLE II
MAPPING OF OBSTACLE SITUATIONS WITH RELEVANT AUDIO AND VOICE FEEDBACK CUES

Sr. No.	Obstacle situation	Short length feedback*
1	Leftward obstacle	Right
2	Rightward obstacle	Left
3	Simultaneous presence of leftward and rightward obstacle	Straight
4	Ascending staircase	Stair
5	Floor-level obstacle	Floor
6	Knee-level obstacle	Knee
7	Waist-level obstacle	Waist
8	Front-way blocked	FrontB
9	Left turn	Lturn
10	Right turn	Rturn
11	All side block	Block
12	Warning situation	High pitch sound
13	Wet floor	Wet
14	Metal floor	Metal
15	Wet and metal floor	Slow

* Right = move little to right-side, Left = move little to left-side, Straight = go straight, Stair = ascending staircase is detected ahead, Floor = floor level obstacle, Knee = knee level height obstacle, Waist = waist level height obstacle, FrontB= blocked front-way situation, Lturn = take left turn, Rturn = take right turn, Block = all side block situation, High pitch sound= obstacle is detected between 321 cm and 400 cm distance in front of the EMC, Wet= wet floor detected; walk carefully, Metal= metal floor detected; walk carefully, Slow = wet and metal floor detected; walk carefully. Duration of all audio and voice feedback is 1 sec for obstacle situations detected beyond safety margin region. Obstacle situation in safety margin region are represented by shortened voice messages of 0.5 sec duration

8) All-Side Blocked Situation: This situation indicates simultaneous presence of front-way and sideway obstructions up to 200 cm distance. This situation is confirmed when SMFO situation (v) and (13) are satisfied. This situation is indexed in the SMFO virtual table with the distance $(ds_3+ds_4+ds_5+ds_6)/4$

$$[(ds_5 \leq 200 \text{ cm})\&\&(ds_6 \leq 200 \text{ cm})]. \quad (13)$$

9) Warning Situation: This situation represents detection of obstacles between 321 to 400 cm distance from the EMC. This situation is indexed in the SMFO virtual table with the distance of the obstacle detected by the corresponding ultrasonic sensor(s).

The entries in the SMFO virtual table are sorted according to their distance from the EMC and the entry with minimum distance is assigned highest rank.

The WRIO algorithm interprets and categorizes obstacle situations in the SMSO and SMFO. Eventually, it shortlists one highest rank obstacle situations from each of the sub-maps and translates them into vibration, voice, or audio feedback cues. The feedback cues for sample obstacle situations are presented in Table II. The WRIO algorithm schedules these feedback cues into a structure table called *feedback queue*. Partially filled or empty *feedback queue* indicates absence of obstacles in the respective sub-map(s). This situation specific information in the *feedback queue* is conveyed to the subject.

C. Nonformal Distance Scaling Approach

The five *alert* category situations [i.e., from (i) to (v)] in the SMFO are represented by NFDS approach. It translates the obstacle distance into the number of walking steps (m) of the subject. This approach divides the obstacle distance by the subject's average step length by using (14)

$$m = \frac{ds_j}{sl} \tag{14}$$

$$p = ds_j \bmod sl \tag{15}$$

m is the distance of obstacle in terms of number of walking steps of the subject, sl is the average (walking) step length (40 cm) of the subject, and p is the remainder. The value of m is rounded off using the value of p that is computed from (15). The WRIO algorithm selects a voice message "*one*" to represent one step distance ($m = 1$), "*two*" for $m = 2$, "*three*" for $m = 3$, etc. Furthermore, it maintains a safety margin of 200 cm distance for above mentioned five obstacle situations. It provisions a strong vibration feedback (at the handle of the EMC) if these obstacle situations are detected in the safety margin region. The WRIO algorithm tags the value of the m and the event of vibration feedback with the shortlisted obstacle situation from the SMFO.

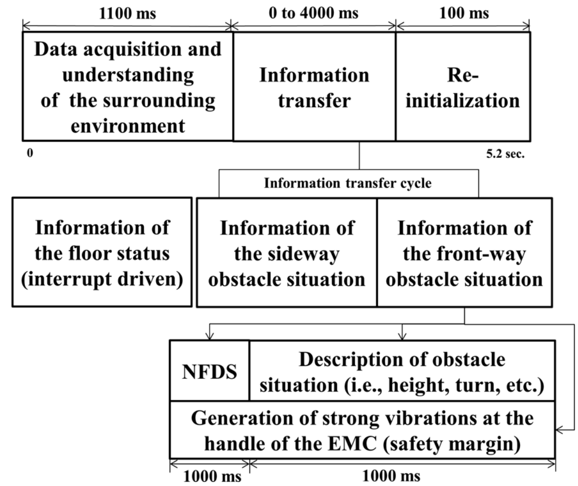

Fig. 2. Timing diagram for the electronic mobility cane operations: Decision cycle and information transfer cycle. Duration of information transfer cycle varies the duration of decision cycle.

III. Implementation and Functional Assessment of the EMC

The EMC is a modular assistive system. It consists of two modules. The first module that interprets the surrounding environment is called data acquisition and decision making (DADM) module. The second module that conveys these interpretations to the subject is named communication module (CM). The DADM module communicates locally generated decisions to the CM module via wireless or wired connectivity.

A. Implementation of the EMC

1) Data Acquisition and Decision Making (DADM) Module: This module has been implemented in the shape of a cane. A Polyvinyl chloride (PVC) conduit of 4 mm wall thickness, 2.5 cm outer diameter, and 100 cm length has been used for fabricating the DADM unit of the EMC. The placement of system components inside this hollow PVC conduit is shown in Fig. 1(a). Amongst the six MaxBotix [33] ultrasonic sensors three are narrow beam width MB1340 (S_1, S_2, and S_3) and remaining three are wide beam width MB1330 (S_4, S_5, and S_6) sensors. The probes of liquid detection sensor are extended till the bottom of the cane and fixed on sides of the cane tip. A metal detection sensor is mounted along S_1, and its face is leveled at the center-cut of the cane tip as shown in Fig. 1(a). A customized circuit of Atmega328 microcontroller (TQFP package) is installed inside the conduit to control this multisensory system. Safety indications of liquid and metal detection sensors are implemented by using external interrupts of this microcontroller. A wireless transceiver circuit and battery are set at rear side of the EMC. Two microvibration dc motors of 11000 r/min are mounted on printed circuit board and are set into 10-cm-long L-shaped cane shaft (handle) of the EMC. An ON/OFF switch has been installed at the rear side near the cane shaft. The EMC system is provided with wireless and wired connectivity between DADM and CM modules. In wired mode, locally generated decisions at DADM unit are brought to the DB9 connecter [Fig. 1(a)], and carried to the CM module via a cable. The wireless mode uses radio frequency 2.4 GHz serial link modules to implement half-duplex communication between DADM and CM modules. A baud rate of 9600 b/s has been used for this communication. The operating voltage and current requirements of the DADM unit is 5 V, 250 mA.

2) Communication Module (CM): This module has been implemented in the shape of an audio player. It consists of a customized Atmega328 microcontroller circuit, wireless transceiver, audio player circuit, mono earphone, and a battery operated 5 V power supply, as shown in Fig. 1(b). The EMC interprets the surrounding environment and stores the shortlisted information into the *feedback queue*. This situation specific information is conveyed to the subject via CM module in a priority sequence, as shown in Fig. 2. The communication of this information to the subject is called *information transfer cycle* (ITC). The interrupt driven IFS feedback assumes the highest priority and is conveyed instantly by using relevant voice feedback according to the status of the floor surface. The microcontroller circuit triggers the audio player to play the relevant audio or voice feedback cues. The duration of each voice, audio, and vibration feedback cue is 1 s. However, obstacle situations detected in the safety margin region are represented by shortened voice messages of 0.5 s. The time interval for initialization, data acquisition, environment understanding, and information transfer is called *decision cycle*. After each ITC, feedback queue and internal variables are reinitialized for new iteration. The operating voltage and current requirements of the CM unit is 5 V, 128 mA.

B. Functional Assessment of the EMC

The functional performance of the EMC was measured before conducting its clinical evaluation. The functional evaluations of the EMC were conducted on a customized rectangular arena of size 200 cm × 400 cm, as shown in Fig. 3.

Total 20 obstacles of varying size and human presence (as dynamic obstacles) were used for this functional evaluation. In these evaluations the EMC was tested for its capacity to detect obstacles, measure obstacle distance, interpretation of the surrounding environment, and communication of feedback cues.

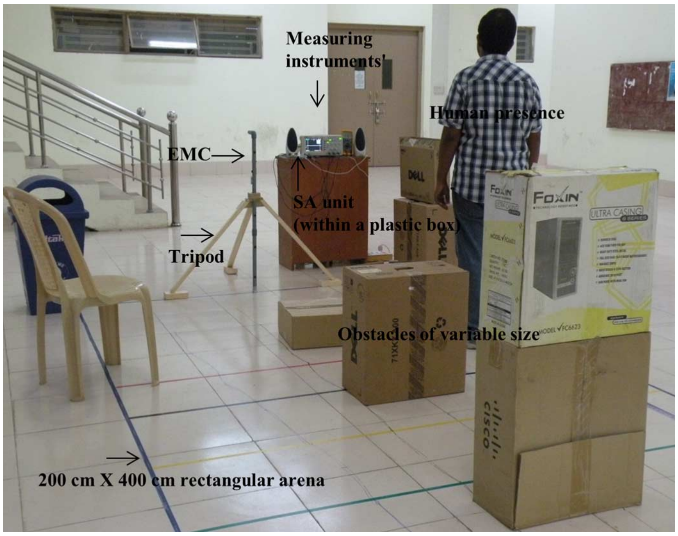

Fig. 3. Functional assessment of the electronic mobility cane: Obstacles of variable size were moved in six directions (up, down, right, left, forward, and backward) in front of side and front ultrasonic sensors of the EMC. A rectangular arena of 200 cm × 400 cm size was prepared for these tests. Safety indicator functions were also assessed during these tests.

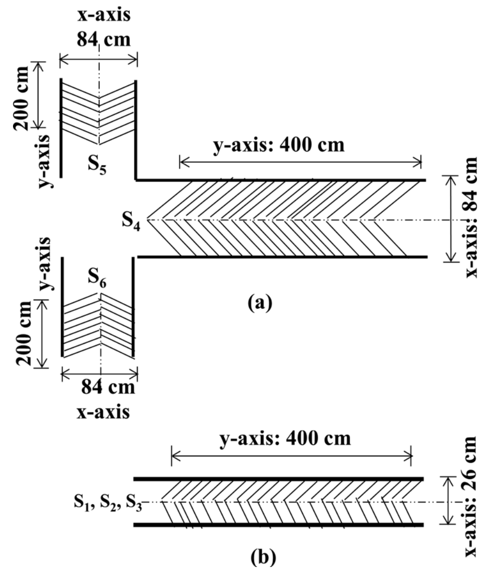

Fig. 4. Obstacle detection and distance measurement capability of the electronic mobility cane along horizontal (x) and vertical (y) axis: (a) for S_4, S_5, and S_6 sensors and (b) for S_1, S_2, and S_3 sensors.

Obstacle detection capacity was defined as the correct detection of obstacles that present along x (horizontal) and y (vertical) axis in front of ultrasonic sensors of the EMC as shown in Fig. 4. Total 50 tests were conducted for evaluation of its obstacle detection capacity. In these tests obstacles were moved in six directions (up, down, right, left, forward, and backward) in front of the sideway and front-way ultrasonic sensors. The EMC detected front-way (S_4), leftward (S_5), and rightward (S_6) knee-level to waist-level obstacles that were placed anywhere in the regions of size 84 cm × 400 cm, 84 cm × 200 cm, and 84 cm × 200 cm, respectively, as shown in Fig. 4(a). It also detected all floor-level to knee-level obstacles that were placed in front of it (S_1, S_2, and S_3) anywhere in the regions of size 26 cm × 400 cm, 26 cm × 400 cm, and 26 cm × 400 cm, respectively, as shown in Fig. 4(b).

The EMC should be hold straight upright with its tip forming an approximately 90° angle with floor plane for its consistent usage. The diagonal or slanted usage of the EMC (similar to a white cane) reduces 1) its angle with the floor and 2) angle of its ultrasonic sensors' beam with the object. An angle of 76° to 90° provides faithful results for detections of obstacles in front of the EMC. However, reduction (i.e., less than 76°) in these angles will cause detection of front-way upward obstacles, but it may miss obstacles in front of the EMC. The detection of sideway obstacles will not be affected because of the straight upright or slanted usage of the EMC.

Distance measurement ability was defined as correct estimation of the distance of the detected obstacle along x and y axis as shown in Fig. 4. This ability was evaluated for full detection range of the EMC (200 cm × 400 cm) along with its obstacle detection capacity. We observed a deviation of 3.6% between actual and the EMC detected distance readings of varying size obstacles. The EMC correctly detected small obstacles of size 2.6 cm × 2.6 cm and 3 cm × 3 cm up to 202 cm and 226 cm distance, respectively. It showed fluctuating response for respective obstacles beyond 202 cm and 226 cm distance. However, it correctly and consistently detected other obstacle of size 10 cm × 10 cm throughout its 200 cm × 400 cm detection range. The EMC requires a floor-level obstacle of (at least) 3 cm height for its consistent detection. During these functional evaluations different obstacle situations were simulated around the EMC. The EMC successfully interpreted these all obstacles and timely activated situations specific feedback cues. In one of the situation, the floor was wet, a leftward obstacle was present at 90 cm distance, floor-level, and waist-level obstacles were placed at 234 cm and 260 cm distance in front of the cane. The EMC conveyed this situation, by playing voice messages *"wet, right, six steps foot"*.

IV. Usability Study Design for the EMC

This study was approved by the Institutional Review Board (IRB) of Midnapore Medical College and Hospital (MMCH), Midnapore, West Bengal, India. MMCH is a state government hospital. This usability study was also approved by Institutional Ethical Committee for Research on Human Subjects (IEC) of IIT Kharagpur, India as per Helsinki Declaration.

A. Subject Recruitment

Sixteen totally blind (11 men, five women) and four low vision (two men, two women) subjects were recruited from Department of Ophthalmology at MMCH. Totally blind subjects had no residual vision at all. Recruited subjects' average age was 39.35 years-the youngest participant was 20 year old and the oldest was 54 years. All participants were received oral and written information of the nature and purpose of the experiments. All participants and primary caretakers gave their written informed consent. All subjects were right-handed. Sixteen totally blind subjects had good skills on usage of white cane and low vision subjects had fair experience of using white cane.

B. Training

A 20-h-long training curriculum was designed for the usage of the EMC. The recruited subjects were trained on this curriculum by two orientation and mobility (O&M) instructors. Total eight working models of the EMC were used for training the subjects and for succeeding usability experiments. A subject was asked to walk holding the EMC straight upright in front of him/her with cane tip forming an approximately 90° angle with floor plane. The cane tip should touch the floor at least once after every step, or stride for acquiring travel surface information. In "ON" condition, the EMC must not be held diagonally or never be swung into the air like white cane. Periodically subject should lift the EMC up to the trunk-level height for exploring trunk and head-level obstructions.

C. Clinical Evaluation Experiments

The EMC was subjected to clinical evaluations in order to verify its design and to assess its ability to assist the visually impaired subjects in their daily-life mobility. The experimental set up and tasks to be performed during these experiments were selected based on the operationalized goals and the mobility requirements in the real-world.

1) Experimental Method: Four experiments were conducted for the usability assessment of the EMC. The first three experiments were conducted in three different environments namely controlled indoor, controlled outdoor and real-world outdoor environment. The controlled indoor and outdoor environments in the first two experiments were created by simulating different obstacle situations. We used forty carton boxes of varying size (3 cm × 3.5 cm × 8 cm, 3.7 cm × 4.5 cm × 21 cm, 4 cm × 5 cm × 25 cm, 10 cm × 8 cm × 10 cm, 20 cm × 20 cm × 16 cm, 20 cm × 60 cm × 42 cm, 30 cm × 50 cm × 33 cm, 30 cm × 60 cm × 52 cm, 50 cm × 60 cm × 34 cm, 50 cm × 90 cm × 52 cm, 60 cm × 80 cm × 45 cm, 90 cm × 100 cm × 80 cm, 100 cm × 110 cm × 90 cm, 100 cm × 170 cm × 120 cm, 150 cm × 100 cm × 92 cm, 100 cm × 200 cm × 156 cm, overhanging clothes, dynamic obstacles, etc.) for simulating these obstacle situations. Subjects' veering in walking (1–2 m) was used as basis for positioning of these obstacle situations. In the first three experiments, a subject was asked to walk the respective environments twice as explained here: 1) once using white cane, and 2) once using the EMC.

Subjects were randomly assigned to the experimental conditions namely cane type and environments to avoid any memory bias. In the existing literature [19], [27], [34]–[36] the effectiveness of an ETA is measured in terms of collision rate and the walking speed of the subject. We also followed these standard measurements along with a few additional performance measures for evaluating the usability of the EMC. All these performance measures used for the EMC are described in the following subsection. The fourth experiment was conducted to evaluate the utility of the EMC for perceiving the wet and/or metal floor.

2) Experimental Environment: In the first experiment, a controlled indoor environment was created in a 2.8-m-wide and 30-m-long "⊏" shaped passage that was ending at an ascending staircase. This staircase and two right turns in the passage were used as obstacle situations. Along with these three obstacles other seven obstacle situations were also simulated in this passage. These additional situations were floor level obstacles (2), knee-level obstacle (1), waist-level obstacles (2), and over hanging clothes as head-level obstacles (2). Numbers in parentheses denote the numbers of corresponding type of obstacles used. Each subject was asked to walk this "⊏" shaped passage perceiving the surrounding environment. Three performance measures namely *number of obstacles avoided* (NOA), *number of obstacles collided and could not avoid* (NOCA) and *percentage preferred walking speed* (PPWS) [36], [37] were recorded for each subject. After evaluation, the subject was asked to describe the obstacle distribution in surrounding environment verbally. A measure called *mental mapping score* (MMS) was defined based on subjects' correct description of the environment. The subject was awarded with 1, 0.5, and 0.5 points for correct description of each turn, obstacle situation, and obstacle direction, respectively. The range of MMS was 0–10.

In the second experiment, a controlled outdoor environment was created on a 4-m-wide and 50-m-long (straight) tar road by simulating 10 obstacle situations. Along with seven obstacle situations described in the first experiment set-up, three additional situations were simulated on this road. These three situations were a 2.5 m wide narrow opening, a left turn, and all side block situation at the end of the road. These obstacle situations were randomly placed on the road. Each subject was asked to walk this 50-m-long environment. Four performance measures namely NOA, NOCA, *number of obstacles did not come in the path* (NONP) and PPWS were recorded for each subject. These evaluations were named part I of this experiment. Furthermore, part II of this experiment was conducted to evaluate the effect of the external acoustic signals on the way-finding performance of the subject. In this part, five external acoustic signal (EAS) situations (distractor tasks) were randomly roped in the environment layout of the part I. In these EAS situations, twice subjects were given verbal instructions, twice a motorbike horn was sounded from the behind, and once a sighted volunteer was asked to walk 3 m distance talking with the subject. Each subject was asked to walk this part II environment and same four performance measures were recorded as described in the part I of this experiment.

In the third experiment, a real-world service road of 4 m width and 200 m straight length was used. This road was busy with pedestrians and slow speed vehicles. Each subject was asked to walk this 200-m-long environment. This experiment was conducted in two parts at two different times of the day i.e., part-I at morning time from 9:00 to 11:30 am and part II at evening time from 5:00 to 6:30 pm. The pedestrian traffic was relatively more at morning time as compared to evening. Two performance measures namely NOCA and PPWS were recorded for each subject.

In the fourth experiment, three different situations namely wet floor, metal floor, and wet-metal floor were created around the subject. Each subject was asked to perceive these situations by touching the tip of the EMC at different positions on the floor. In each evaluation the subject was asked to perceive the floor status three times. Such three evaluations were conducted with each subject. The position of the subject and these three situations around him/her were randomly altered to avoid memory bias. Three performance measures namely *number of correct detections of the wet floor* (NCW), *number of correct detections of the metal floor* (NCM), and *number of correct detections of the wet-metal floor* (NWM) were recorded for each subject.

The complete usability study was conducted at MMCH, Midnapore under the supervision of O&M instructors. Analysis of these usability experiments is presented in the succeeding section.

V. Results

In the first three experiments, 20 subjects walked the controlled and the real-world test environments using white cane and the EMC. Paired t-tests were applied to compare the subjects' performances using white cane and the EMC. The SPSS 16.0 software was used for statistical analysis.

The controlled indoor environment in the first experiment was little cluttered. Subjects systematically swept white cane and touched obstacles with its tip to perceive the surrounding environment. On the contrary, proactive alerts of the EMC assisted the subjects to negotiate with these obstacles from a safe distance (outcome used NOA: $p < 0.001$). The rate of collisions was quite high for white cane than the EMC (outcome used NOCA: $p < 0.001$). However, walking speed was much faster with white cane as compared to the EMC (outcome used PPWS: $p < 0.001$). Subjects could detect the ascending staircase from 243.80 ± 32.19 cm distance while using the EMC, whereas with white cane they detected it after touching the cane tip from 78.45 ± 15.47 cm. Subjects were found applying significant perceptual effort with white cane to perceive the surrounding environment. Nevertheless they were comfortably able to understand it while using the EMC. Subjects' environment descriptions with the EMC (outcome used $\mathrm{MMS} = 7.35 \pm 1.34$) were relatively better than the white cane (outcome used $\mathrm{MMS} = 5.65 \pm 0.93$).

In the second experiment, consistent way-finding performances were observed with the EMC during both parts i.e., in absence (outcome used NOA: $p < 0.001$; NOCA: $p < 0.001$) and presence (outcome used NOA: $p < 0.001$; NOCA: $p < 0.001$) of EAS than white cane. The EMC performances without EAS were better than with EAS (outcome used NOA: $p = 0.053$; NOCA: $p = 0.001$). In presence of EAS the average value of the NOCA measure for the EMC was increased to 1.9 from 1.05. White cane performances with and without EAS were almost same. Subjects showed faster walking speed with white cane as compared to the EMC (outcome used PPWS in absence of EAS: $p < 0.001$; PPWS in presence of EAS: $p < 0.001$).

In the third experiment, subjects walked on the 200-m-long real-world service road and came across 19.96 ± 6.06 numbers of obstacles throughout the evaluations with white cane and the EMC. The pedestrian traffic on this road was relatively more at morning time as compared to the evening. Subjects demonstrated balanced way-finding performances with the EMC irrespective of more and less (pedestrian) traffic situations. The NOCA measure was quite less for the EMC performances as compared to white cane (NOCA in more traffic: $p < 0.001$; NOCA in less traffic: $p < 0.001$). Subjects were found prepared and comfortable with the EMC while negotiating the real-world obstacle situations. However, in this experiment also subjects' walking speed was faster with white cane than the EMC (PPWS in more traffic: $p = 0.003$; PPWS in less traffic: $p < 0.001$). In this experiment, some subjects walked faster than their preferred walking speed while using whitecane. Therefore, their PPWS was greater than 100% as shown in Fig. 6(b).

Initially these three experiments were analyzed considering 20 subjects in a single category, but later their performances were analyzed using three different classification schemes. These schemes were based on the number of years of blindness and visual-like perception (classification I), age (classification II), and gender (classification III). According to classification-I, performances (subjects) were divided into four groups namely congenitally blind, late blind, newly blind, and low vision. There were three congenitally blind subjects, eight late blinds, five newly blinds, and four low vision subjects. Late blind subjects were having acquired blindness after age 17 and lived with blindness for more than 15 years. Newly blind subjects had lost their sight approximately one year before the time of this study. Low vision subjects could identify shapes at around 1 m distance, but they were blindfolded throughout the study. As per classification II, performances (subjects) were divided into two age groups, first group was of 20–35 years old and second of 36–55 years old. There were nine subjects in the first age group and 11 in the second age group. According to classification III, there were seven women and 13 men subjects.

Subjects' performances were analyzed according to classification schemes I, II, and III. The statistics of the way-finding performances in the controlled and real-world environments are presented in Figs. 5 and 6, respectively. In general, the results in Figs. 5 and 6 have shown that the late blind subjects performed relatively better than the congenitally blind, newly blind, and the low vision subjects.

Low vision subjects showed increased difficulty in understanding unfamiliar environments. The age of the subjects seem to influence the way-finding performance. Subjects in second age group (i.e., 36–55 years) performed moderately well than first age group. The gender of the subjects also found to influence the way-finding performance. Male subjects performed relatively well as compared to female subjects.

In the fourth experiment, total 180 tests were performed for perceiving wet floor (60), metal floor (60), and wet-metal floor (60). Subjects systematically used the EMC to perceive the status of the floor. The percentage values of the three performance measures NCW, NCM, and NWM measured in this experiment were 96.66%, 91.66%, and 85%, respectively. The EMC tip should approximately make a right angle (76° to 90°) with the floor for correct detection of its status. However, in 16 testes of this experiment seven subjects hold the EMC slanted and therefore could not detect the correct status of the floor.

Subjective measurements of white cane and the EMC were conducted after these four usability experiments. Two measures named *system capability and utility score* (SCU) and *degree of comfort* (DOC) were defined for these measurements. SCU is a measure of subject's viewpoint about cane's useful functions,

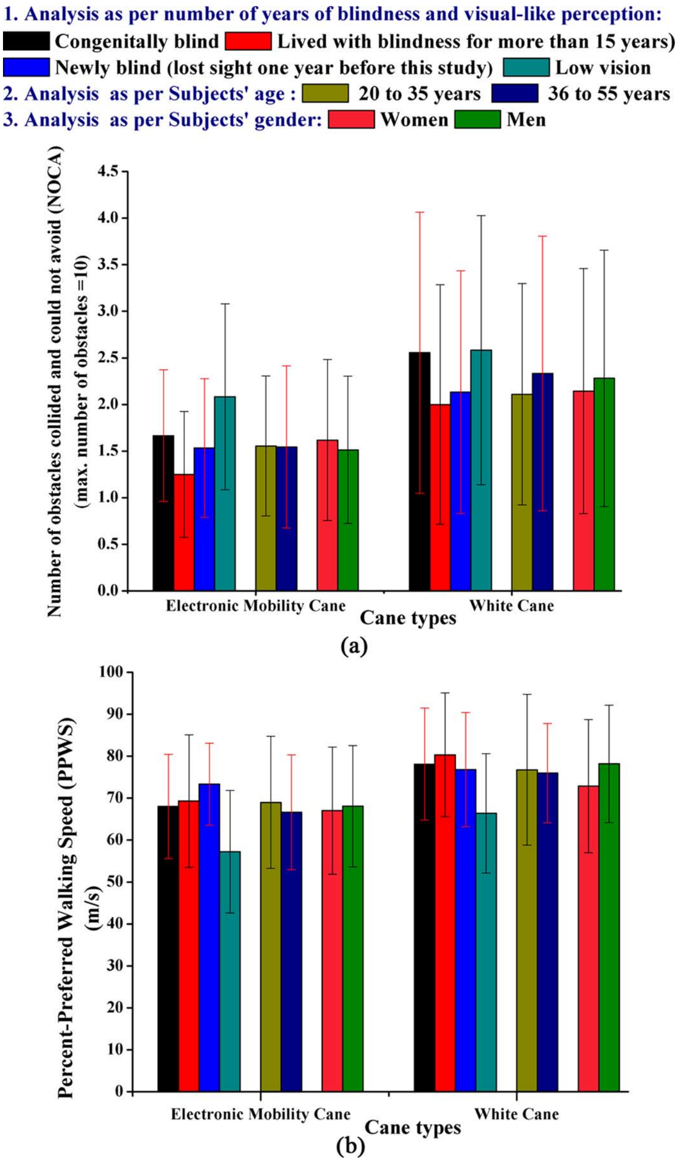

Fig. 5. Analysis of 20 subjects' way-finding performances in controlled environments: (a) number of obstacles collided and could not avoid using white cane and the EMC and (b) percent preferred walking speed using white cane and the EMC. This analysis is combined representation of subjects' way-finding performances in controlled indoor and controlled outdoor environments.

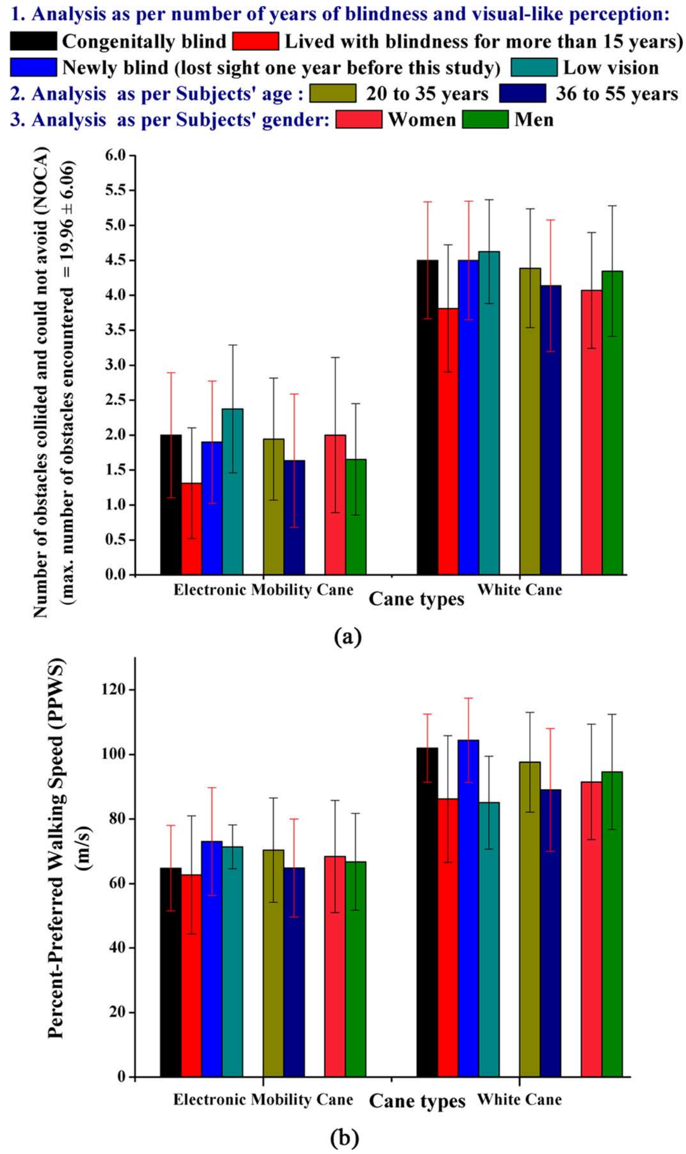

Fig. 6. Analysis of 20 subjects' way-finding performances in real-world environments: (a) number of obstacles collided and could not avoid using white cane and the EMC and (b) percent preferred walking speed using white cane and the EMC. This analysis is combined representation of subjects' way-finding performances in more (morning time) and less (evening time) traffic situations.

information content, and user interface. Similarly, DOC represents subjects' mental state and stress level while using cane types. SCU and DOC scores were computed by interviewing all subjects with two structured sets of questionnaires. Each of the two sets had 40 questions and the range of scores was 0 to 40. Subjects' positive response to a question was counted as a point and negative response as a zero. The average SCU and DOC scores of white cane ($\mathrm{SCU} = 21.90 \pm 2.24$; $\mathrm{DOC} = 24.95 \pm 1.98$) and the EMC ($\mathrm{SCU} = 32.05 \pm 2.13$; $\mathrm{DOC} = 30.75 \pm 3.02$) were substantially different. The significant values of SCU and DOC scores of the EMC showed its acceptability among visually impaired subjects. Amongst the subjects 90% (60%) appreciated usable functions, reliability of information, and relevance of the EMC to improve their personal autonomy. Percentage number in bracket denotes subjective measurements of white cane. Of the subjects, 75% (70%) expressed satisfaction with physical interface and 85% (70%) appreciated user interface of the EMC. All subjects were satisfied with appearance (cane type), size (2.5 cm $\times$ 100 cm), weight (0.503 kg), and projected cost ($280) of the EMC.

VI. Discussion

The EMC was evaluated in low and high density obstacle environments with 20 visually impaired subjects. All these subjects confidently and comfortably negotiated with obstacles while using the EMC. The assistance of the EMC enabled them to proactively and categorically detect the obstacles. The score of number of collisions throughout the usability experiments was significantly low for the EMC. This suggests that subjects were more aware about the surrounding environment while using the EMC than white cane. Subjects were able to perceive the obstacle distribution with less effort. They were very confident about the reliability of the information provided by the EMC. We did not conduct separate experiment to measure the cognitive and perceptual load. However, scores of subjective measurements (DOC) showed that walk anxiety of subjects reduced while using the EMC. Among subjects, 85% accepted reduction in cognitive effort and 75% subjects acknowledged decrease in perceptual effort because of the EMC. This suggested that the simplified representation of the surrounding environment is effective in improving the walk anxiety.

Many previous research studies have provided different ETAs to address mobility difficulties of visually impaired people. Every system resulted from these studies attempted to provide little incremental over the other. The sonic torch [16], miniguide [15], CyARM [14], Kaspa system [17], electronic bracelet [21], and similar handhold devices provides the information of obstacles detected in front of them. Navbelt [19], vOICe [24], and the head mounted kaspa system are relatively rich in information as compared to handhold devices. These devices reduce the perceptual load, but increases cognitive effort. Furthermore, detection of floor-level obstacles is a major concern for these devices. Therefore these devices are used in conjunction with primary aids (e.g., white cane). GuideCane [13] is effective in reducing perceptual as well as cognitive effort. However, it is an autonomous device. When an obstacle is detected, this cane guides the subject to an alternate direction until the obstacle is cleared. This self-governing function of the GuideCane may be unsafe as it excludes the user from navigational decisions [4]. Ultracane [12] and K-sonar cane [11] are promising aids. These canes require basic cane techniques for their systematic use similar to a white cane. Laser Cane [7] is a reliable solution. However its high cost ($3000) and significant perceptual efforts are major concerns. Minitact [9], ESB [22], and binaural sonar [23] are prototype aids and their field evaluation details are not provided. The behavioral studies on majority of the existing ETAs have been either conducted with small sample size or with blindfolded normally sighted volunteers. Majority of these studies are conducted in controller indoor environment. More behavioral studies in real world environments are needed to demonstrate the usefulness of these ETAs [4]. Majority of existing mobility devices provide limited information of the surrounding environment, and none of them categorize or prioritize acquired information. However, the EMC analyses the distribution of obstacles in the surrounding environment to deduce the priority information. It categorizes detected obstacle situations and provides clear and concise information about the environment to the subject. It provides a simplified representation of the surrounding environment without causing any information overload to the subject. The overall design of the EMC underlines the inclusiveness of physical and psychological aspects of the potential users. The unique features of the EMC namely WRIO algorithm, NFDS approach and safety margin scheme are distinctions over other mobility aids. However there is a constraint on method of usage of the EMC. It has to be hold straight upright with its tip forming an approximately 90° angle with floor plane for its consistent results.

One limitation of the current study is that the usability experiments were conducted with subjects immediately after completion of their training on the EMC. Therefore subjects did not get substantial experience on the EMC. Subjects' 20 h of association with the EMC was insignificant as compared to their long term experience with white cane. Therefore subjects showed reduced walking speed using the EMC as compared to the white cane. However, the overall collision rate while using the EMC was significantly lower than the white cane. The regular use of the EMC can improve the walking speed of the subject.

VII. Conclusion

The visually impaired subjects evaluated the EMC in real and controlled environments. The EMC underwent total 100 evaluations in the first three usability experiments. Throughout the evaluations, subjects experienced reliable performance of the EMC. Majority of the subjects performed consistently irrespective of number of years of blindness. All subjects were satisfied with user interface and functions of the EMC. Overall results of the clinical evaluation and significant scores of subjective measurements ($SCU = 32.05 \pm 2.13$ and $DOC = 30.75 \pm 3.02$) showed the usefulness of the EMC for vision rehabilitation services. Future studies will concentrate on more number of real-world experiments and measurement of subjects' quality of life improvement after using the EMC.

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