Wearable Obstacle Avoidance Electronic Travel Aids for Blind: A Survey

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***Abstract*—The last decades a variety of portable or wearable navigation systems have been developed to assist visually impaired people during navigation in known or unknown, indoor or outdoor environments. There are three main categories of these systems: Electronic travel aids (ETAs), electronic orientation aids (EOAs), and position locator devices (PLDs). This paper presents a comparative survey among portable/wearable obstacle detection/avoidance systems (a subcategory of ETAs) in an effort to inform the research community and users about the capabilities of these systems and about the progress in assistive technology for visually impaired people. The survey is based on various features and performance parameters of the systems that classify them in categories, giving qualitative–quantitative measures. Finally, it offers a ranking, which will serve only as a reference point and not as a critique on these systems.**

***Index Terms*—Electronic travel aids, navigation systems, obstacle avoidance, survey, wearable systems.**

I. Introduction

According to National Federation for Blind (NFB) [1] and American Foundation for the Blind (AFB) [2], the estimated number of legally blind people in the United States is 1.3 million and the total number of blind and visually impaired is approximately 10 million with around 100.000 to be students. Worldwide more than 160 million people are visually impaired with 37 million to be blind [3]. The need to for assistive devices was and will be constant. There is a wide range of navigation systems and tools available for visually impaired individuals. White cane and dog guides are the most popular. White cane is the simplest, cheapest, most reliable and thus the most popular navigation aid. However, it does not provide all the necessary information such as speed, volume, and distances, which are normally gathered by eyes and are necessary for the perception and the control of locomotion during navigation [4].

Since 1960s evolving technology helped many researchers built electronic devices for navigation. A first level categorization is as follows: 1) vision enhancement, 2) vision replacement, and 3) vision substitution. The function of any sensory aid, as described in [4], is "...to detect and locate objects and provide information that allows user to determine (within acceptable tolerances) range, direction, and dimension and height of objects. It makes non-contact trailing and tracking possible, enabling the traveler to receive directional indications from physical structures that have strategic locations in the environment" with additional object identification if possible. Vision enhancement involves input from a camera, process the information, and output on a visual display. In its simplest form it may be a miniature head-mounted camera with the output on a head-mounted visual display (as used in some virtual reality systems). Vision replacement involves displaying the information directly to the visual cortex of the human brain or via the optic nerve. We will not deal with this category since they deal with scientific, technological and medical issues whose study is beyond the purpose of this survey. Vision substitution is similar to vision enhancement but with the output being nonvisual, typically tactual or auditory or some combination of the two and since the senses of touch and hearing have a much lower information capacity than vision, it is essential to process the information to a level that can be handled by the user. The category that we will focus in this work is the "vision substitution." Here someone can find these subcategories:

1) *Electronic travel aids (ETAs):* devices that transform information about the environment that would normally be relayed through vision into a form that can be conveyed through another sensory modality.
2) *Electronic orientation aids (EOAs):* devices that provide orientation prior to, or during the travel. They can be external to the user and/or can be carried by the user (e.g., infrared light transmitters and handheld receivers).
3) *Position locator devices (PLDs):* which include technologies like GPS, European Geostationary Navigation Overlay Service (EGNOS), etc.

We are mostly interested in ETAs and more specifically in obstacle detection systems, not emphasizing in GPS features.

Electronic travel aids can also be categorized depending on how the information is gathered from the environment and depending on how this information is given to the user. Information can be gathered with sonars, laser scanners, or cameras, and the user can be informed through the auditory and/or tactile sense. Sounds or synthetic voice are the options for the first case and electrotactile or vibrotactile stimulators for the second. Tactile feedback has some great advantage because it does not block the auditory sense (free-ears), which is the most important perceptual input source (the others are touch, wind, odors, and temperature) for a visually impaired user.

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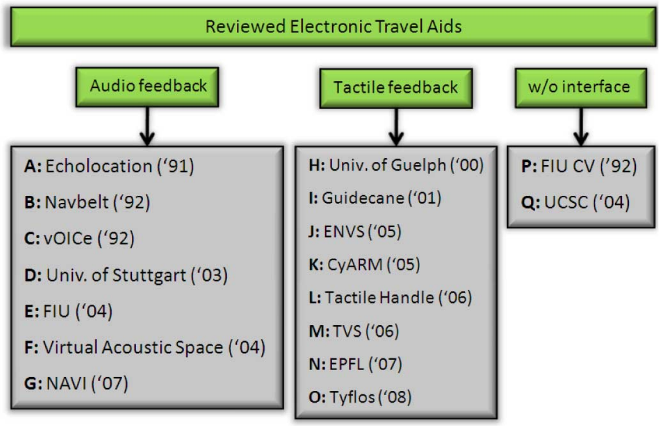

Fig. 1. Reviewed ETAs with categorization based on how the information is sent to the user (the latest prototype's year is shown in parenthesis).

In addition, some ETAs offer to the user free-hands since they are wearable but some others do not since the user is required to hold them; it is up to the user to select which is more appropriate to his/her habits.

The National Research Council's guidelines for ETAs [4] are listed below:

1) Detection obstacles in the travel path from ground level to head height for the full body width.
2) Travel surface information including textures and discontinuities.
3) Detection of objects bordering the travel path for shorelining and projection.
4) Distant object and cardinal direction information for projection of a straight line.
5) Landmark location and identification information.
6) Information enabling self-familiarization and mental mapping of an environment.
7) In addition: ergonomic, operate with minimal interface with natural sensory channels, single unit, reliable, user choice of auditory or tactile modalities, durable, easily repairable, robust, low power and cosmetically accepted.

The paper is organized as follows. In Section II, 22 ETAs (five are products already in the market) are briefly described and reviewed. Section III provides a maturity analysis for all the aids, based on structural and operational features and Section IV concludes with some discussion.

II. Electronic Travel Aids

Next, there is list of the most important projects with a brief description for each one. We will study these systems taking the above guidelines into consideration and then give some comparative results to answer the questions of how advance, useful, and desirable each system is. The systems are presented based on how the feedback is sent to the user (Fig. 1). The first eight use audio feedback, the next seven use tactile, and the last two do not have an interface yet.

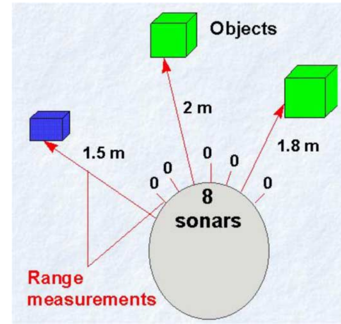

Fig. 2. Navbelt's operation: eight ultrasonic sensors create and angle map that represents the distance of obstacles in those angles.

A. Echolocation

The main goal of this project, which started in the early 1990s in Japan, was to design a new mobility aid modeled after the bat's echolocation system [5].

Two ultrasonic sensors are attached on conventional eyeglasses and their data, using a microprocessor and A/D converter, are downconverted to a stereo audible sound, sent to the user via headphones. The different intensities and time differences of the reflected ultrasound waves transmitted by the sensors indicate the different directions and sizes of obstacles, creating a form of localized sound images.

Some preliminary experiments were performed to evaluate the user's capability to discriminate between objects in front of the user's head, using different ultrasound frequencies. The results provided show that the users can identify and discriminate objects in some limited cases, but more experiments and statistical results are required to support the viability of the project. The simplicity and portability of the prototype are also major advantages.

B. Navbelt

Navbelt is developed by Borenstein and coworkers in University of Michigan [6] as a guidance system, using a mobile robot obstacle avoidance system. The prototype as implemented in 1992 and it is consisted of ultrasonic range sensors, a computer and earphones. The computer receives information from the eight ultrasonic sensors (Fig. 2) and creates a map of the angles (each for every sensor) and the distance of any object at this angle. Then the obstacle avoidance algorithm (including noise reduction algorithm EERUF) produce sounds appropriate for each mode.

Navbelt has two modes: the guidance mode and the image mode. During the guidance mode, the computer knows the user's destination and with a single recurring beep guides him/her in the generated optimal direction of travel. But in practice, a realistic (nonsimulation) implementation would require more sensors. In the image mode, eight tones of different amplitudes are played in quick succession from eight different virtual directions (similar to a radar sweep). The computer translates (depending on the mode) these maps to sounds that the user can listen from his earphones. The disadvantages of the systems are the use of

Fig. 3. Implementation of the vOIce—“Seeing with sound” system (glasses with attached camera, earspeakers, and portable computer).

Fig. 4. Sensor of the University of Stuttgart’s project.

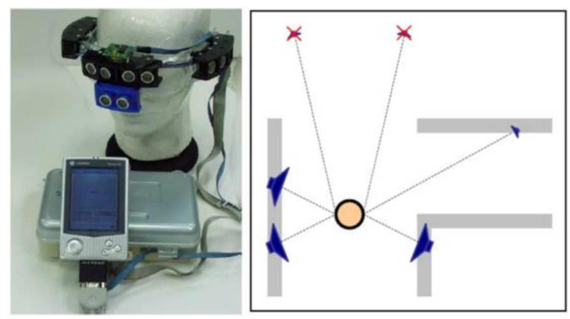

Fig. 5. FIU project prototype (left) and an example of its operation (right).

audio feedback (exclusively), the bulky prototype and that the users are required extensive training periods.

C. *vOICe*

Meijer [7] started a project having the basic argument that human hearing system is quite capable of learning to process and interpret extremely complicated and rapidly changing sound patterns. The prototype shown in “Fig. 3” consists of a digital camera attached to conventional eyeglasses, headphones, and a portable computer with the necessary software.

The camera captures images and the computer uses a direct, unfiltered, invertible one-to-one image-to-sound mapping. The sound is then sent to the headphones. No filters were used to reduce the risk of filtering important information since the main argument is that human brain is powerful enough to process complex sound information. The system is very simple, small, lightweight, and cheap. Lately, the software was embedded on a cellphone, and thus the user can use the cellphone’s camera and earphones. In addition, sonar extension is available for better representation of the environment and increased safety. Many individuals tried the system returning very promising feedback, but they required extensive training because of the complicated sound patterns.

D. *University of Stuttgart Project*

A portable–wearable system that assists blind people orienting themselves in indoor environments was developed by researchers in University of Stuttgart in Germany [8]. The prototype is consisted of a sensor module with a detachable cane and a portable computer. The sensor (Fig. 4) is equipped with two cameras, a keyboard (similar to those in cellphones), a digital compass, a 3-D inclinator, and a loudspeaker. It can be handled like a flashlight and *“By pressing designated keys, different sequence and loudness options can be chosen and inquiries concerning an object’s features can be sent to the portable computer. After successful evaluation these inquiries are acoustically answered over a text-to-speech engine and the loudspeaker.”*

The computer contains software for detection of color detection distance and size of objects and wireless local area network (WLAN) capabilities. The device works almost in real time. In order to improve the performance of the system, a virtual 3-D model of the environment was built, so the information from the sensor can be matched with the data stored in the 3-D model. A matching algorithm for sensor information and 3-D model’s data and embedding the system to Nexus framework (a platform that allows a general description of arbitrary physical real-world and virtual objects) are the future work proposals.

Concluding, the system’s positives are the robustness of the sensor, the near real-time operation and the friendliness to the user. The negatives are that the hold-and-scan operation and the, until this moment, limited, simulated testing.

E. *FIU Project*

This project from researchers in Florida International University (FIU) [9] is an obstacle detection system that uses 3-D spatialized sounds based on readings from a multidirectional sonar system. The prototype (Fig. 5) is consisted of two subsystems: the sonar and compass control unit, which is consisted of six ultrasonic range sensors pointing in the six radial directions around the user and a microcontroller; and the 3-D sound rendering engine, which is consisted of headphones and a personal digital assistant (PDA) equipped with software capable of processing information from the sonar and compass control.

The algorithm, using head-related transfer functions (HRTF), creates a 3-D sound environment that represents the obstacles detected by the sensors. The user in that way creates a mental map of the layout of his/her surroundings so that obstacles can be avoided and open passages can be considered for path planning and navigation. The system was tested on four blind-folded individuals, who were asked to navigate in a building. The results were promising but the navigation speed was slow. As seen in

Fig. 6. Virtual acoustic space prototype (cameras and headphones mounted on eyeglasses and microprocessor) (right).

"Fig. 5", the design of the ranging unit is not ergonomic, but the system is small and wearable.

F. Virtual Acoustic Space

Virtual acoustic space was developed by researchers in Instituto de Astrofísica de Canarias (IAC) [10]. A sound map of the environment is created and so the users can orientate by building a perception of space itself at neuronal level.

The prototype (Fig. 6) is consisted of two color microcameras attached to the frame of some conventional eyeglasses, a processor and headphones. The cameras, using stereoscopic vision, capture information of the surroundings. The processor, using HRTF, creates a depth map with attributes like distance, color, or texture and then generates sounds corresponding to the situation in which sonorous sources exist in the surroundings. The experimental results on visually impaired people showed that in most cases (>75%), individuals could detect objects and their distances and in small simple experimental rooms, it was possible for them to move freely and extract information for objects like walls, table, window, and opened door.

The major advantage of this system is that the eyeglasses are convenient and the size of the processor is small (like a portable CD-player). The major disadvantage is that is not tested in real environments.

G. Navigation Assistance for Visually Impaired

Sainarayanan *et al.* from University Malaysia Sabah [11] developed an ETA (sound-based) to assist blind people for obstacle identification during navigation, by identifying objects that are in front of them. The prototype navigation assistance for visually impaired (NAVI) (Fig. 7) is consisted of a digital video camera, headgear (holds camera), stereo headphones, the single-board processing system (SBPS), rechargeable batteries, and a vest (that holds SBPS and batteries).

The idea is that humans focus on objects that are in front of the center of vision and so it is important to distinguish between background and obstacles. The video camera captures grayscale video, which is resampled to 32×32 resolution. Then using a fuzzy learning vector quantization (LVQ) neural network the pixels are classified to either background or objects using different gray level features. Then the object pixels are enhanced and the background suppressed. The final stage cut the processed image into left and right parts, transform to (stereo) sound that is sent to the user through the headphones.

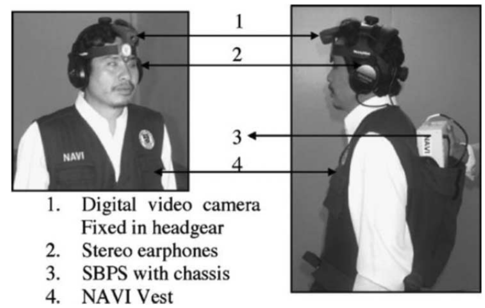

Fig. 7. NAVI and its components.

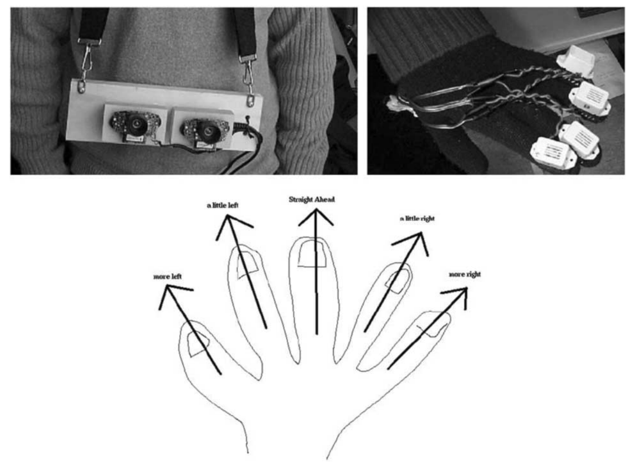

Fig. 8. Prototype from the University of Guelph and the hand spatial correspondence.

Blind persons were trained with simulated experiments and then asked to identify obstacles of indoor environment, and they were able to identify slowly moving objects. Although the distance of objects was not (and is not) aimed to be identified, is possible to be done by the change of an object's shape, e.g., when the user approaches an object, its size will become bigger. The advantage of this system that the prototype is developed and it is operational and real time. The disadvantages are the use of audio feedback and that no information about the distances of objects is given.

H. University of Guelph Project

Zelek with students from University of Guelph [12], in Canada, developed an inexpensive, built with off-the-shelf components, wearable and low power device that will transform depth information (output of stereo cameras) into tactile or auditory information for use by visually impaired people while navigation. The prototype, shown in "Fig. 8" (top) is consisted of two stereo cameras, a tactile unit (glove with five piezoelectric buzzers on each fingertip), and a portable computer. Each finger corresponds to a spatial direction (Fig. 8 bottom). For example, the middle finger corresponds to straight ahead. Using a standard stereovision algorithm, the depth map is created and then divided into five vertical sections, each one corresponding to a vibration element. If a pixel in an area corresponds to a threshold distance (here 3 ft) then the corresponding vibration

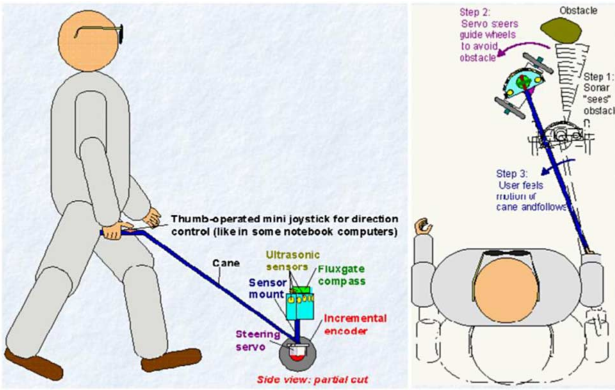

Fig. 9. Schematic (left) and operation (right) of the Guidecane prototype.

element is activated, informing the user about a close obstacle in that direction. The low power/cost is the pros but the lack of sophisticated methodologies (e.g., the stereovision algorithm needs improvement) does not offer interesting results.

I. Guidecane

Guidecane [13] is the second project by Borenstein, and it serves as an update for Navbelt. It is a device that the user can hold like a white cane and that guides the user by changing its direction when an obstacle is detected (Fig. 9).

The sketch of the prototype is shown in "Fig. 3" (left). A handle (cane) is connected to the main device. The main device has wheels, a steering mechanism, ultrasonic sensors, and a computer. The operation is simple: the user moves the Guidecane, and when an obstacle is detected the obstacle avoidance algorithm chooses an alternate direction until the obstacle is cleared and route is resumed (either in a parallel to the initial direction or in the same). There is also a thumb-operated joystick at the handle so that the user can change the direction of the cane (left or right). The sensors can detect small obstacles at the ground and sideways obstacles like walls.

Compared to the competitive ETAs, the Guidecane does not block the users hearing with audio feedback and since the computer automatically analyzes the situation and guides the user without requiring him/her to manually scan the area, there is no need for extensive training. The drawbacks are the limited scanning area since, small or overhanging objects like pavements or tables cannot be detected and that the prototype is bulky difficult to hold or carry when needed.

J. Electron-Neural Vision System

The electron-neural vision system (ENVS) by Meers and Ward from University of Wollongong in Australia [14] aims to achieve obstacle avoidance and navigation in outdoor environments with the aid of visual sensors, GPS, and electrotactile simulation. The prototype (Fig. 10) is consisted of a headset with two stereo cameras and digital compass, a portable computer with GPS capabilities and database of landmarks, the transcutaneous electrical nerve stimulation (TENS) unit (microcontroller), and the TENS gloves.

Fig. 10. ENVS and its components.

The basic concept behind the ENVS prototype is the stereo cameras, using stereoscopic vision, create a depth map of the environment and using the portable computer, information regarding the obstacles (from the depth map) or landmarks (from GPS) is transformed via TENS to electrical pulses that stimulate the nerves in the skin via electrodes located in the TENS data gloves. The user perceives the information if imagines that his/her hands are positioned in front of abdomen with fingers extended. The amount of stimulation is directly proportional to the distance of the objects in the direction pointed by each finger.

The prototype was tested with blindfolded users in outdoor campus environment, working in real time (video of 15 frames/s). With a minimum training (1 h) the users were able to report the location of obstacles, avoid them and arrive at a predefined destination. The system is one of the most complete in this survey because it is portable, real time, it has GPS capabilities, it does not block user's hearing, and the first experimental results are very promising. Some of the drawbacks are that the ground or overhanging objects are not detected, that a flat path is required (i.e., no stairs or drop-offs) and that the user is required to wear the TENS gloves.

K. CyARM

CyARM is developed by researchers in Japan (Future University-Hakodate, Kanazawa University, Ochanomizu University and Fuji Xerox Company Ltd.) [15]. It is an aid for use in guiding orientation and locomotion, using a nonstandard interface: ultrasonic sensors detect obstacles and calculate their distance from the user. The user is informed about the distance via the tension of a wire that is attached on him (e.g., his belt): high tension indicates close distance (the user can reach the obstacle by extending his/her hand), while a lower tension indicates longer distance.

The prototype is a handheld device weighting 500 g. It contains a microcontroller that processes the information from the sensors and operates a geared motor/reel that controls the tension of the wire (Fig. 11).

Small-scale experiments were performed to evaluate CyARM's efficiency in detecting obstacles, navigation through paths and target tracking. The results for the obstacle detection and navigation through tasks were promising since more than 90% of the times the subjects were able to detect the large obstacles placed in front of them or to judge if it is possible

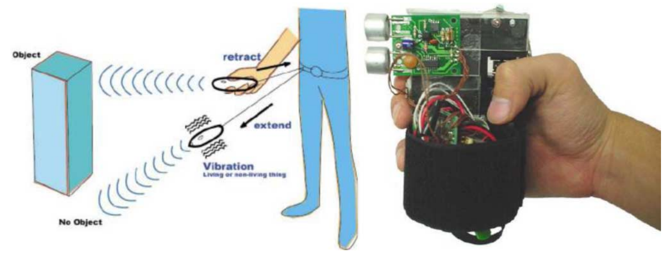

Fig. 11. Prototype CyARM and the concept of operation.

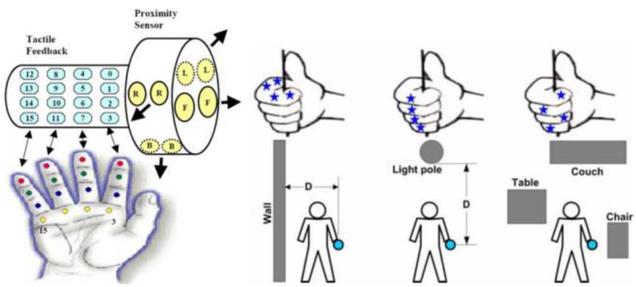

Fig. 12. Description of vibrotactile actuators positions on the Tactile Handle and three navigation scenarios.

to navigate through two of them. On the contrary, the moving target tracking results were not so encouraging.

The system's major advantage is its easy-to-learn (as the authors claim) alternative interface. The main disadvantages are that the user needs to hold it and scan the environment continuously and the lack of many experimental results with visually impaired users.

L. Tactile Handle

Bouzit and coworkers from State University of New Jersey developed the tactile handle [16], [17], a device that will help visually impaired people navigate in familiar and nonfamiliar environments without any assistance. The prototype is a compact (5 cm $\times$ 5 cm $\times$ 20 cm), lightweight, ergonomic, low-power (80 h autonomy) handheld device. It embeds a microcontroller, a 4 $\times$ 4 tactile array, where each actuator matches one finger phalanx, and 4 sonar sensors, which detect obstacles in the front, left, right, and bottom.

Information about the obstacles is given in an encoded form through the actuators. The location of the feedback represents different direction of the obstacle (Fig. 12). The intensity represents different distance and the timing of the feedback makes the user feel more comfortable and helps him/her understand dynamic aspects of the environment such as speed. Simple experiments with blind-folded users were performed in controllable indoor environments. The results show that training is necessary and the device can perform as an obstacle detection system.

The contributions of this project are mostly the development of low-power ergonomic and compact prototype actuators, which do not block the user's hearing. On the other hand, it requires from the user to constantly scan and use one of his/her hand. Furthermore, the results show that excessive training is necessary.

Fig. 13. TVS prototype.

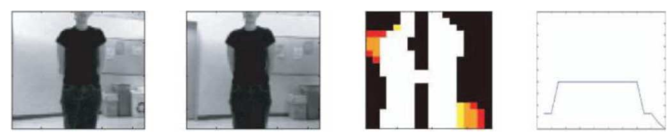

Fig. 14. Example of TVS operation: image from the two camera, disparity map, and the corresponding signals sent to the tactor belt.

M. Tactile Vision System

The objective of Johnson and Higgins from University of Arizona [18] was to create a wearable device that converts visual information into tactile signal to help visually impaired people self-navigate through obstacle avoidance. The prototype is named tactile vision system (TVS) (Fig. 13) and is consisted of a tactor belt with 14 vibrator motors spaced laterally, a camera belt with two web cameras attached and a portable computer carried in a backpack.

A 2-D depth map is created using the images from the two cameras. Then it is sliced in 14 vertical regions. Each vibrator motor is assigned one region and the value of the closest object in each region is transformed to vibration (Fig. 14). Vibration frequency and distance of object are nonlinear (increases dramatically for closer objects) and very far or very close objects are ignored. Information given by the tactor belt is applied on the skin of the abdomen (flat, large, easily accessible, no interference with other navigation functions of user). Video is captured with rate up to 10 frames/s, which makes the system real time for normal walking speeds.

The major advantages of TVS are that it is wearable, it gives user free hands without blocking hearing,. and it operates in real time. The disadvantages are that it cannot differentiate between overhanging and ground obstacles and that no real experiments with visually impaired people have been performed. Future works consists of using different stereovision algorithms, different configuration of the tactor array and a possible very large scale integration (VLSI) implementation. In addition, studies will be performed on what type and what quantity is minimally necessary for navigation and what is the point of saturation beyond which perceptual improvements are minimal.

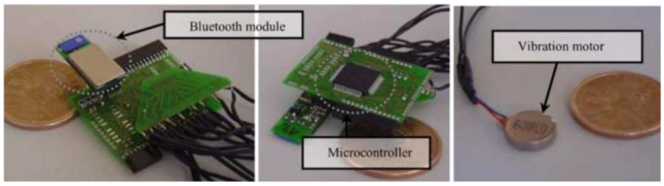

Fig. 15. Hardware details of the EPFL prototype.

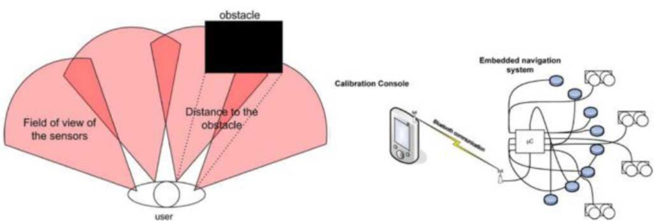

Fig. 16. Operation and high-level design of the EPFL prototype.

N. EPFL Project

Cardin *et al.* from École Polytechnique Fédérale de Lausanne (EPFL) [19] developed a wearable system that detects obstacles on shoulder height via a stereoscopic sonar system and sends back a vibrotactile feedback to inform the user about its localization. The prototype consists of sonar sensors, a microcontroller, eight vibrators, and a calibration console (PDA).

The microcontroller (Fig. 15) gathers information from the sonars (Fig. 16) proportional to the distance of the obstacle detected. It calculates the approximate distance of the obstacle and then converts the distance to a pulse width modulation (PWM) signal that is redirected to the vibrators (different vibration speeds), so that the user can be informed for the detection. The sonars and the vibrators are mounted on the clothes of the user, starting from one shoulder and ending to the other. Finally the calibration console communicates with the microcontroller via bluetooth and allows dynamical modification of the calibration curve (real distance between object and sensor).

Experimental results were obtained by testing the device in a controlled indoor environment (corridor with people walking and doors opening and closing) on 5 users. The results were encouraging since the users managed after a small training to walk through the corridor, distinguish obstacles (which are on the left or on the right side) and localize themselves in the corridor.

The pros of this project are that it is a wearable light, low-power consumption, and low-cost system. The cons are that is not tested on visually impaired people and that four sonars cannot represent adequately 3-D space (different heights). Another practical problem mentioned by the authors is the interference of hands and their detection as obstacles.

O. Tyflos

Tyflos navigation system was conceived by Bourbakis and workers in the mid-1990s and various prototypes have been developed [20]–[22]. The Tyflos navigation system is consisted of two basic modules: the Reader and the Navigator (ETA).

Fig. 17. Tyflos' second prototype hardware components. Left: stereo cameras attached on dark eyeglasses, microphone, earphones, and portable computer. Right: 2-D vibration array vest attached on a user's abdomen.

The main goal for the Tyflos system is to integrate different navigation assistive technologies such as a wireless handheld computer, cameras, range sensors, GPS sensors, microphone, natural language processor, text-to-speech device, and a digital audio recorder, etc., and methodologies such as region-based segmentation, range data conversion, fusion, etc., in order to offer to the blind more independence during navigation and reading. The audio–visual input devices and the audio-tactile output devices can be worn (or carried) by the user. Data collected by the sensors are processed by the Tyflos' modules each specialized in one or more tasks. In particular, it interfaces with external sensors (such as GPS, range sensors, etc.) as well as the user, facilitating focused and personalized content delivery. The user communicates the task of interest to the mobility assistant, using a multimodal interaction scheme.

The main role of the navigator is to capture the environmental data from various sensors and map the extracted and processed content onto available user interfaces in the most appropriate manner. Previous Tyflos prototypes are designed using many of the technologies mentioned above and tested yielding promising results. The latest Tyflos navigator system prototype developed in Wright State University is shown in "Fig. 17". It consists of two cameras, an ear speaker, a microphone, a 2-D vibration array vest (attached on the user's abdomen) controlled by a microprocessor, and a portable computer, and it integrates various software and hardware components [21], [22].

The stereo cameras create a depth map of the environment (which can be verified by the range sensor's output). A high-to-low resolution algorithm drops the resolution of the depth map into a low resolution, keeping necessary information for navigation such as safe navigation paths and objects of interest (moving objects and people, using motion detection and face-detection methodologies) [22]. This final "image" is a representation of the 3-D space, and it is converted into vibration sensing on a 2-D vibration array/vest that is attached on the user's abdomen or chest. The element of the array that vibrates represents the direction, where an object is detected and the different vibration levels represent the distance of the object [21] (Fig. 18). Optional audio feedback can inform the user for objects of interest.

The main advantages of the Tyflos are that is free-ears and that the use of the 2-D vibration array with the variable vibration frequencies offers the user a more accurate representation of the 3-D environment (including ground and head height obstacles) giving also information for distances. The disadvantages are

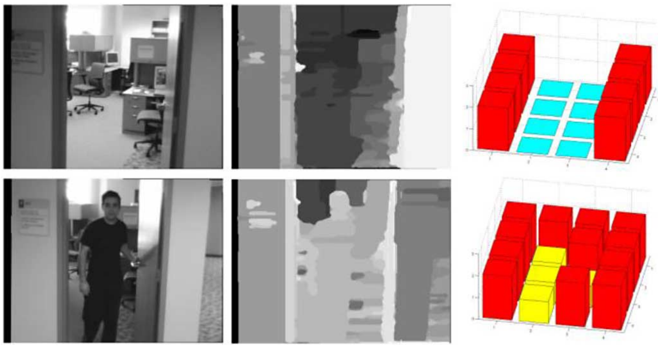

Fig. 18. Operation of the Tyflos with two navigation scenarios (one in each row). Left column shows the images captured by the cameras; middle columns are the depth maps; right column is what the user senses via the 4 × 4 vibration array. (Light blue = no bar = no vibration = obstacle further than 4 m, Yellow = low bar = vibration level 1 = obstacles in range [2,4) m, Red = tall bar = vibration level 2 = obstacle in range [1,2) m). In the second, the user feels that there is no open path.

that the system is not yet tested on blind users, which is an important step for receiving feedback for future hardware and software changes.

P. FIU Computer Vision Project

Adjouadi from Florida International University [23] worked on a computer vision project in order to exploit, in an optimal fashion, the information acquired by cameras to yield useful descriptions of the viewed environment. Then, efficient and reliable cane cues can be sought in order to improve the mobility needs of individuals with visual impairments.

The system is consisted of digital cameras and a microcomputer, which is equipped with software for detection of depression or drop-offs, discrimination of upright objects from flat objects, identification of shadows, identification of special objects (staircase, crosswalk, doorway, etc.), planning of safety path/direction.

This project is not yet to be considered as an operational ETA since issues, as how the user will be informed during navigation are still open, but the algorithms are specially designed and implemented for navigation of blind and visually impaired. The author proposed audio verbal messages or tactile devices. As far as the software part, the strong points are that the algorithms were tested with good results since many special cases are considered (staircases, vertical edges, depressions, etc.) with the limitation that there are good-lightning conditions.

Q. UCSC Project

Manduchi and Yuan from University of California Santa Cruz (UCSC) [24] developed a noncontact handheld tool for range sensing and environment discovery for the visually impaired. The basic argument is that a perception through exploratory movements (similar to those using a white cane), appears to be a natural procedure for environment discovery. Thus, the tool is handheld and as the user swings it around (vertical or horizontal) he/she will receive information by means of tactile devices. The system deals only with 1-D data, which is

Fig. 19. UCSC's handheld device equipped with laser range sensor.

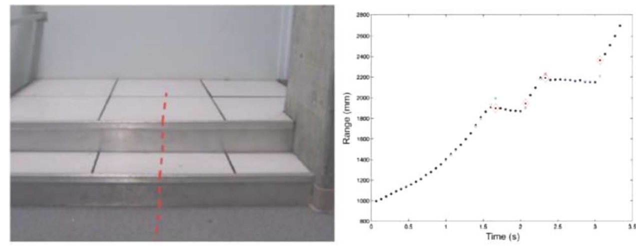

Fig. 20. Time profile of two steps acquired as the device was pivoted in an upward motion.

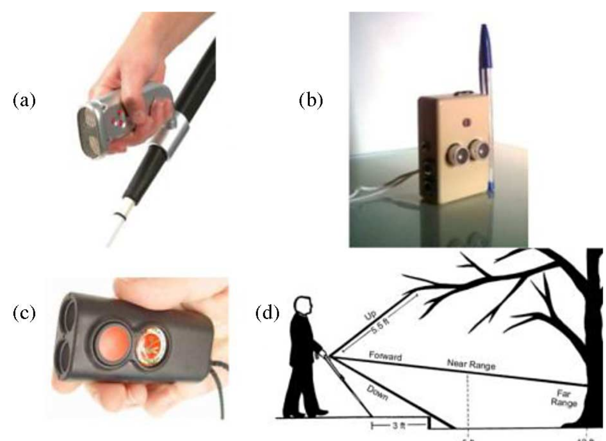

Fig. 21. Commercial products: (a) K-Sonar Cane; (b) Mini-radar; (c) Mini-guide; and (d) LaserCane.

computationally cheaper than computer vision or spatial sound techniques. The prototype is consisted of a laser range sensor (point laser matched with a matrix CCD), as seen in "Fig. 19", and a computer. The rage sensor is based on active triangulation. In addition, the time profile of the range is analyzed by the computer to detect environmental features that are critical for mobility, such as curbs, steps, and drop-offs (Fig. 20), by means of an extended Kalman filter tracker. The detection technique used works for detecting planar structures.

The system is reliable for local range measurements and gives promising environmental features detection. In addition, although it is handheld, it is small and easy to carry. The disadvantages are that it is not tested with visually impaired people, there is no interface between device and user and that it is constraint in the detection of only planar structures and objects near the ground. Some of the future improvements that are proposed by the authors are improvement of feature detection algorithms; replace of point laser with laser striper; built in processor in

TABLE I
STRUCTURAL AND OPERATIONAL FEATURES

#	Feature	Description
F1	Real time	The system operates fast enough so that the information exchange with the user is useful e.g. if an obstacle detection system needs 10 seconds to detect an obstacle that is 6 feet in front of the walking-user, then the device is not real time.
F2	Wearable	The device is worn on the user's body or as a piece of his clothing. Wearable devices are useful for applications that require computational support while the user's hands, voice, eyes, ears or attention are actively engaged with the physical environment. The interaction between the user and the device is constant. Another feature is the ability to multi-task: it is not necessary to stop what you are doing to use the device; it is augmented into all other actions.
F3	Portable	The device is light and small with an ergonomic shape so that the user can carry it without effort, for long distances and time.
F4	Reliable	The system functions correctly in routine but also in different hostile or/and unexpected circumstances.
F5	Low-cost	The device is (or it will be, when it comes to the massive production stage) affordable for most users.
F6	Friendly	The device is easy to learn, easy to use and encourages the user to regard the system as a positive help in getting the job done.
F7	Functionalities	The number and the importance of the system's functionalities.
F8	Simple	The complexity of both hardware and software is small. The hardware parts are few and simple to use (from the user's part) and simple to build (from the designer's part).
F9	Robust	The device is well constructed so it can resist in difficult environmental conditions or in hard use. Its functionality varies minimally despite of disturbing factor influences. It can still function in the presence of partial failures.
F10	Wireless connectivity	The device is connected wireless to a computer (server/database) in order to continuously exchange information. Additionally, part of the processing needed for its operation can be done on the remote computer.
F11	Performance	Overall performance
F12	Originality	The idea and the methodology are original promoting scientific and technological knowledge.
F13	Availability	The system is implemented. A device that is ready to use and real-time experiments can be performed e.g. a system that is only in the software stage is not available.
F14	Future	Future improvements or enhancements

Features F1–F7 correspond to user's needs, while F8–F14 reflect the developer's and engineer's views.

the device will replace computer; and tactile devices that will inform user for features detected.

R. Commercial Products

There are various commercial products available in the market. Their functionalities are limited and they have small scientific and technological value. In addition, their cost is relatively high, and they are not widely accepted by the users. Therefore, we will present some of them with a small description, without going into deeper analysis.

K-Sonar Cane [25] is a device that is attached in traditional white canes [Fig 21(a)]. It is consisted of an ultrasonic range sensor (sonar) and a microprocessor that converts the distances to sound that the user can listen through earphones. Distant objects are related to high-pitch sounds and near objects to low-pitch sounds. Its price is approximately $700. Mini-Radar [26] is a device [Fig. 21(b)] that uses sonar to detect frontal obstacles. It produces audio language messages when an object is detected. It can also provide information about the distance of the object. Another function is the "directional stability" that helps user to walk straight without changing his direction. It is priced approximately $600. Miniguide [27] is a small device like a handlight [Fig. 21(c)] that indicates the distance to the closest object, via its vibration rate. It has multiple modes and ranges (up to 8 m). The faster the vibration rate, the closer the object. The aid has an earphone socket that can provide audio feedback. It is priced at approximately $330. LaserCane [28] is a cane with three laser range sensors: for head-height, straight-ahead and drop-offs obstacles [Fig. 21(d)], and an audio system that produces warning sounds (or corresponding to the obstacles distance) and vibration stimulators for warnings. The user can select between sound, vibration, or both. It is priced at approximately $3000. Ultracane [29] is also a cane with embedded laser range scanners. If an obstacle is detected then certain vibration buttons warn the user. There are different vibrations for different directions and different vibration rates depending on the distance of the obstacle. Its price is approximately $900.

III. MATURITY ANALYSIS

A. Structural and Operational Features

After discussion with several groups of users (visually impaired), software developers and engineers, we came up with a set of features that better represent their views about an ETA. Those features will be used for the maturity analysis of each ETA. Table I describes those features.

B. Maturity Tables

At this point, we attempt to quantitatively evaluate the systems' progress/maturity in order to offer some reference work for them rather a comparison. For every feature we assign a weight (w_i), which reflects its importance from the user's view. The weights are calculated using a win-or-lose one-by-one comparison described below.

Every feature is compared with every other feature. A binary table is created following this procedure: if the feature from the row i is more important than feature from column j then we assign element (i, j) of the table as 1 (win). If it is less important, we assign else 0 (lose). The weight for every feature is calculated by summing the number of the 1s and normalizing to 10. The weights are shown in Table II.

For every feature (F_i) and for every system (A–Q), we assign a score based on the information we have for each system, which most of the times is solely got from the literature, and our discussion with our groups of users and engineers. Thus, each feature for each system will have a value (x_i) between 0

TABLE II
TABLE OF SCORES FOR ALL SYSTEMS AND FEATURES

	Features	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
	Weights	*9.3*	*8.6*	*5.7*	*7.1*	*5.0*	*4.3*	*2.7*	*2.9*	*2.1*	*1.4*	*10.0*	*1.4*	*5.0*	*6.4*
	System								**Scores**						
A	Echolocation	*9*	*9*	*9*	*4*		*3*	*3*	*9*	*5*		*2*	*5*	*10*	*3*
B	Navbelt	*7*	*5*	*7*	*4*	*6*	*3*	*4*	*6*	*6*		*5*	*5*	*10*	*1*
C	vOICe	*6*	*9*	*9*	*3*	*9*	*3*	*3*	*9*	*5*		*6*	*4*	*10*	*6*
D	University of Stuttgart	*8*	*0*	*9*	*6*	*7*	*8*	*6*	*6*	*7*	*10*	*6*	*8*	*10*	*8*
E	FIU	*7*	*8*	*9*	*5*	*7*	*4*	*5*	*7*	*5*		*6*	*5*	*10*	*8*
F	Virtual Acoustic Space	*6*	*9*	*9*	*6*	*8*	*4*	*5*	*6*	*5*		*6*	*7*	*10*	*7*
G	NAVI	*9*	*8*	*8*	*6*	*8*	*4*	*5*	*6*	*5*		*6*	*7*	*10*	*7*
H	University of Guelph	*9*	*8*	*8*	*5*	*6*	*7*	*8*	*5*	*5*		*3*	*6*	*10*	*9*
I	GuideCane	*9*	*0*	*5*	*6*	*6*	*7*	*6*	*5*	*7*		*6*	*7*	*10*	*5*
J	ENVS	*9*	*8*	*8*	*8*	*6*	*7*	*9*	*5*	*7*	*10*	*7*	*8*	*10*	*7*
K	CyARM	*8*	*0*	*9*	*5*	*9*	*8*	*5*	*7*	*5*		*6*	*9*	*10*	*7*
L	Tactile Handle	*9*	*0*	*8*	*7*	*7*	*7*	*6*	*7*	*8*		*4*	*8*	*10*	*6*
M	TVS	*9*	*8*	*8*	*7*	*6*	*8*	*8*	*5*	*6*		*5*	*7*	*10*	*8*
N	EPFL	*9*	*9*	*9*	*6*	*9*	*9*	*5*	*9*	*6*		*6*	*8*	*10*	*8*
O	Tyflos	*6*	*8*	*8*	*7*	*5*	*9*	*8*	*5*	*5*		*6*	*9*		*9*
P	FIU cv project	*5*	*0*	*7*	*6*	*9*	*5*	*8*	*4*	*7*			*8*		*3*
Q	UCSC	*9*	*0*	*8*	*4*	*6*	*4*	*3*	*5*	*3*		*5*	*6*	*10*	*6*

A–G: Audio feedback; H–O: tactile feedback; P–Q: no interface.

and 10 (Table II). If we do not have enough information for a feature of a system, we do not assign any score. Note that in this evaluation we provide for availability of the device, and its wireless feature the value 10 or no value for computational reasons. Finally using the formula below, we calculate a total score for each system, presented in "Fig. 20" (maturity ranking).

$$S = \sum_{i=1}^{N} \frac{w_i x_i}{N} + b$$

where i refers to a specific feature, N is the total number of features for each system, and b is bias (for now, $b = 2$).

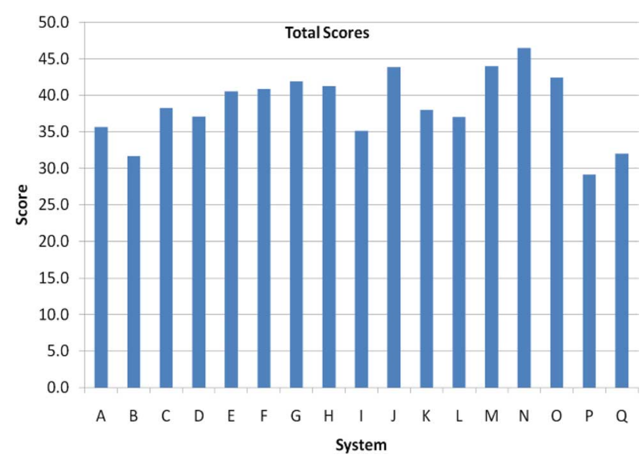

Fig. 22. Maturity ranking that shows the total score for each system.

IV. DISCUSSION

The table of scores (Table II) shows that there is no system incorporating all the features in a satisfactory degree. Features reflect mostly the user's perspective but also the designer's perspective. Every system offers something special over the others but it cannot meet all the needs, since an ideal system should have all the features and many functionalities (e.g., reliability, wireless capabilities, low price, etc.). The most important finding here is that there is no system yet that the visual impaired users are confident about its reliability, its robustness, and its overall performance. This is because most of the systems are, in the best-case, at the prototype stage, and real time, long-time experiments with visually impaired people have not been performed.

The maturity ranking (Fig. 22) gives us a big picture for all the reviewed ETAs; a measure of the system's progress/maturity. The ones with higher scores show better progress and/or more features. The systems that got lower scores are not of less technological or usage value, but they are still in the early stage of their progress and they have not reached their maximum of their performance. Finally, we want to mention that the commercial products have limited functionalities, small scientific/technological value and high cost, so they were excluded from the analysis.

After carefully studying the above systems and taking into account previous works [4], [30], [31] and our personal experience we gained from the research, design and development of our system, we can summarize some guidelines for the development of electronic travel aids. Some of them are already mentioned in the introduction of this survey.

The difficulty is not developing a system that has all the "bells and whistles" because technology is progressing rapidly, but to conceive the idea/system that will last in time and be useful.

In the development of ETAs, the most challenging is to define the proper interface between the system and the user; how and what information is sent to the user; define a robust human–computer interaction scheme. We would like to emphasize in the following characteristics:

1) *Free-hands:* not requiring from the user to hold them. Remember that the users will still hold the white cane, the most undisputable travel aid;
2) *Free-ears:* despite the advantages of echolocation, spatial sound, and similar techniques, the user's ability to listen environmental should not be interfered;
3) *Wearable:* it offers flexibility to the users and utilizes the advantages of wearable technologies;
4) *Simple:* easy to use (operation and interface not loaded with unnecessary features) and without the need of extensive training period.

REFERENCES

[1] National Federation of the Blind. (2009, May 8). [Online]. Available: http://www.nfb.org/

[2] American Foundation for the Blind. (2009, May 8). [Online]. Available: http://www.afb.org/

[3] International Agency for Prevention of Blindness. (2009, May 8). [Online]. Available: http://www.iapb.org/

[4] B. B. Blasch, W. R. Wiener, and R. L. Welsh, *Foundations of Orientation and Mobility*, 2nd ed. New York: AFB Press, 1997.

[5] T. Ifukube, T. Sasaki, and C. Peng, "A blind mobility aid modeled after echolocation of bats," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 5, pp. 461–465, May 1991.

[6] S. Shoval, J. Borenstein, and Y. Koren, "Mobile robot obstacle avoidance in a computerized travel aid for the blind," in *Proc. 1994 IEEE Robot. Autom. Conf.*, San Diego, CA, May 8–13, pp. 2023–2029.

[7] P. B. L. Meijer. (1992, Feb.). An experimental system for auditory image representations. *IEEE Trans. Biomed. Eng.* [Online]. *39(2)*, pp. 112–121. Available: http://www.seeingwithsound.com/

[8] A. Hub, J. Diepstraten, and T. Ertl, "Design and development of an indoor navigation and object identification system for the blind," in *Proc. ACM SIGACCESS Accessibility Computing*, Sep. 2003/Jan. 2004, no. 77–78, pp. 147–152.

[9] D. Aguerrevere, M. Choudhury, and A. Barreto, "Portable 3D sound / sonar navigation system for blind individuals," presented at the 2nd LACCEI Int. Latin Amer. Caribbean Conf. Eng. Technol. Miami, FL, Jun. 2–4 2004.

[10] J. L. González-Mora, A. Rodríguez-Hernández, L. F. Rodríguez-Ramos, L. Díaz-Saco, and N. Sosa. (2009, May 8). Development of a new space perception system for blind people, based on the creation of a virtual acoustic space. Tech. Rep. [Online]. Available: http://www.iac.es/proyect/eavi

[11] G. Sainarayanan, R. Nagarajan, and S. Yaacob, "Fuzzy image processing scheme for autonomous navigation of human blind," *Appl. Softw. Comput.*, vol. 7, no. 1, pp. 257–264, Jan. 2007.

[12] R. Audette, J. Balthazaar, C. Dunk, and J. Zelek, "A stereo-vision system for the visually impaired," Sch. Eng., Univ. Guelph, Guelph, ON, Canada, Tech. Rep. 2000-41x-1, 2000.

[13] I. Ulrich and J. Borenstein, "The guidecane – applying mobile robot technologies to assist the visually impaired people," *IEEE Trans. Syst., Man Cybern., A: Syst. Hum.*, vol. 31, no. 2, pp. 131–136, Mar. 2001.

[14] S. Meers and K. Ward, "A substitute vision system for providing 3D perception and GPS navigation via electro-tactile stimulation," presented at the *1st Int. Conf. Sens. Technol.*, Palmerston North, New Zealand, Nov. 21–23, 2005.

[15] K. Ito, M. Okamoto, J. Akita, T. Ono, I. Gyobu, T. Tagaki, T. Hoshi, and Y. Mishima, "CyARM: An alternative aid device for blind persons," in *Proc. CHI05*, Portland, OR, Apr. 2–7, 2005, pp. 1483–1488.

[16] M. Bouzit, A. Chaibi, K. J. De Laurentis, and C. Mavroidis, "Tactile feedback navigation handle for the visually impaired," presented at the 2004 ASME Int. Mech. Eng. Congr. RD&D Expo., Anaheim, CA, Nov. 13–19.

[17] C. Shah, M. Bouzit, M. Youssef, and L. Vasquez, "Evaluation of RU-netra – tactile feedback navigation system for the visually impaired," in *Proc. Int. Workshop Virtual Rehabil.*, New York, 2006, pp. 71–77.

[18] L. A. Johnson and C. M. Higgins, "A navigation aid for the blind using tactile-visual sensory substitution," in *Proc. 28th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, New York, 2006, pp. 6298–6292.

[19] S. Cardin, D. Thalmann, and F. Vexo, "A wearable system for mobility improvement of visually impaired people," *Vis. Comput.*, vol. 23, no. 2, pp. 109–118, Jan. 2007.

[20] N. G. Bourbakis and D. Kavraki, "Intelligent assistants for handicapped people's independence: Case study," in *Proc. 1996 IEEE Int. Joint Symp. Intell. Syst.*, Nov. 4–5, pp. 337–344.

[21] D. Dakopoulos, S. K. Boddhu, and N. Bourbakis, "A 2D vibration array as an assistive device for visually impaired," in *Proc. 7th IEEE Int. Conf. Bioinf. Bioeng.*, Boston, MA, Oct. 14–17, 2007, vol. 1, pp. 930–937.

[22] D. Dakopoulos and N. Bourbakis, "Preserving visual information in low resolution images during navigation for visually impaired," *presented at the 1st Int. Conf. PErvasive Technol. Related Assist. Environ.*, Athens, Greece, Jul. 15–19, 2008.

[23] M. Adjouadi, "A man-machine vision interface for sensing the environment," *J. Rehabil. Res. Develop.*, vol. 29, no. 2, pp. 57–56, 1992.

[24] D. Yuan and R. Manduchi, "A tool for range sensing and environment discovery for the blind," in *Proc. 2004 Conf. Comput. Vis. Pattern Recogn. Workshop*, Washington, DC, Jun. 27–Jul. 02, vol. 3, pp. 39–39.

[25] Bay Advanced Technologies Ltd. (2009, May 8). [Online]. Available: http://www.batforblind.co.nz/index.htm

[26] BestPluton World Cie. (2009, May 8). [Online]. Available: http://bestpluton.free.fr/EnglishMiniRadar.htm

[27] GDP Research, Australia. (2009, May 8). [Online]. Available: http://www.gdp-research.com.au/

[28] Nurion-Raycal. [Online]. Available: http://www.lasercane.com/

[29] Sound Foresight Ltd. (2009, May 8). [Online]. Available: http://www.batcane.com/

[30] T. C. Davies, C. M. Burns, and S. D. Pinder, "Mobility interfaces for the visually impaired: What's missing?" in *Proc. CHINZ 2007*, Hamilton, New Zealand, Jul. 2–4, vol. 254, pp. 41–47

[31] R. D. Easton, "Inherent problems of attempts to apply sonar and vibrotactile sensory aid technology to the perceptual needs of the blind," *Optom. Vis. Sci.*, vol. 69, no. 1, pp. 3–14, 1992.

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