

## NAVBELT AND GUIDECAKE

### Robotics-Based Obstacle-Avoidance Systems for the Blind and Visually Impaired

by

**Shraga Shoval<sup>1</sup>, Iwan Ulrich<sup>2</sup>, Johann Borenstein<sup>3</sup>**

#### **Abstract**

This article presents two novel travel aids for blind pedestrians. The two computerized devices are based on advanced mobile robotics obstacle avoidance technologies. The first aid – the NavBelt – is worn by the user like a belt and is equipped with an array of ultrasonic sensors. It provides, via a set of stereo earphones, acoustic signals that guide the user around obstacles, or “displays” a virtual acoustic panoramic image of the traveler’s surroundings. One limitation of the NavBelt is that it is exceedingly difficult for the user to comprehend the guidance signals in time to allow fast walking.

A newer device, called GuideCane effectively overcomes this problem. The GuideCane uses the same mobile robotics technology as the NavBelt but it is a wheeled device pushed ahead of the user via an attached cane. When the GuideCane detects an obstacle it steers around it. The user immediately feels this steering action and can follow the GuideCane’s new path easily and without any conscious effort. This article describes the two devices, including the mechanical, electronic, and software components, user-machine interface, and some experimental results.

## 1 Introduction

There are about two million visually impaired or blind persons in the United States alone [Jackson, 1995]. Many of these persons use the white cane – the most successful and widely used travel aid for the blind. This purely mechanical device is used to detect obstacles on the ground, uneven surfaces, holes, steps, and other hazards. The inexpensive white cane is so lightweight and small that it can be folded and slipped into a pocket. The main problem with the white cane is that users must be trained in its use for more than one hundred hours – a substantial “hidden” cost. In addition, this device requires the user to actively scan the small area ahead of him/her, and it cannot detect obstacles beyond its reach of 1 - 2 m (3.3 – 6.6 feet). Another drawback of the white cane is that obstacles can be detected only by contact. This can become inconvenient to the traveler and the surroundings, for example, when traveling in a crowded street.

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<sup>1)</sup> Faculty of Industrial Engineering and Management – Academic college of Judea and Samaria, Ariel, Israel.

<sup>2)</sup> Iwan Ulrich died in a tragic traffic accident on July 5th, 2000. At the time of his death he was a Ph.D. student at the Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA.

<sup>3)</sup> **Corresponding Author.** Department of Mechanical Engineering, The University of Michigan, Ann Arbor, Michigan, USA. Email: [johannb@umich.edu](mailto:johannb@umich.edu), Ph.: 734-763-1560, Fax: 209-879-5169.

This research was conducted at the University of Michigan’s Mobile Robotics Laboratory

Guide dogs are very capable guides for the blind, but they require extensive training. Fully trained guide dogs cost between \$12,000 to \$20,000 [Jackson, 1995], and their useful life is typically on the order of only five years. Furthermore, many blind and visually impaired people are elderly and find it difficult to care appropriately for another living being. As a result, only 1% of the visually impaired people in the U.S. have guide dogs.

With the development of radar and ultrasonic technologies, a new series of devices, known as *electronic travel aids* (ETAs) was developed for blind travelers during the past four decades. In terms of operational principles, most ETAs are similar to radar systems: a laser or ultrasonic “beam” is emitted in a certain direction in space and the beam is reflected back from objects that it confronts on its way. A matching sensor detects the reflected beam, measures the distance to the object, and indicates that information to the user through audible or tactile signals. Most existing ETAs can detect objects in the range of up to 5 m (16 feet) away from the user, but require continuous scanning of the environment in the desired direction.

One of the best known ETAs is the *C5 Laser Cane* [Benjamin et al., 1973], which is based on optical triangulation with three transmitters and three photodiodes as receivers. An UP channel detects obstacles at head-height, the FORWARD channel detects obstacles from the tip of the cane forward in the range of 1.5 - 3.5 m (5 – 11 feet) and the DOWN channel detects drop-offs in front of the user.

The *Mowat Sensor* [Pressey, 1977] is another hand-held device that informs the user of the distance to detected objects by means of tactile vibrations, where the frequency of the vibrations is inversely proportional to the distance between the sensor and the object. The Mowat sensor is a secondary aid for use in conjunction with a white cane or a guide dog. The Mowat sensor has been found helpful, and users feel they benefit from it [Shao, 1985].

The *Binaural Sonic Aid (Sonicguide)* [Kay, 1974] came in the form of a pair of spectacle frames, with one ultrasonic wide-beam transmitter ( $55^\circ$  cone angle) mounted between the spectacle lenses and one receiver on each side of the transmitter. Signals from the receivers are shifted and presented separately to the left and right ear. The resulting interaural amplitude difference allows the user to determine the direction of the reflected echo and thus of the obstacle. The distance to an object is encoded in the frequency of the demodulated low-frequency tone, which, together with the wearer’s head orientation, provides clear information about the object’s location. As the Sonicguide does not require active manual scanning, it can serve either as a primary or as a secondary device, in conjunction with an additional hand-held device or a guide dog.

The Sonicguide has undergone continuous improvements and it’s latest incarnation is an award-winning system called *KASPA* [SonicVisioN]. Unlike the Sonicguide, KASPA is worn on the user’s forehead by means of a headband. KASPA creates an auditory image of the objects ahead of the user, and, with sufficient training, allows users to distinguish different objects and even different surfaces in the environment.

As illustrated by the examples discussed in the foregoing section, three fundamental shortcomings can be identified in most ETAs:

1. The user must *actively* scan the environment to detect obstacles (no scanning is needed with the Sonicguide or KASPA). This procedure is time-consuming and requires the traveler’s constant activity and conscious effort.
2. The traveler must perform additional measurements when an obstacle is detected in order to determine the dimensions and shape of the object. The user must then plan a path around the obstacle – again, a conscious effort that reduces walking speed.

- Another problem with all ETAs based on acoustic feedback is their interference (called “masking”) with sound cues from the environment, reducing the blind person’s ability to hear these essential cues. [Lebedev and Sheiman, 1980; Kay, 1974; Brabyn, 1982].

This article introduces two novel ETAs that differ from the ETAs described above in their ability to not only detect obstacles, but to also guide the user around detected obstacles. To do so, both ETAs make use of technologies originally developed for mobile robots, as explained in Section 2. The first robotics-based ETA, called *NavBelt*, is described in Section 3. Shortcomings of the NavBelt led to the development of the substantially more practical second ETA, called *GuideCane*, which is described in Section 4.

## 2 Mobile Robotics Technologies for the Visually Impaired

Visually impaired humans and mobile robots face common problems when navigating through cluttered environments. It therefore appears logical to apply mobile robotics technologies to assist the visually impaired. *Obstacle avoidance systems* (OASs), originally developed for mobile robots, lend themselves well for incorporation in electronic travel aids for the visually impaired.

An OAS for mobile robots typically comprises a set of ultrasonic or other sensors and a computer algorithm that use the sensor data to compute a safe path around detected obstacles. One such algorithm is the Vector Field Histogram (VFH), developed at the University of Michigan’s Mobile Robotics Laboratory. The VFH method is based on information perceived by an array of ultrasonic sensors (also called “sonars” throughout this article) and a fast statistical analysis of that information. The VFH method builds and continuously updates a local map of its immediate surroundings based on the recent sonar data history. The algorithm then computes a momentary steering direction and travel speed and sends this information to the mobile robot<sup>2</sup>, as explained in more detail below.

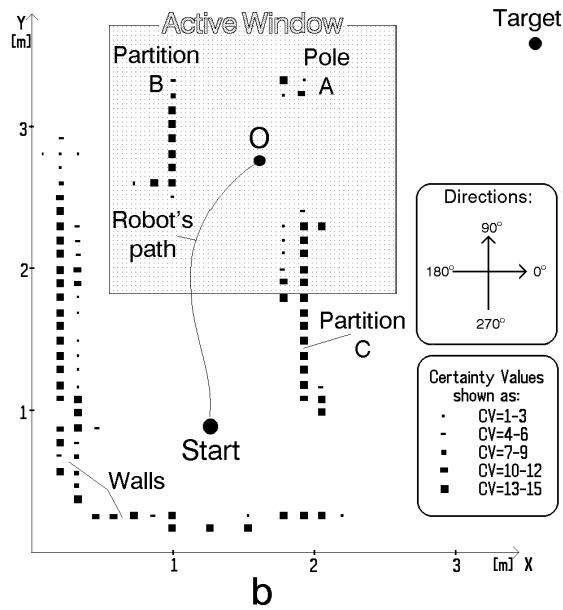
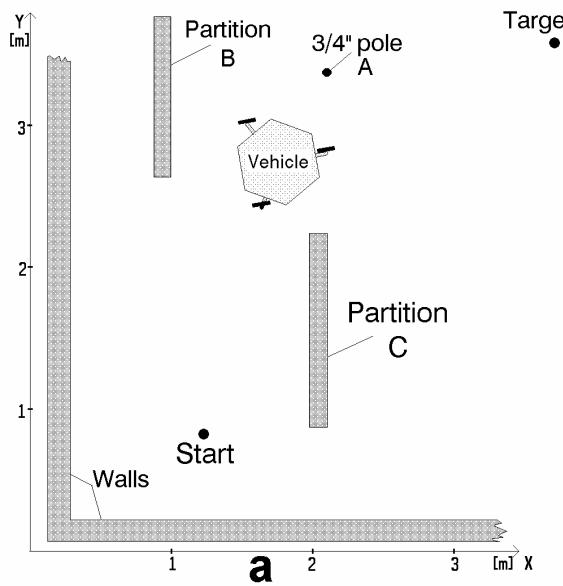
The ultrasonic sensors are controlled by the *Error Eliminating Rapid Ultrasonic Firing* (EERUF) method [Borenstein and Koren, 1995]. EERUF allows sonars to fire at rates that are 5-10 times faster than conventional methods. Each of the 10 sonars is fired at a rate of 10 Hz, so that the VFH algorithm receives 100 sonar readings per second. However, fast firing with multiple sonars can result in crosstalk, a phenomenon in which one sensor receives the echo from another sensor. By employing alternating delays before firing each sensor, EERUF is able to detect and reject crosstalk. The faster firing rate improves the reliability of the obstacle avoidance performance and is necessary for safe travel at fast walking speed.

In the VFH method the local map is represented by a two-dimensional array, called a *histogram grid* [Borenstein and Koren, 1991], which is based on the earlier *certainty grid* [Moravec, 1988] and *occupancy grid* [Elfes, 1989] approaches. Each cell contains a *certainty value* that indicates the measure of confidence that an obstacle exists within the cell area. This representation is especially suited for sensor fusion, as well as for the accommodation of inaccurate sensor data such as range measurements from ultrasonic sensors. Figure 1, which was created in an actual experiment, illustrates how a typical experimental environment translates into the histogram grid representation.

Next, the two-dimensional histogram grid is reduced to a one-dimensional *polar histogram* that is constructed around the robot’s momentary location (the mathematical process is beyond the scope of this text and is omitted here). The polar histogram provides an instantaneous 360-degree panoramic view of the immediate environment, in which elevations

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<sup>2</sup> The term “robot” is used here because the VFH method was originally developed for mobile robots. However, the discussion is also true for travel aids for the blind as described in this article.

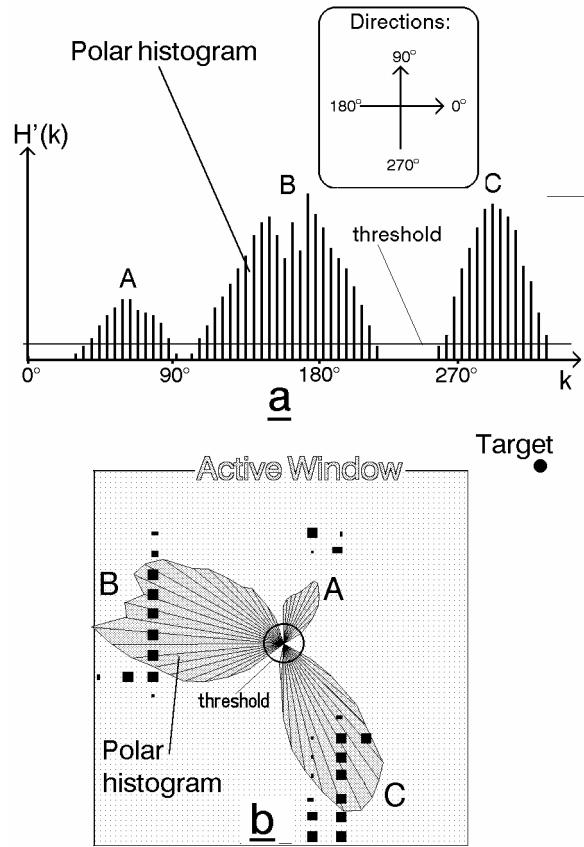


**Figure 1:** (a) A typical experimental environment. A vehicle is shown traversing the environment at some instance  $t$ . (b) The histogram grid, built from the sonar data, comprises of cells, each holding a value that expresses the certainty for the existence of an obstacle.

obstacle density values are shown as taller bars in the bar chart-type representation of Figure 2a. Note that Figure 2b represents the same polar histogram as that of Figure 2a, except that it has been overlaid onto the histogram grid for better illustration.

Although the description in this section is fairly complex, the necessary computations are performed in just a few milliseconds. Indeed, during motion a new polar histogram is recomputed every 10 milliseconds.

It is evident from Figure 2b that the polar histogram provides comprehensive information about the environment (with regard to obstacles), yet the amount of numeric information is quite small. Exactly how the information of the polar histogram is used for obstacle avoidance differs for each of the two robotics-based ETAs described in the following two sections.



**Figure 2:** Two ways of visualizing the same polar histogram generated at instant  $t$  for the environment of Figure 1.

suggest the presence of obstacles and valleys suggest that the corresponding directions are free of obstacles. The polar histogram has 72 sectors that are each  $5^\circ$  wide. The numerical values associated with each sector are called “*obstacle density*” values. High obstacle density values suggest a high likelihood for either a small object nearby or a larger object further away in the direction of that sector. Figure 2 shows the polar histogram for the environment of Figure 1 and it was also created from an actual experiment. High

### 3 The NavBelt

The Navbelt consists of a belt, a portable computer, and an array of ultrasonic sensors mounted on the front of the belt. In the experimental prototype shown in Figure 3 the user wears a “fanny pack” on the abdomen and a portable computer as a backpack. Eight ultrasonic sensors, each covering a sector of  $15^\circ$  are mounted on the front pack, providing a total scan range of  $120^\circ$ .

The computer processes the signals that arrive from the sensors, and applies the robotics obstacle avoidance algorithms described in Section 2. One fundamental difference between the OAS implemented on a robot and on the Navbelt is illustrated in Figure 4: The electrical guidance signals, which originally controlled the steering and drive motors of the robot (see Figure 4a) are replaced by acoustic signals that are relayed to the user by stereophonic headphones (see Figure 4b).

A binaural feedback system based on internal time difference (i.e., the phase difference between the left and right ear) and amplitude difference (i.e., the difference in amplitude between the two ears) creates a *virtual direction* (i.e., an impression of directionality of virtual sound sources). The binaural feedback system is used differently in each of the three operating modes that are described next.

#### 3.1 Operation modes

The NavBelt is designed for three basic operational modes, each offering a different type of assistance to the user:

##### 3.1.1 Guidance Mode

In the Guidance mode the NavBelt provides the user only with the recommended travel speed and direction, generated by the VFH obstacle avoidance algorithm. In Guidance mode the system attempts to bring the user to a specified absolute target location. This is useful when the NavBelt works in conjunction with a GPS or other map-based system, where the user can specify the target name, such as a street address or a named building. The VFH method calculates its recommendation for the momentary travel direction from the polar histogram by searching for sectors with a low obstacle density value. In practice, the algorithm determines a threshold level, and all sectors with lower obstacle density than that level become candidate sections. Next, the VFH algorithm searches for the candidate sector that is closest to the direction of the target and recommends it to the user (explained below). The recommended travel speed is determined by the VFH method according to the proximity of the user to the nearest object.

The recommended travel speed and direction are relayed to the user by a single stereophonic signal. The virtual direction of the signal is the momentary direction recommended by the VFH algorithm. The pitch and amplitude are proportional to the recommended travel speed. Higher pitch and amplitude attract more human attention



**Figure 3:** The experimental prototype of the NavBelt.

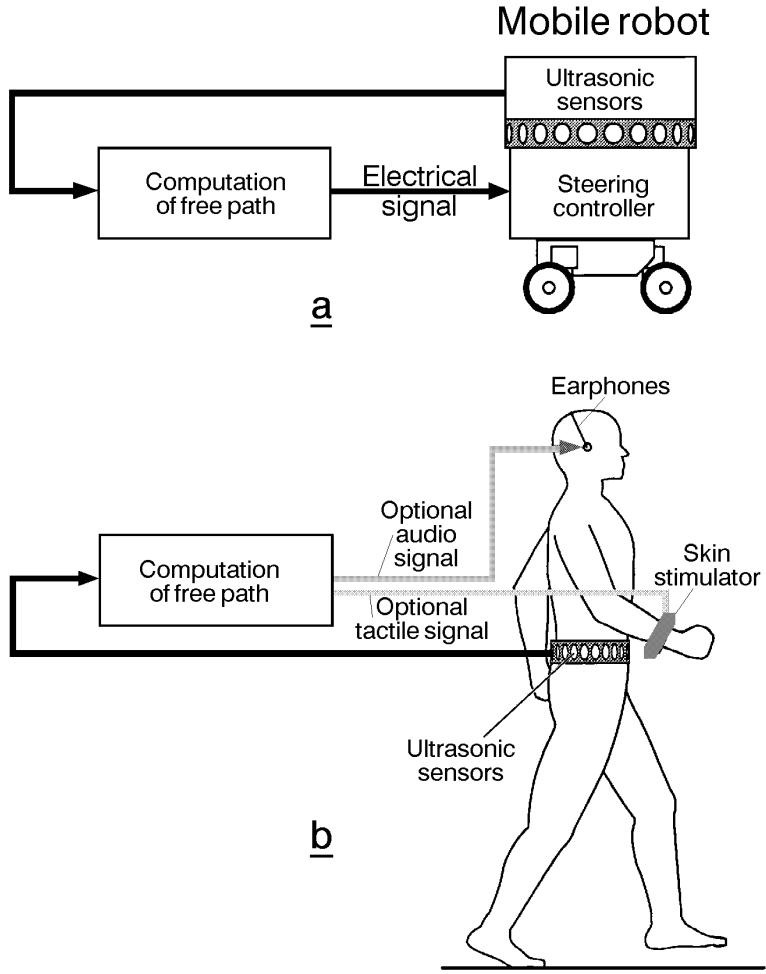
[Benson, 1986], thereby motivating the traveler to reduce the walking speed and to concentrate on the stereophonic signal. A special low pitch signal (250 Hz) is transmitted when the direction of motion coincides (within  $\pm 5^\circ$ ) with the required direction. This special tone is a simple feedback signal for the user, indicating that the travel direction is correct. This is because low pitch tones occlude external sound from the environment less than medium and high pitch tones do [Benson, 1986]. The higher pitch tone is transmitted only when the traveler needs to change the travel direction, and as soon as that direction coincides with the recommended direction the low pitch returns.

Another important parameter involved in the Guidance mode is the rate at which signals are transmitted. Although a low transmission rate causes less occlusion of external sounds, it may also be too slow to alert the traveler to hazards. An adaptive information transfer system adjusts the transmission rate according to changes in the process and the user's requirements. When the user is traveling in an unfamiliar environment cluttered with a large number of obstacles, the transmission rate increases, and may reach up to 10 signals per second. On the other hand, when traveling in an environment with little or no obstacles, the transmission rate is reduced to one signal every three seconds.

One fundamental technical difficulty with the Guidance mode is that the momentary position and orientation of the user must be known at all times (so that the system can compute the desired direction toward the absolute target location). At the time of testing the NavBelt such position technology was not commercially available. Recent advances in technology, however, make person-mounted positioning feasible and commercially available (see, for example, the *PointMan* system made by [POINT RESEARCH]).

### 3.1.2 Directional Guidance Mode

The Directional Guidance mode gives the user more control over the global aspects of the navigation task, while the NavBelt only provides reflexive obstacle avoidance. In this mode the traveler uses a joystick or other suitable input device to define a temporary target direction as follows: when the joystick is in its neutral position, the system selects a default



**Figure 4:** Transferring mobile robotics technology to a portable navigation aid for the blind: The concept of the NavBelt.

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direction straight ahead of the user, no matter which way the user is facing. If the user wishes to turn sideways, he/she deflects the joystick in the desired direction and a momentary target is selected five meters diagonally ahead of the user in that direction. In case an obstacle is detected, the NavBelt provides the user with the relevant information to avoid the obstacle with minimal deviation from the target direction. The recommended travel speed and direction are conveyed to the user through a single stereophonic signal, similar to the method used in the Guidance mode. Directional Guidance mode does not require that the user's position be measured and fed back into the system, because only directions relative to the user are relevant. However, if the user's position cannot be measured, then a simplified version of the VFH method must be used, which provides less reliable obstacle avoidance.

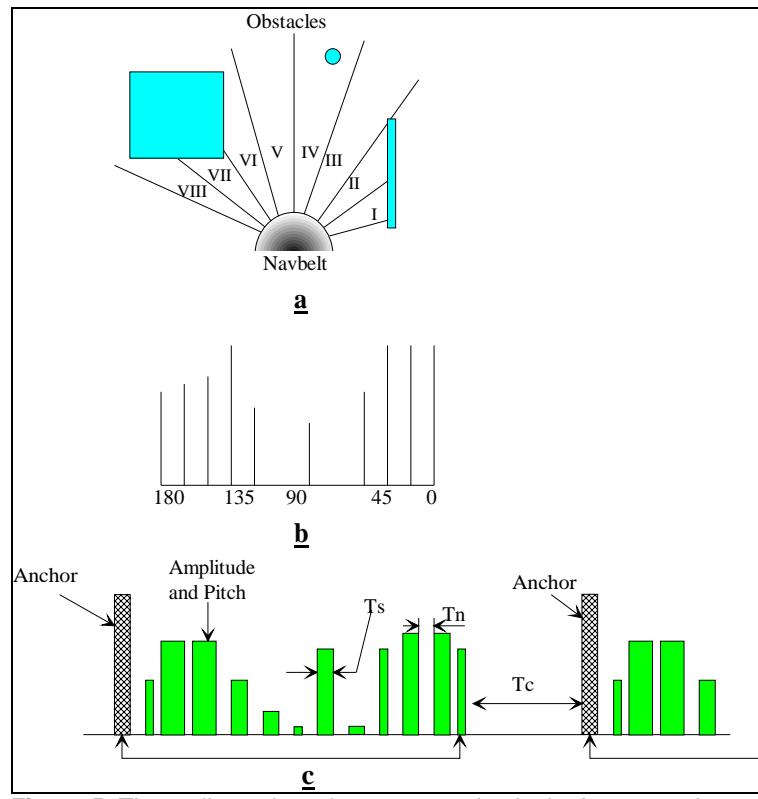
### 3.1.3 Image Mode

This mode presents the user with a panoramic *virtual acoustic image* of the environment. A virtual acoustic image is a series of stereophonic sounds that appears to “travel” through the user’s head from the right to the left ear. The principle is similar to the operation of radar systems used in air traffic control. A virtual beam travels from the right side of the user to the left through the sectors covered by the NavBelt’s sonars (a range of  $120^\circ$  and 3 m radius). The binaural feedback system invokes the impression of a virtual sound source moving with the beam from the right to the left ear in what we call a “sweep.” This is done in several discrete steps, corresponding to the discrete virtual direction steps. The angular displacement of the virtual sound source is implemented by a combination of the interaural phase and amplitude shift of the left and right stereophonic signals.

At each step, the amplitude of the signal is set proportionally to the distance to the obstacle in that virtual direction. If no obstacles are in a given virtual direction, then the virtual sound source is of a low amplitude and barely audible. Otherwise the amplitude of the virtual sound source is larger.

Figure 5 illustrates the implementation of the Image mode. Obstacles are detected by the ultrasonic sensors (Figure 5a), and are projected onto the polar histogram, as shown in Figure 5b. Based on the polar histogram, the binaural feedback system generates the sweep, which comprises of 12 steps (Figure 5c). Each step “covers” a sector of  $15^\circ$ , so that the whole sweep covers a panorama of  $180^\circ$ . Each of the eight sectors in the center of the panorama (covering the sectors between  $30^\circ$  and  $150^\circ$ ) is directly proportional to the corresponding sensor.

Each signal is modulated by an amplitude  $A$  (indicating the distance to the obstacle in that direction), the duration  $T_s$ , for



**Figure 5:** The auditory obstacle representation in the Image mode.  
(a) Obstacles are detected by the ultrasonic sensors.  
(b) Sonar range readings are projected onto the polar histogram.  
(c) An acoustic sweep is generated from the polar histogram.

which the square wave signal is audible, and the pitch  $f$  of the square wave. The *spacing time*  $T_n$  is the length of the interval between consecutive signals during a sweep. After each sweep there is a pause of duration  $T_c$ , to allow the user to comprehend the conveyed auditory image. Many meaningful combinations of these parameters are possible. For example, because of the short-term memory capability of the human ear, a sweep may be as short as 0.5 sec. Given enough cognition time  $T_c$ , the user can comprehend the image. Alternatively, the sweep time may be as long as one second, combined with a very short cognition time. Each sweep starts with an anchor signal. This signal has a unique pitch, which marks the start of a sweep.

One of the important features of the Image mode is the *acoustic directional intensity* (ADI), which is directly derived from the polar histogram. The virtual direction of the ADI provides information about the source of the auditory signal in space, indicating the location of an object. The intensity of the signals is proportional to the size of the object and its distance from the person as directly derived from the polar histogram.

The ADI is a combination of the signal duration  $T_s$ , the amplitude  $A$ , and the pitch. Experiments with human auditory perception [Benson, 1986] show that the perceived intensity increases with the signal's amplitude, pitch, and duration. Adjusting the ADI according to the location of obstacles in the surroundings attracts the user's attention to the most relevant sections in the environment, while suppressing irrelevant data.

Since the Image mode provides only information about the location of obstacles relative to the traveler, this mode does not require knowledge about the user's momentary position.

### 3.2 Experimental Results

The NavBelt was extensively tested during its five-year long development. Some of the key experimental results are presented in this section.

In one set of experiments subjects walked through laboratory obstacle courses comprising various types of obstacles and using the various operation modes of the NavBelt. In the first experiment vertical poles with different diameters were positioned throughout the room. We found that the NavBelt can detect objects as narrow as 10 mm. However, this can be done only if the objects are stationary and the subject is walking slowly (less than 0.4 m/s). We also found that the NavBelt can reliably detect objects with a diameter of 10 cm or more, regardless of the travel speed. Other tests were conducted in office building where subjects walked along corridors, located doors, and detected and avoided furniture.

In other experiments subjects walked outside buildings, detecting and avoiding common objects such as trees and large bushes, parked cars, walls, bicycles, and other pedestrians. One major concern of users was the lacking ability of the current prototype NavBelt to detect overhanging objects, up- and down-steps, sidewalk edges, etc. Future improvements to the NavBelt will require the addition of sonars pointing up and down to detect these type of obstacles.

The next set of experiments tested the NavBelt when used as a secondary ETA, together with the white cane. Even though the white cane is very thin, it can interfere with the sonars, mainly when the cane is used to detect objects at heights of 0.5 m (1.6 feet) above ground. However, since the cane is used mainly to detect objects at ground level, while the NavBelt is designed to detect objects above ground level, this interference appears not to be critical. The current detection range of the NavBelt is set for 3 meters. This range can be changed by selecting a different schedule for controlling the ultrasonic sensors. However, an increased detection range of up to 5 meters resulted in erroneous data, due to a large amount of noise

added to the incoming ultrasonic echoes. A reduced detection range of 1.5 meters resulted in insufficient warning time for walking speeds greater than 0.75 meters.

The experiments with the NavBelt prototype showed the importance of training. Subjects with more experience traveled faster and generally were more comfortable with the device. After 20 hours of practice with a NavBelt simulator and 40 hours of practice with the experimental prototype subjects walked at 0.8 m/sec in the Guidance and Directional Guidance modes and at 0.3 - 0.4 m/sec in the Image mode. Subjects with less experience (10 hours with the simulator and 10 hours with the prototype) traveled at an average speed of 0.6 m/sec in the Guidance mode. However, it took substantially longer to become practiced in the interpretation of the acoustic images in Image mode. After 100 hours of practice with the Image mode a user could walk through a moderately dense obstacle course at walking speeds of about 0.3 - 0.4 m/sec.

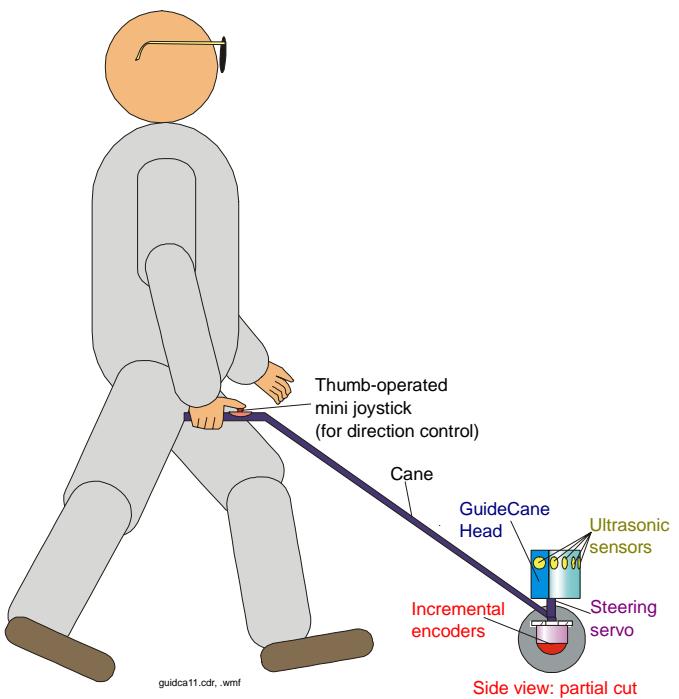
The NavBelt uses a 2D representation of the environment. This representation becomes unsafe when traveling near overhanging objects or approaching bumps and holes. This problem was addressed by Bourbakis and Kavraki in their Tyflos intelligent assistant device [Bourbakis and Kavraki, 1996]. In this device, a camera attached to a special helmet detect objects according to the user's head orientation. Adding more sonars to the front pack of the NavBelt (pointing upwards and downwards) can provide additional information. However, this requires substantial modifications to the obstacle avoidance algorithm and to the auditory interface.

## 4 The GuideCane

The foremost problem with the NavBelt in Image mode, as concluded above, is the difficulty of conveying information to the user to allow him/her to react in time to obstacles ahead. This problem is less pronounced in the Guidance mode, where, as we recall from the previous section, the problem is mostly with the practical implementation of position estimation for a human traveler. However, even if that problem could be overcome, users would still need to concentrate on the acoustic guidance signals and to react to them quickly.

An invention made at the University of Michigan's Mobile Robotics Lab aimed at overcoming these problems. This invention, called *GuideCane*, can be thought of as a robotic guide-dog. Using a mobile robot as a guide dog for the blind has been proposed in the literature as early as 1981 [Tachi et al., 1981; Preising et al. 1991]. However, mobile robots require drive motors and battery power for driving and are too heavy to be lifted up by a user, making it impossible to negotiate stairs or steps.

Figure 6 shows a schematic view of the GuideCane and its functional components. Much like the white cane, the user holds the GuideCane in front of himself/herself while walking. The GuideCane is considerably heavier than



**Figure 6:** Functional components of the GuideCane.

the white cane, but it rolls on wheels that support the GuideCane's weight during regular operation. A servomotor, operating under the control of the built-in computer, can steer the wheels left and right relative to the cane. Both wheels are equipped with encoders to determine their relative motion. For obstacle-detection, the GuideCane is equipped with ten ultrasonic sensors. To specify a desired direction of motion, the user operates a mini joystick located at the handle. Based on the user input and the sensor data from its sonars and encoders, the computer decides where to head next and turns the wheels accordingly.

#### 4.1 Functional Description

During operation, the user pushes the GuideCane forward. Similar to the NavBelt's Directional Guidance mode the user can prescribe a desired direction of motion. On the GuideCane this is done using a thumb-operated mini joystick located near the handle. This directional command is understood to be relative to the GuideCane's current direction of motion. For example, if the user presses the button forward, then the system considers the current direction of travel to be the desired direction. If the user presses the button to the left, then the computer adds 90° to the current direction of travel and, as soon as this direction is free of obstacles, steers the wheels to the left until the 90-degree left turn is completed. It is important to note that the user can usually indicate a new direction well before the change of direction should occur. In the case of a corridor, if the user presses the button to the left, then the GuideCane will continue down the corridor until it reaches an intersection where it can turn to the left. More sophisticated navigation, similar to that of the NavBelt's Guidance mode could easily be implemented on the GuideCane, allowing effective interfacing with GPS, mapping, or other orientation/navigation aids. However, in our current prototype we have not yet implemented these functions.

While traveling, the ultrasonic sensors detect any obstacle in a 120° wide sector ahead of the user (Step 1 in Figure 7). The built-in computer uses the sensor data to instantaneously determine an appropriate direction of travel. If an obstacle blocks the desired travel direction, then the obstacle avoidance algorithm prescribes an alternative direction to circumnavigate the obstacle and then resumes in the desired direction (Step 2 in Figure 7).

Once the wheels begin to steer sideways to avoid the obstacle, the user feels the resulting horizontal rotation of the cane (Step 3 in Figure 7). In a fully intuitive response, requiring virtually no training time, the traveler changes his/her orientation to align himself/herself with the cane at the "nominal" angle. In practice, the user's walking trajectory follows the trajectory of the GuideCane similar to the way a trailer follows a truck. Because of the handle's short length, the user's trajectory is very close to the GuideCane's trajectory. Once the obstacle is cleared, the wheels steer back to the original desired direction of travel, although the new line of travel will be offset from the

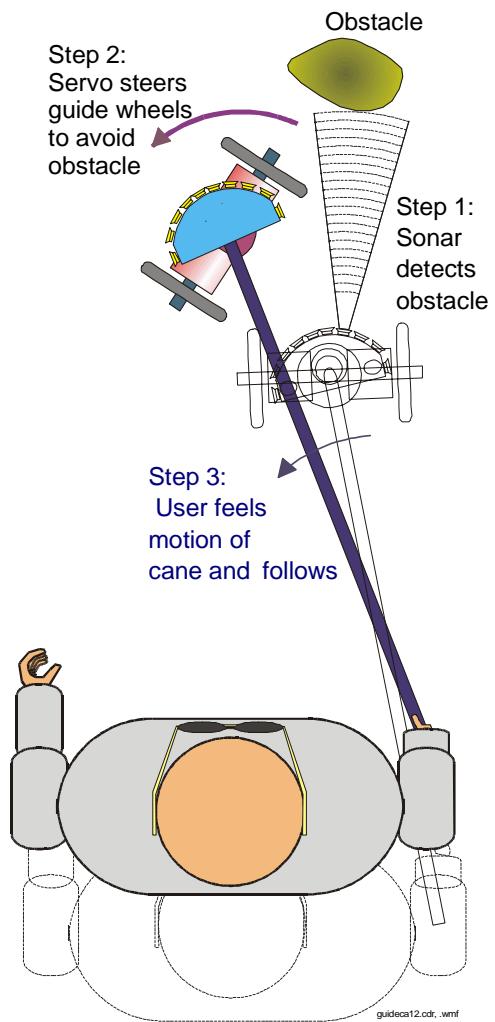


Figure 7: How the GuideCane avoids obstacles.

original line of travel. Depending on the circumstances, the traveler may wish to continue walking along this new line of travel, or the system can be programmed to return to the original line of travel. This latter option is made possible by the GuideCane's dead-reckoning capability.

A particular problem is the detection of stairs. The GuideCane offers separate solutions for down-steps and up-steps. Down-steps are detected in a fail-safe manner: when a down-step is encountered, the wheels of the GuideCane drop off the edge until the shock-absorbing bottom hits the step – without a doubt a signal that the user cannot miss. Because the user walks behind the GuideCane, he/she has sufficient time to stop. Up-steps can be detected by additional front-facing sonars as described in [Borenstein and Ulrich, 1997]; however, this method is not yet implemented in our current prototype.

## 4.2 Guidance Signals versus Obstacle Information

Existing ETAs are designed to inform the user about obstacles, usually requiring him/her to perform some sort of scanning action. The user must then analyze the obstacle information and decide on a suitable travel direction. In sighted people, such relatively high bandwidth information is processed almost reflexively, usually without the need for conscious decisions. Nature had millions of years of evolution to perfect this skill. However, the evaluation of obstacle information presented acoustically is a new skill that must be acquired over hundreds of hours of learning, as we concluded in Section 3.2 and in [Shoval et al., 1998b]. Even then, exercising such a skill requires a great deal of conscious effort, and thus processing time. The required effort further increases with the number of detected obstacles.

The GuideCane is fundamentally different from other devices in that it first analyzes the environment and then computes the momentary optimal direction of travel. The resulting guidance signal is a single piece of information – a direction – which means that the bandwidth of the information is much smaller. Consequently it is far easier and safer to follow the low-bandwidth guidance signal of the GuideCane than to follow the high-bandwidth information of other existing systems.

## 4.3 Information Transfer

In prior research with the NavBelt different methods were tested that use binaural (stereophonic) signals to guide the user around obstacles as described in Section 0. Subjects found it difficult to recognize and react to such signals at walking speed [Shoval et al., 1998b]. By contrast, our tests with the GuideCane showed that untrained subjects could *immediately* follow the GuideCane at walking speed, even among densely cluttered obstacles.

This fundamental advantage can be credited to another unique feature of the GuideCane: information transfer through direct physical force. This process is completely intuitive so that everybody can use the system right away without learning how to interpret artificially defined acoustic or tactile signals, as with existing ETAs. Yielding to external forces is a reflexive process that does not require a conscious effort. Moreover, many blind persons are accustomed to being guided by sighted people in a similar fashion. In recent years the term “haptic display” has become popular among scientists to describe a machine-to-human interface, in which physical forces provide easy-to-comprehend information to the human. Typical examples for other haptic displays are force-feedback joysticks or the recently introduced *iFeel MouseMan* force-feedback computer mouse made by Logitech.

The GuideCane takes full advantage of the force-feedback approach, and even though its wheels are unpowered, the GuideCane can apply a substantial amount of physical force on

the user. This is because the sideways motion of the wheels results in a rotation of the handle of the cane, which is clearly noticeable. Even if the user was ignoring the initially small rotation of the handle, the GuideCane veering off to a side develops into a substantial and forceful impediment to the user's straight-ahead collision course that cannot be ignored. This becomes quite obvious when considering the scenario of Figure 7.

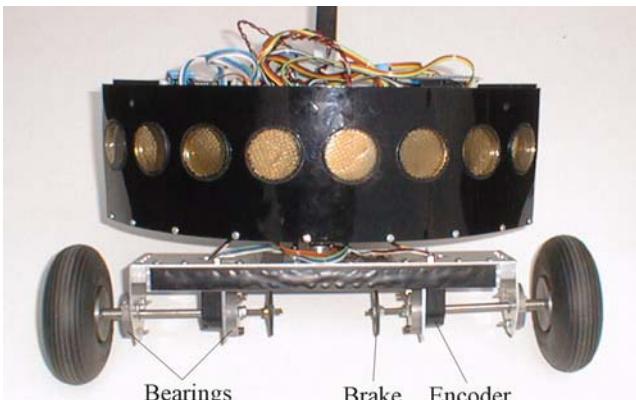
A second force, immediately felt after the wheels change their orientation (but even before the user feels the rotation of the cane), is the increased reaction force that is opposed to pushing the cane forward. When walking while the cane and the wheels are aligned, the user must only overcome a reactive force,  $F_r$ , which is the result of friction in the bearings and the roll resistance of the wheels. If the wheels steer at an angle  $\theta$  in either direction of the cane, then the user has to push the cane with an increased force equal to  $F_r/\cos\theta$  to overcome the reactive force of the wheels. This change in reactive force is immediately felt by the user and prepares him/her for an upcoming steering maneuver.

#### 4.4 Hardware Implementation

The GuideCane must be as compact and as lightweight as possible so that the user can easily lift it, e.g., for coping with stairs, steps, and for access to public transportation. For the same reason, the electronic components should require minimal power in order to minimize the weight of the batteries. In addition, both the mechanical and electronic hardware must be designed to facilitate the software's task: allowing real-time performance with limited on-board processing power. The current prototype is not yet optimized for minimal power consumption; it uses 12 AA-sized rechargeable NiMH batteries that power the system for two hours. We estimate that state-of-the-art power management technology, once implemented on the GuideCane, should allow 4- 6 hours of continuous operation. We estimate that the total weight of a commercially made GuideCane would be on the order of 2.5 kg (5.7 lbs).

##### 4.4.1 Mechanical Hardware

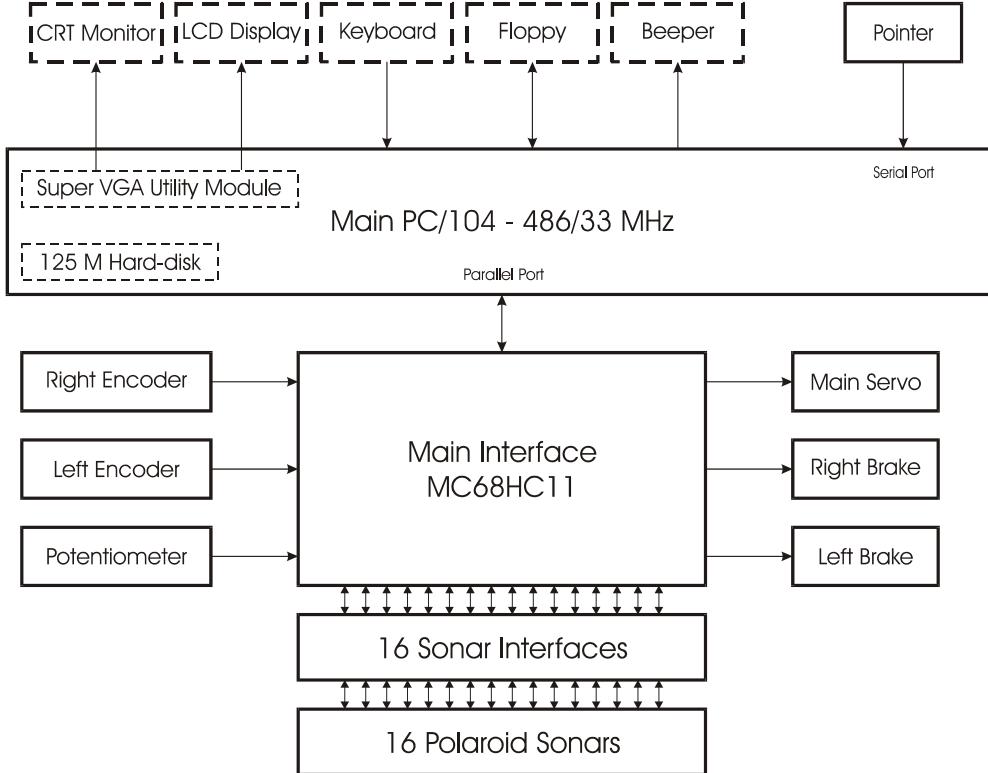
The GuideCane consists of a housing, a wheelbase, and a handle. The housing contains and protects most of the electronic components as shown in Figure 8. The current prototype is equipped with ten Polaroid ultrasonic sensors that are located around the housing. Eight of the sonars are located in the front in a semi-circular fashion with an angular spacing of  $15^\circ$ , thereby "covering" a 120-degree sector ahead of the GuideCane. The other two sonars face directly sideways and are particularly useful for following walls and for going through narrow openings, such as doorways.



**Figure 8:** The GuideCane housing and wheelbase.

The wheelbase is steered by a small servomotor and supports two unpowered wheels. Two lightweight quadrature encoders mounted to the wheels provide data for odometry. The GuideCane's odometry equations are the same as those of a differential drive mobile robot. However, because the wheels are unpowered, there is much less risk of wheel slippage.

The handle serves as the main physical interface between the user and the GuideCane. The vertical angle of the handle can be adjusted to accommodate users of different heights. At the level of the user's hand, a joystick-like pointing device is fixed to the handle. The pointer



**Figure 9:** The GuideCane system. Dashed lines indicate components that are only required during the development stage.

consists of a mouse button (similar to the pointing devices used on some laptop computers) that the user can press with his/her thumb in any direction.

#### 4.4.2 Electronic Hardware

The electronic system architecture of the GuideCane is shown in Figure 9. The brain of the GuideCane is a 486/33 MHz PC-compatible single board computer. A custom-built, so-called micro-controller interface board (MCIB) interfaces between the PC and the sensors (encoders, sonars, and potentiometer) and actuators (main servo and brakes) via a standard parallel port. The MCIB performs many time-critical tasks, such as firing the sonars at specific times, constantly checking the sonars for an echo, generating the PWM signals for the servos, and decoding the encoder outputs. The MCIB also acts as an asynchronous buffer for the sonar data.

#### 4.5 Software Implementation

The GuideCane is a semi-autonomous system, providing full autonomy for *local* navigation (obstacle avoidance), but relying on the skills of the user for *global* navigation (path planning and localization). Combining the skills of a mobile robot with the existing skills of a visually impaired user is the key idea behind the NavBelt and the GuideCane. This combination of skills is what makes this particular application feasible at the current stage of mobile robotics research. While reliable global navigation algorithms might be available in the future, they are not essential for the GuideCane. Although visually impaired people have difficulties performing fast local navigation without a travel aid, they are in most cases perfectly capable of performing global navigation.

Like the NavBelt, the GuideCane also uses EERUF to control the ultrasonic sensors to achieve a fast firing rate [Borenstein and Koren, 1995]. Each of the ten sonars is fired at a

rate of 10 Hz, so that the GuideCane receives 100 sonar readings per second. EERUF's fast firing rate is a key factor for the reliability and robustness of the GuideCane's obstacle avoidance performance and is necessary for allowing safe travel at fast walking speeds. And, also as in the NavBelt, the GuideCane employs the VFH obstacle avoidance method described in Section 2. However, several improvement over the original VFH method were implemented in the GuideCane. These improvements are described in detail in [Ulrich, 1997] and [Ulrich and Borenstein, 1998; 2000].

## 4.6 Experimental Results

The actual GuideCane prototype, shown in Figure 10, was extensively tested at the University of Michigan's Mobile Robotics Laboratory.

A performance analysis of the experimental GuideCane prototype can be divided into two categories: 1) the usefulness of the concept and 2) the performance of the obstacle avoidance system. The GuideCane concept fulfilled all our expectations and confirmed our initial hypothesis that following the GuideCane is a completely intuitive process. All subjects were able to follow the GuideCane easily at fast walking speeds of up to 1 m/sec, while completing complex maneuvers through cluttered environments. Subjects rarely needed more than a few minutes to get used to the GuideCane. Actually, blind subjects needed a few minutes to understand the GuideCane concept, as they could not visually observe how the device was working. Blindfolded subjects, on the other hand, needed some time to simply become accustomed to walking around without sight. Nonetheless, blind and blindfolded subjects alike observed that walking with the GuideCane was completely intuitive and did not require any conscious effort.

The second category, the obstacle avoidance performance, is adequate in many indoor environments. The performance of the combined EERUF/VFH system is excellent as long as the obstacles are indeed detected by the sonars. Screen captures of two test runs with the actual GuideCane are shown in Figure 11, demonstrating the processes of the local map building and the functioning of the obstacle avoidance algorithms.

Failures of the obstacle avoidance system were in most cases caused by obstacles that were not detected by the sonars. For example, the GuideCane is currently not able to detect overhanging obstacles like tabletops. However, these obstacles could easily be detected with the additional upward-looking sonars. The addition of these sonars is expected to improve the GuideCane's performance to a level where a visually impaired person could effectively use the device indoors. Outdoors, however, the implementation of an additional type of sensor will be required to allow the GuideCane to detect important features, such as sidewalk borders. In order for the GuideCane to become a truly useful tool for a visually impaired person, it will be essential to develop a real-time method for the detection of these features.



**Figure 10:** The actual GuideCane prototype.



**Figure 11:** Two screen captures showing the path of the actual GuideCane through corridors. In both experiments the target direction is towards the right. The dots indicate filled cells in the histogram grid. Cell with a higher Certainty Value are darker. The continuous gray line indicates the GuideCane's trajectory, based on its odometry.  
 a). The GuideCane moves along a straight corridor. b) The GuideCane makes a left turn at a T-shaped intersection

## 5 Conclusions and Discussion

Both the NavBelt and the GuideCane are novel navigation aids designed to help visually impaired users to navigate quickly and safely among densely cluttered obstacles. Both devices use mobile robotics-based obstacle avoidance technologies to determine, in real-time, a safe path for travel and to guide the user along that path. This is fundamentally different from existing ETAs, which, at best, only inform the user about the existence and location of obstacles but do not guide the user around them.

Theoretically, conveying to the user just a single piece of information (i.e., a safe direction to walk in) is efficient and fast and suitable in practice to full walking speeds. On the other hand, visually impaired users sometimes desire the more detailed information that is provided by existing ETAs. This is so even though it requires time-consuming active scanning of the environment, as well as the conveying of more detailed obstacle information, which further slows the user down and requires more concentration. Nonetheless, the NavBelt's Image mode can provide the user with the more detailed obstacle information, and the GuideCane could easily be adapted to offer that same function, although we are not convinced of the need for doing so.

The foremost problem with the NavBelt is that the preferable (since faster) Guidance mode requires accurate real-time knowledge of the user's position. At the time of developing the NavBelt no man-mounted dead-reckoning system was commercially available. More recent developments, both commercially and within our own lab, may provide this function and may thus make Guidance Mode more feasible. Travel using the currently available Image mode on the NavBelt is usually quite slow, at less than half of a typical adult's full walking speed. Furthermore, and much like with other ETAs, use of the Image Mode on the NavBelt requires hundreds of hours of training and practice.

The GuideCane overcomes this limitation of the NavBelt and of other existing ETAs, in that it provides highly effective, highly intuitive haptic guidance that any user can follow after just a few minutes of instruction. In addition, the GuideCane's haptic guidance does not mask the user's hearing as most other ETAs do, and the user does not need to concentrate much on following the GuideCane – the nature of the haptic guidance is such that the force, with which the GuideCane pulls the user into the safe travel direction, increases quickly and dramatically if the user pays no attention to the initially small haptic force.

One further advantage of the GuideCane over all existing ETAs is that it rolls on wheels that are in contact with the ground, thus allowing position estimation by odometry. Odometry is in itself valuable for visually impaired travelers as it enhances the function of GPS and other position estimation tools that can be easily integrated into the GuideCane (position estimation is an important issue but was not addressed in this article because of space limitations).

Yet another advantage of the wheels is that rolling the GuideCane ahead of the user provides some of the functionality of the white cane, namely the detection of drop-offs and of small protrusions on the ground. Furthermore, the vibration of the wheels as they roll over different floor surfaces provides useful additional information to the traveler.

One major problem with both the NavBelt and the GuideCane is that the ultrasonic sensor-based obstacle avoidance system is not sufficiently reliable at detecting all obstacles under all conditions. This fundamental problem is well known in the mobile robotics research community and it is widely considered as one of the foremost impediments to the commercial use of most mobile robots. Newer laser scanners and laser range cameras provide better obstacle detection performance, but they are still too expensive, bulky, and heavy for use on the NavBelt or GuideCane.

Substantial resources are being poured into the development and improvement of mobile robot obstacle avoidance technologies, and these technologies will be immediately applicable to the GuideCane and possibly to the NavBelt. We therefore feel confident that the steady pace of technological advances in the area of mobile robot obstacle avoidance will immediately benefit the two devices described in this article, and will eventually allow to turn them into viable products of hitherto unattained functionality for the visually impaired.

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