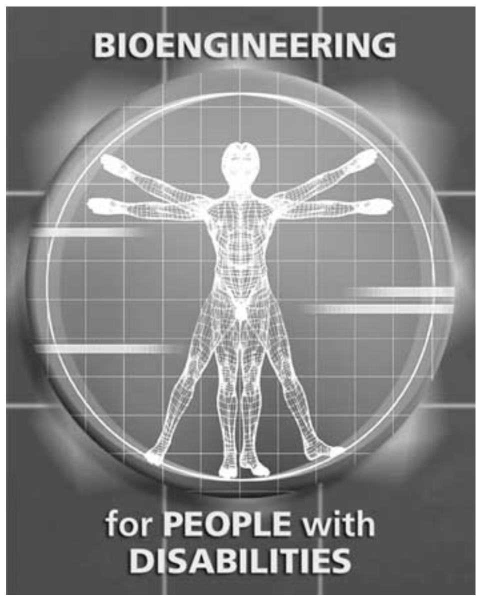
Robotics-Based Obstacle-Avoidance Systems for the Blind and Visually Impaired

NavBelt and the GuideCane



The NavBelt and the GuideCane are computerized devices based on advanced mobile robotics obstacle-avoidance technologies. NavBelt is worn by the user like a belt and is equipped with an array of ultrasonic sensors. It provides acoustic signals via a set of stereo earphones that guides 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 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 without any conscious effort. This article describes the two devices, including the mechanical, electronic, and software components, user-machine interface, and some experimental results.

Background

There are about 2 million visually impaired or blind persons in the United States alone [1]. 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 100 h—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 ft). Another drawback of the white cane is that obstacles can only be detected by contact, which can be inconvenient to the traveler and the surroundings, for example, when traveling in a crowded street.

Guide dogs are very capable guides for the blind, but they require extensive training. Fully trained guide dogs cost between US$12,000-20,000 [1], and their useful life is only about 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 United States have guide dogs.

With the development of radar and ultrasonic technologies over the past four decades, a new series of devices, known as electronic travel aids (ETAs), was developed. 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 confront it. 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 ft) away from the user, but require continuous scanning of the environment in the desired direction.

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1070-9932/03$17.00©2003IEEE

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One of the best known ETAs is the C5 Laser Cane [2], 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 ft), and the "down" channel detects drop-offs in front of the user.

The Mowat sensor [3] 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 [4].

The binaural sonic aid (Sonicguide) [5] came in the form of a pair of spectacle frames, with one ultrasonic wide-beam transmitter (55° 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 ears. 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 that, 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 as either a primary or secondary device in conjunction with an additional hand-held device or a guide dog.

The Sonicguide has undergone continuous improvements, and its 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:

- 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.
- 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. [5]-[7].

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

Mobile Robotics Technologies for the Visually Impaired

Visually impaired humans and mobile robots face common problems when navigating through cluttered environments. Therefore, it appears logical to apply mobile robotics technologies to assist the visually impaired. Obstacle-avoidance systems (OASs), originally developed for mobile robots, lend themselves well to 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 uses 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 recent sonar data history. The algorithm then computes a momentary steering direction and travel speed and sends this information to the mobile robot (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.)

The ultrasonic sensors are controlled by the error-eliminating, rapid ultrasonic firing (EERUF) method [8]. EERUF allows sonars to fire at rates that are five to ten times faster than conventional methods. Each of the ten 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 speeds.

In the VFH method, the local map is represented by a two-dimensional (2-D) array, called a histogram grid [9], that is based on the earlier certainty- [10] and occupancy-grid [11] 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 2-D 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° panoramic view of the immediate environment, in which elevations 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° wide. The numerical values associated with each sector are called obstacle density values. High obstacle density values suggest a high likelihood of 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 obstacle density values are shown as taller bars in the bar chart-type representation of Figure 2(a). Note that Figure 2(b) represents the same polar histogram as that of Figure 2(a), except that it has been overlaid onto the histogram grid for better illustration.

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

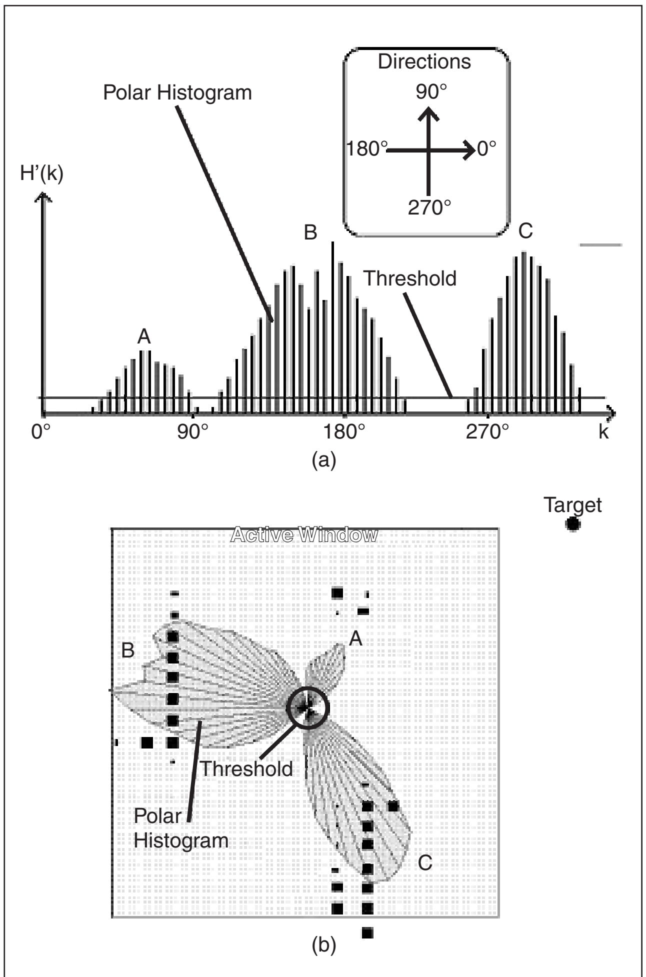

Figure 1. (a) A typical experimental environment. A vehicle is shown traversing the environment at some instance t. (b) The histogram grid, built from the sonar data, comprised of cells, each holding a value that expresses the certainty for the existence of an obstacle.

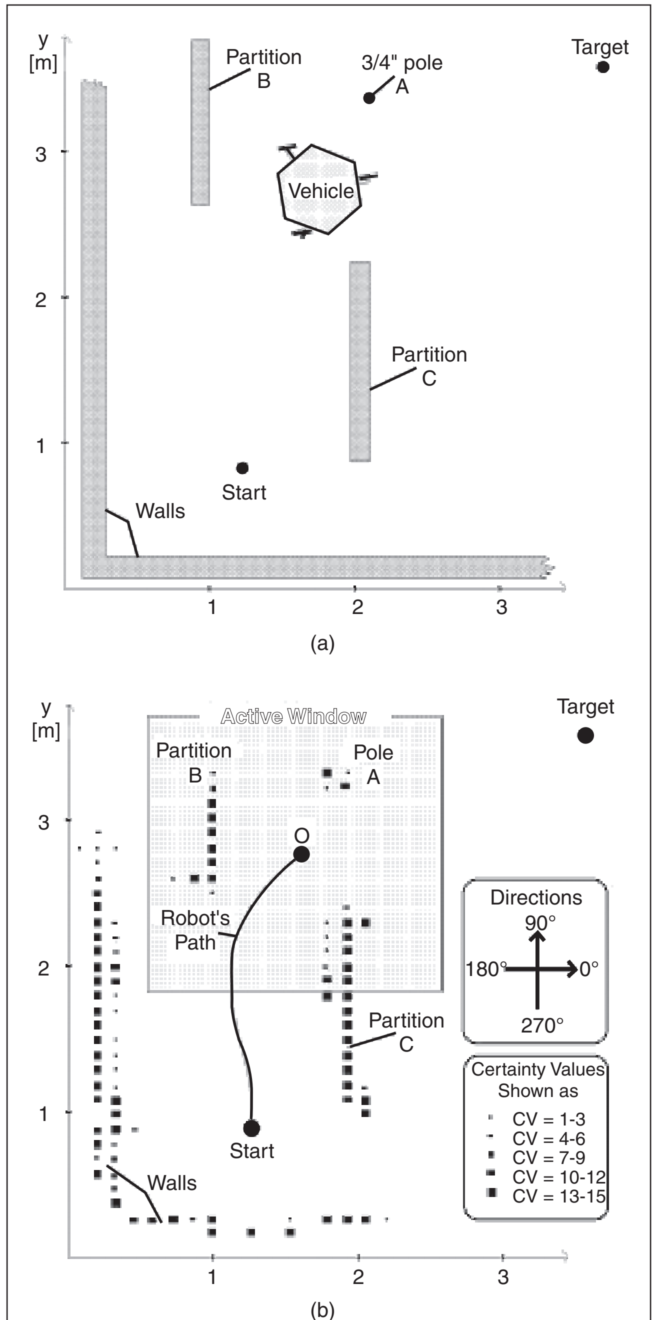

Figure 2. Two ways of visualizing the same polar histogram generated at instant t for the environment of Figure 1.

It is evident from Figure 2(b) 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.

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

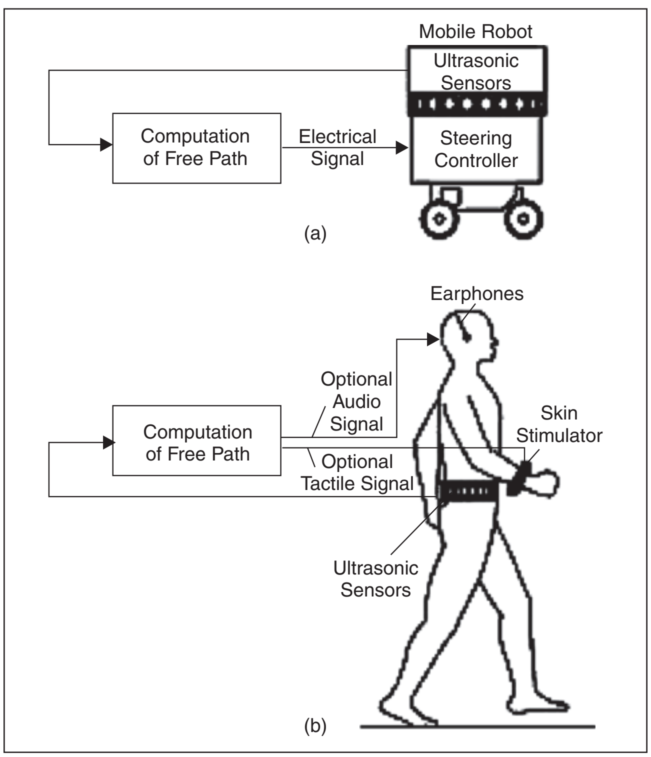

Figure 4. *Transferring mobil-robotics technology to a portable navigation aid for the blind: the concept of the NavBelt.*

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° are mounted on the front pack, providing a total scan range of 120°.

The computer processes the signals that arrive from the sensors and applies the robotic obstacle-avoidance algorithms. 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 4(a)], are replaced by acoustic signals that are relayed to the user by stereophonic headphones [see Figure 4(b)].

A binaural feedback system based on internal time difference (i.e., the phase difference between the left and right ears) 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.

Operation Modes

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

GUIDANCE MODE

In the guidance mode, the NavBelt only provides the user with the recommended travel speed and direction, generated by the VFH obstacle-avoidance algorithm. In the 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 global-positioning system (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 sectors. Next, the VFH algorithm searches for the candidate sector that is closest to the direction of the target and recommends it to the user. 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 [12], 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 ±5°) 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 [12]. 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 3 s.

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 (Point Research Corporation, http://www.pointresearch.com/)].

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 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 5-m diagonally ahead of the user in that direction. In case an obstacle is detected, the NavBelt provides the user with 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. The 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, a simplified version of the VFH method must be used, which provides less reliable obstacle avoidance.

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° and a 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, 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 5(a)] and are projected onto the polar histogram, as shown in Figure 5(b). Based on the polar histogram, the binaural feedback system generates the sweep, which is comprised of 12 steps [Figure 5(c)]. Each step covers a sector of 15°, so that the whole

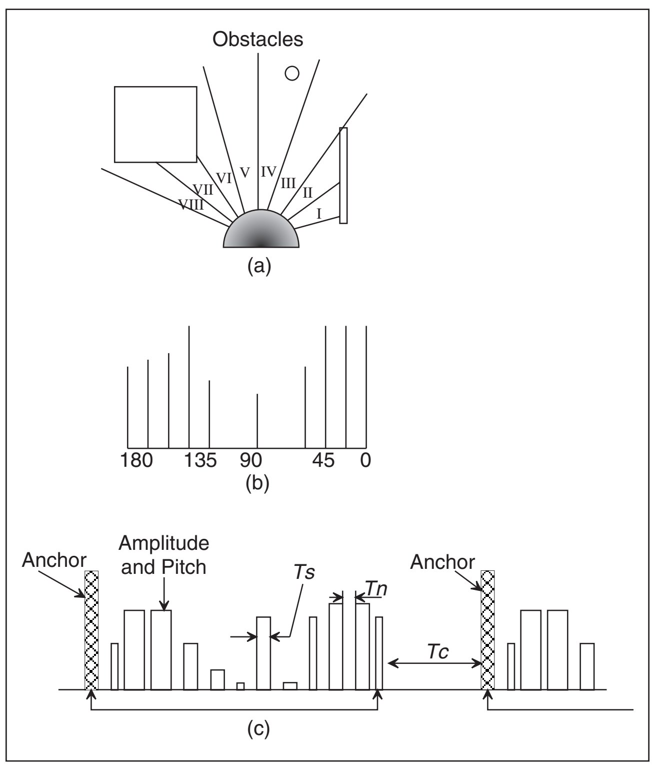

Figure 5. The auditory obstacle representation in the image mode. (a) Obstacles are detected by the ultrasonic sensors. (b) Sonar range readings are projected onto the polar histogram. (c) An acoustic sweep is generated from the polar histogram.

The evaluation of obstacle information presented acoustically is a new skill that must be acquired over hundreds of hours of learning.

sweep covers a panorama of 180°. Each of the eight sectors in the center of the panorama (covering the sectors between 30° and 150°) 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 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 s. Given enough cognition time T_c, the user can comprehend the image. Alternatively, the sweep time may be as long as 1 s combined with a very short cognition time. Each sweep starts with an anchor signal. This signal has a unique pitch that 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 [1] 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.

Experimental Results

The NavBelt was extensively tested during its five-year long development. Some of the key experimental elements are presented here.

In one set of experiments, subjects walked through laboratory obstacle courses, which were comprised of various types of obstacles, and used 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 only be done 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 an 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 that the current prototype NavBelt lacked the ability to detect overhanging objects, 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 ft) 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 does not appear to be critical. The current detection range of the NavBelt is set for 3 m. This range can be changed by selecting a different schedule for controlling the ultrasonic sensors. However, an increased detection range of up to 5 m resulted in erroneous data due to a large amount of noise added to the incomming ultrasonic echoes. A reduced detection range of 1.5 m resulted in insufficient warning time for walking speeds greater than 0.75 m/s.

The experiments with the NavBelt prototype showed the importance of training. Subjects with more experience traveled faster and were generally more comfortable with the device. After 20 h of practice with a NavBelt simulator and 40 h of practice with the experimental prototype, subjects walked at 0.8 m/s in the guidance and directional-guidance modes and at 0.3–0.4 m/s in the image mode. Subjects with less experience (10 h with the simulator and 10 h with the prototype) traveled at an average speed of 0.6 m/s in the guidance mode. However, it took substantially longer to become practiced in the interpretation of the acoustic images in image mode. After 100 h 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/s.

The NavBelt uses a 2-D 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 [13]. In this device, a camera and a laser scanner 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.

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 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 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 [14]. 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 him/herself while walking. The GuideCane is considerably heavier than 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.

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, the system considers the current direction of travel to be the desired direction. If the user presses the button to the left, 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° 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, 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, the obstacle-avoidance algorithm prescribes an alternative direction to circumnavigate the obstacle and then resumes in the desired direction (Step 2 in Figure 7).

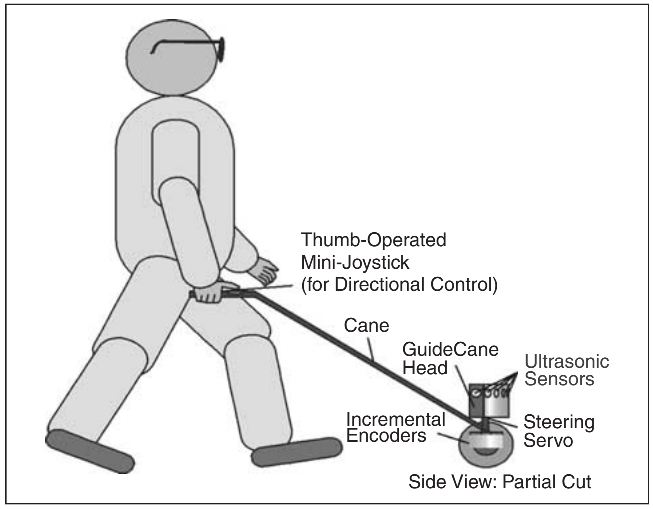

Figure 6 *Functional components of the GuideCane.*

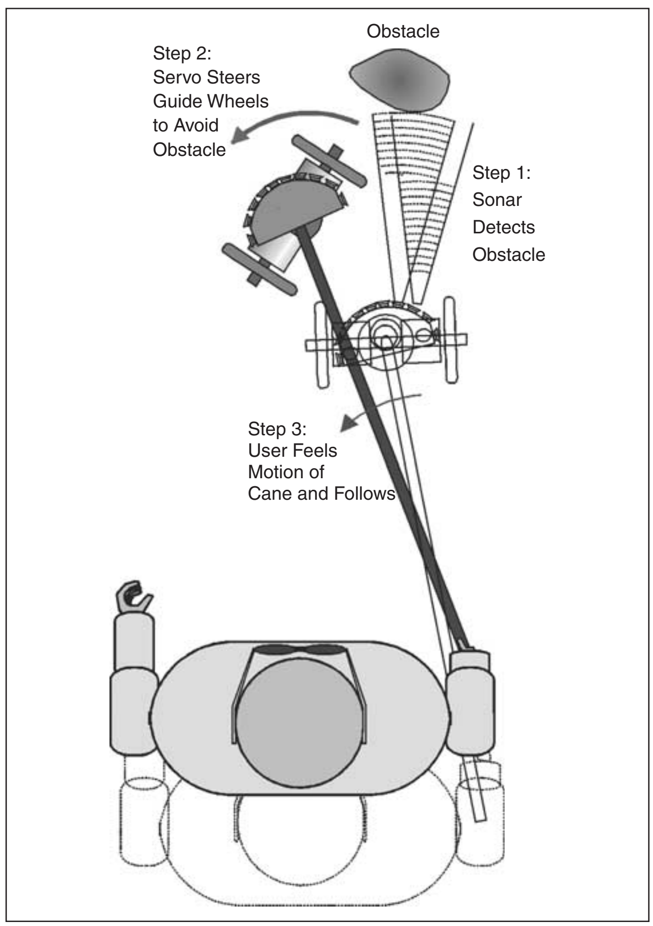

Figure 7. *How the GuideCane avoids obstacles.*

Both the NavBelt and GuideCane are novel navigation aids designed to help visually impaired users navigate quickly and safely among densely cluttered obstacles.

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 him/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 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 through odometry.

A particular problem is the detection of stairs. The GuideCane offers separate solutions for downward steps and upward steps. Downward steps are detected in a fail-safe manner: when a downward 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. Upward steps can be detected by additional front-facing sonars, as described in [15]; however, this method is not yet implemented in our current prototype.

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 earlier in this article and in [16]. 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.

Information Transfer

In prior research with the NavBelt, different methods were tested that use binaural (stereophonic) signals to guide the user around obstacles. Subjects found it difficult to recognize and react to such signals at walking speed [16]. 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 that 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 θ in either direction of the cane, 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.

Hardware Implementation

The GuideCane must be as compact and 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 onboard processing power. The current prototype is not yet optimized for minimal power consumption; it uses 12 AA rechargeable NiMH batteries that power the system for 2 h. We estimate that state-of-the-art power management technology, once implemented on the GuideCane, should allow 4-6 h 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).

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 semicircular fashion with an angular spacing of 15°, thereby "covering" a 120° sector ahead of the GuideCane. The other two sonars face directly sideways and are particularly useful for following walls and going through narrow openings, such as doorways. 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 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.

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 microcontroller 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 pulsewidth modulation (PWM) signals for the servos, and decoding the encoder outputs. The MCIB also acts as an asynchronous buffer for the sonar data.

Software Implementation

The GuideCane is a semiautonomous 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 [8]. 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

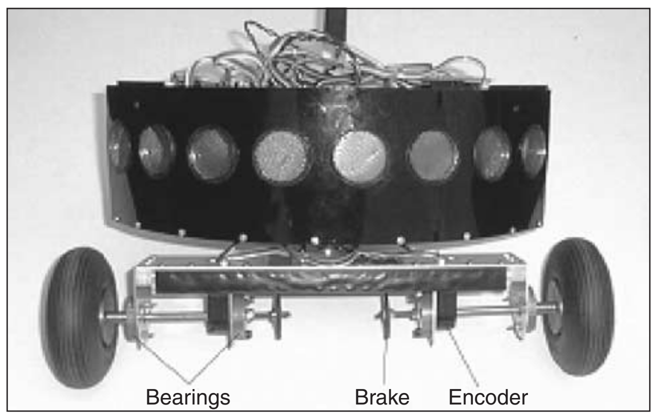

Figure 8. *The GuideCane housing and wheelbase.*

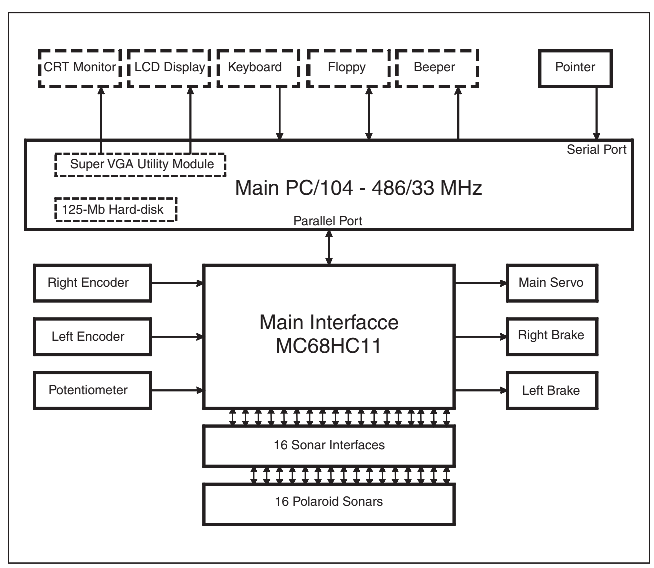

Figure 9. *The GuideCane system. Dashed lines indicate components that are only required during the development stage.*

Technological advances in the area of mobile-robot obstacle avoidance will allow these devices to become viable products of hitherto unattained functionality for the visually impaired.

necessary for allowing safe travel at fast walking speeds. Also, as in the NavBelt, the GuideCane employs the VFH obstacle-avoidance method. However, several improvements over the original VFH method were implemented in the GuideCane. These improvements are described in detail in [17]-[19].

Experimental Results

The 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: the usefulness of the concept and 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/s while completing complex maneuvers through cluttered environments. Subjects rarely needed more than a few minutes to get used to the GuideCane.

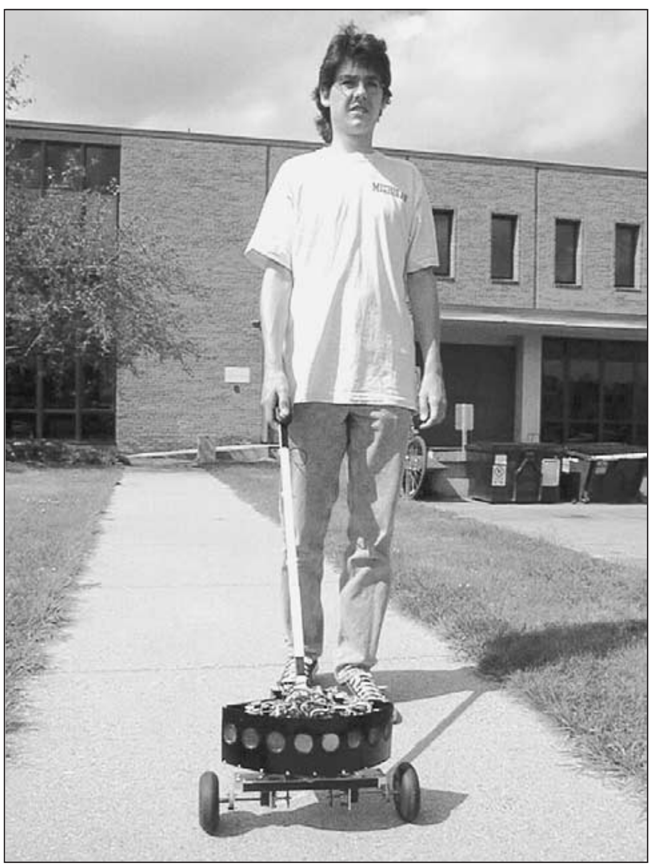

Figure 10. The GuideCane prototype.

Actually, blind subjects needed a few additional 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, 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 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 not currently able to detect overhanging obstacles, like tabletops. However, these obstacles could easily be detected with 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.

Conclusions and Discussion

Both the NavBelt and the GuideCane are novel navigation aids designed to help visually impaired users 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 that, 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, fast, and suitable in practice to full walking speeds. On the other hand, visually impaired users sometimes desire the more detailed information than is provided by existing ETAs even though this requires time-consuming active scanning of the environment, as well as the conveying of more detailed obstacle information that further slows the user down and requires more concentration. Nonetheless, the NavBelt's image mode can provide the user with more detailed obstacle information, and the

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. Cells 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.*

GuideCane could easily be adapted to offer that same function, though we are not convinced of the need for doing so.

The foremost problem with the NavBelt is that the preferable (since it is 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 the 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 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 is widely considered 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. Therefore, we 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 them to become viable products of hitherto unattained functionality for the visually impaired.

Acknowledgments

Development of the NavBelt was funded by the Michigan Consortium for Enabling Technologies (MCET). Development of the GuideCane was funded by the Whitaker Foundation. Ultrasonic sensor-based obstacle-avoidance methods used on both the NavBelt and the GuideCane were originally developed with funding by the U.S. Department of Energy.

The authors are grateful to *Discover Magazine*, which bestowed upon the GuideCane its Best Innovation of the Year Award (Robotics category, 1998).

Keywords

Rehabilitation robotics, mobile robots, travel aid, blind and visually impaired.

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