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The GuideCane — Applying Mobile Robot Technologies to Assist the Visually Impaired

by

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ABSTRACT

The *GuideCane* is a novel device designed to help blind or visually impaired users navigate safely and quickly among obstacles and other hazards. During operation, the user pushes the lightweight GuideCane forward. When the GuideCane's ultrasonic sensors detect an obstacle, the embedded computer determines a suitable direction of motion that steers the GuideCane and the user around it. The steering action results in a very noticeable force felt in the handle, which easily guides the user without any conscious effort on his/her part.

I. INTRODUCTION

There are about two million visually impaired or blind persons[3] in the United States alone [10]. 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 this device is that users must be trained in its use for more than 100 hours – a substantial "hidden" cost. In addition, the white cane requires the user to actively scan the small area ahead of him/her. The white cane is also not suited for detecting potentially dangerous obstacles at head level.

Guide dogs are very capable guides for the blind, but they require extensive training. Fully trained guide dogs cost between $12,000 and $20,000, and they are only useful for about five years [10]. 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 estimated two million visually impaired people in the U.S. have guide dogs.

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[3] In the remainder of this article the term "blind persons" will be used for severely visually impaired persons as well as for totally blind persons.

During the past three decades, several researchers have introduced devices that use sensor technology to improve the blind users' mobility in terms of safety and speed. Examples of these devices, collectively called *Electronic Travel Aids* (ETAs), are *the C-5 Laser Cane* [1], the *Mowat Sensor* [19], the *Nottingham Obstacle Detector* [2], and the *Sonicguide* [11]. These ETAs, however, have not found wide use among their targeted users, likely because the utility of this group of systems is limited [3]. In particular, conventional ETAs suffer from the following three fundamental shortcomings:

1) The user must *actively* scan the environment to detect obstacles (no scanning is needed with the *Sonicguide*, but it does not detect obstacles at floor level). This procedure is time-consuming and requires the user's constant activity and conscious effort.
2) The user 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 time-consuming, conscious effort that reduces the walking speed.
3) 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 [12; 11; 9].

For over a decade, the University of Michigan Mobile Robotics Laboratory has conducted active research in applying mobile robot obstacle technologies to assistive devices for the disabled. In 1989 it developed the *NavBelt*, which is a portable device equipped with ultrasonic sensors and a computer [14]. Although the NavBelt successfully eliminated some of the problems common to conventional ETAs, the device lacked odometry capabilities and required a considerable conscious effort for the user to comprehend its audio cues. The NavBelt's successor, the GuideCane, was developed to overcome these problems.

II. THE GUIDECANE CONCEPT

Figure 1 shows a schematic view of the GuideCane and its functional components. Much like the widely used *white cane*, the user holds the GuideCane in front of himself/herself while walking. The GuideCane is considerably heavier than the white cane, but it rolls on *passive* wheels that support its weight during regular operation. Both wheels are equipped with encoders to determine the relative motion. A servomotor, controlled by the built-in computer, can steer the wheels left and right relative to the cane. To detect obstacles, the GuideCane is equipped with ten ultrasonic sensors. A mini joystick located at the handle allows the user to specify a desired direction of motion.

A. Functional Description

During operation, the user pushes the GuideCane forward. While traveling, the ultrasonic sensors detect obstacles in a 120^o wide sector ahead of the user (see Step 1 in Figure 2). Based on the sonar and encoder data, the embedded computer instantaneously determines an appropriate direction of travel. If an obstacle blocks the desired travel direction, then the obstacle avoidance algorithm prescribes an alternative direction that clears the obstacle and then resumes in the original direction (see Step 2 in Figure 2).

Once the wheels begin to steer sideways to avoid the obstacle, the user feels the resulting horizontal rotation of the cane (see Step 3 in Figure 2). In a fully intuitive response, requiring virtually no training time, the user 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 direction of travel. The new line of travel will be offset from the original line of travel. Depending on the circumstances, the user 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.

The user can prescribe a desired direction of motion with the thumb-operated mini joystick. This directional command is discretized into eight directions and is understood to be relative to the GuideCane's current direction of motion. For example, if the user presses the button to the left, then the computer adds 90° to the current direction of motion and, as soon as the new desired motion of travel 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, then the GuideCane will continue down the corridor until it reaches an intersection or an open door where it can turn to the left. The ability to indicate a desired direction of motion in advance significantly enhances the GuideCane's ease-of-use.

The detection of stairs is a particular problem for most ETAs. The GuideCane offers separate solutions for down-steps and up-steps. Down-steps are detected in a fail-safe

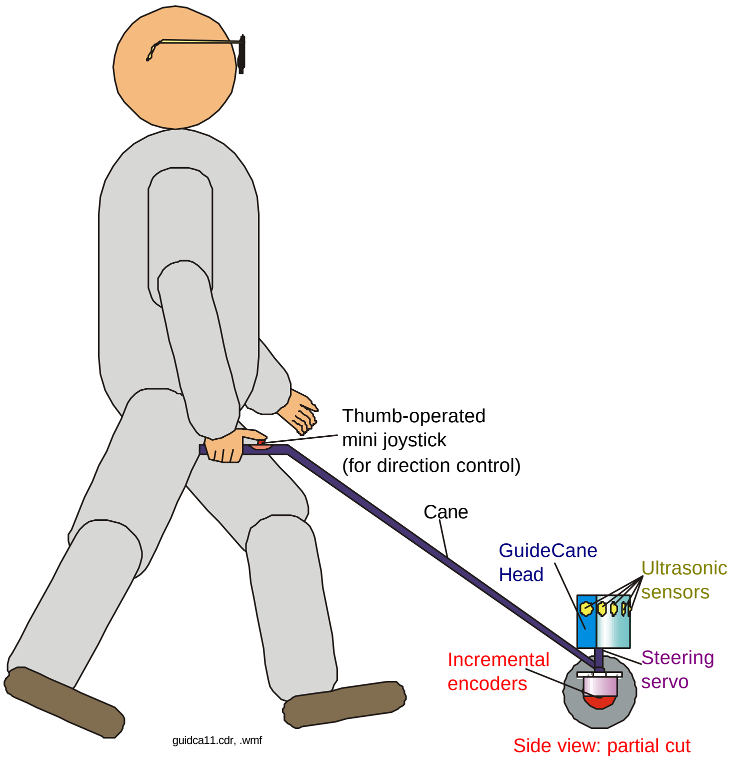

Figure 1: Functional components of the GuideCane.

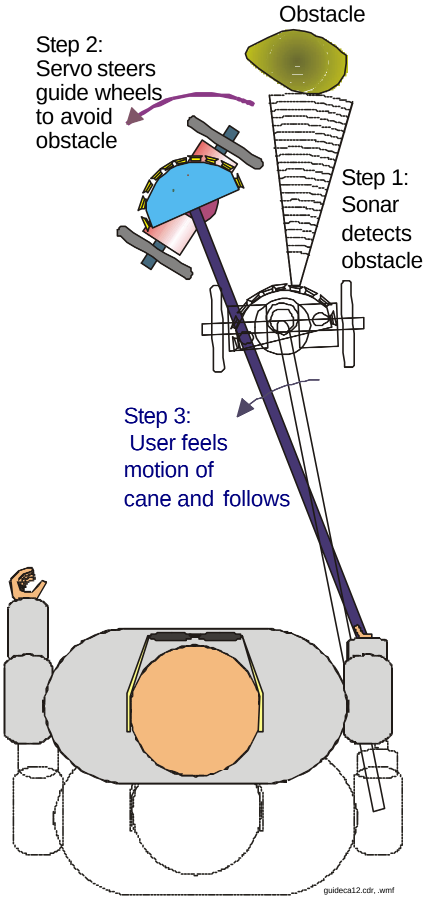

Figure 2: Avoiding an obstacle.

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 can not miss. Because the user walks about 60 cm behind the GuideCane, he/she has enough time to stop. Up-steps can be detected by additional front-facing sonars as described in [8]; however, this method has not yet been implemented in the GuideCane. Because the GuideCane is compact and lightweight, it can easily be lift up whenever the user needs to cope with stairs.

B. Guidance Signals versus Obstacle Information

Conventional ETAs are designed to notify the user of obstacles, usually requiring the user to perform additional scanning once the obstacle is detected. The user must evaluate all of the obstacle information, which comprises of the size and proximity of each obstacle, and then 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 by acoustic or tactile signals is a new skill that must be acquired over hundreds of hours of learning [15]. 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 substantially reduces the information bandwidth. As a consequence, 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. However, reducing the high-bandwidth obstacle information to a momentary optimal direction of travel requires the implementation of a reliable obstacle avoidance system.

C. Information Transfer

In prior research with the NavBelt [14], different methods were tested that use binaural (stereophonic) signals to guide the user around obstacles. Subjects found that it is generally extremely difficult to recognize and react to such signals at walking speed [15]. Even after 100 hours of training, its developer could not walk safely at walking speed. By contrast, our tests have shown that untrained subjects could *immediately* follow the GuideCane at walking speed, even among densely cluttered obstacles.

This advantage can be credited to another unique feature of the GuideCane: information transfer through direct physical force (also called “haptic display” in the scientific literature). 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 conventional 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.

Although the GuideCane’s wheels are unpowered, the GuideCane can apply a substantial amount of physical force on the user. The sideways motion of the wheels results in a rotation of the handle of the cane, which is clearly noticeable. A second force, immediately felt after the wheels change their orientation, is the increased reaction force that is opposed to pushing the cane forward. This change in reactive force is immediately felt by the user and prepares him/her for an upcoming obstacle avoidance maneuver.

D. Mobile Robots as Guides for the Blind

In general terms, one could argue that any mobile robot with obstacle avoidance can be used as a guiding device for the blind. However, conventional mobile robots with powered wheels are inherently unsuited to the task of guiding a blind person. Actively driven wheels require motors and thus more powerful batteries, making a standard mobile robot larger and heavier than the GuideCane. The added weight and size are a considerable inconvenience for a user whenever he/she encounters situations like stairs or sidewalk ledges.

Another problem with powered wheels is that the speed of the robot could make the user feel uncomfortable by either pulling a cautious user forward or by unnecessarily slowing a confident user down. An additional interface would be required so that the user could indicate the desired speed to the robot. However, with the GuideCane configuration, the user is in direct control of the speed, allowing for the most intuitive and easiest use possible.

Another concept is to have a visually impaired person sit in a powered semi-autonomous wheelchair equipped with sensors and obstacle avoidance technology. The main problem of this approach is that a visually impaired user with healthy legs would unnecessarily be burdened with the additional handicap of limited mobility. It was this observation with the NavChair that had led to the development of the NavBelt [7].

III. THE GUIDECANE SYSTEM

The GuideCane is a fully embedded system, implementing all components on-board. The main constraints in the mechatronic design of the GuideCane are size and weight. The mechanical hardware must be as compact and as lightweight as possible so that the user can easily lift the GuideCane, e.g., for coping with stairs and 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.

A. Mechanical Hardware

The GuideCane consists of three main modules: housing, wheelbase, and handle. The housing, made of acrylic, contains and protects most of the electronic components. 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°, covering the area ahead of the GuideCane with a total angular spacing of 120°. The other two sonars face sideway and are useful for following walls and for going through narrow openings, such as doorways. The sonars are close to the ground so that the GuideCane can also detect obstacles that protrude only slightly above the ground. One disadvantage of this location is that the sonars sometimes detect *minor* irregularities in the ground, which erroneously trigger an avoidance maneuver~~)~~. By placing the sonars at a small upward-looking angle, we hope to eliminate this potential problem with the next prototype.

The housing and wheelbase are about 43 cm (17") wide, 25 cm (10") high, and 23 cm (9") deep. The current GuideCane prototype weighs about 4 kg (9 lbs). However, we expect that a commercial version can be built that weighs only 2.5 – 3 kg (5.7 – 6.8 lbs).

As shown in Figure 3, the wheelbase uses ball bearings to support two unpowered wheels. To perform odometry, both wheels are equipped with lightweight quadrature encoders. Using full quadrature decoding, the resolution of the encoders is 2,000 pulses per revolution, resulting in more than 5 pulses for a wheel advancement of 1 mm. The GuideCane's odometry equations are the same as for a differential drive mobile robot. However, because the wheels are unpowered, there is considerably less risk of wheel slippage.

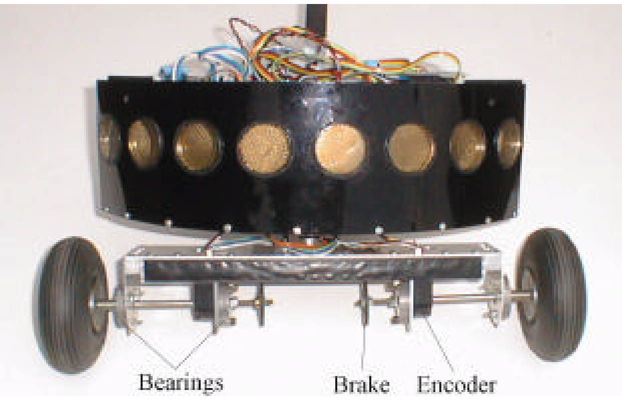

Figure 3: The GuideCane housing and wheelbase.

The wheelbase is attached to the housing with a pivot screw and can be rotated by a small servomotor. A push-rod couples the wheelbase to the servo, which is fixed to the housing bottom. Because the servo shaft is rigidly linked to the wheelbase, the built-in computer can access the potentiometer inside the servomotor to determine the relative angle between the wheelbase and the housing. This information is important for correctly updating the local map based on the sonar and the odometry data.

The handle serves as the main physical interface between the user and the GuideCane. It consists of an extruded aluminum bar with a square-shaped profile. A square shape is better than a circular shape as it allows the user to determine the handle's orientation through tactile contact. The handle is attached to the housing with a hinge, whose angle can be adjusted to accommodate users of different heights.

B. Electronic Hardware

The electronic system architecture of the GuideCane is shown in Figure 4. The main brain of the GuideCane is an embedded PC/104 computer, equipped with a 486 microprocessor clocked at 33 MHz. The PC/104 stack consists of four layers. Three of the modules are commercially available, including the motherboard, the VGA utility module, and a miniature 125-MB harddisk. The fourth module, which we custom-built, serves as the *main interface* between the PC and the sensors (encoders, sonars, and potentiometer) and actuators (main servo and brakes). The main interface executes many time-critical tasks, such as firing the sonars at specific times, constantly checking the sonars for echoes, generating PWM signals for the servos, and decoding the encoder data. The main interface also acts as an asynchronous buffer for the sonar data. Although the GuideCane currently uses only ten sonars, the main interface provides hardware and software support for up to 16 sonars.

The main interface is connected to the PC's bi-directional parallel port. The interface preprocesses most of the sensor data before the data is read by the PC. In addition, all communications are buffered. The preprocessing and buffering not only minimize the communications between the PC and the interface, but also minimize the computational burden on the PC to control the sensors and actuators. Because the main interface completes all the low-level tasks, almost all of the PC's computational power can be dedicated to medium and high-level tasks. The interface consists mainly of three MC68HC11E2 microcontrollers, two quadrature decoders, a FIFO buffer, and a decoder.

The embedded PC/104 computer provides a convenient development environment. For stationary development, the system is connected to a regular keyboard and a CRT monitor. For mobile tests, the PC is connected to a smaller keyboard and a color LCD screen that is attached to the handle below the developer's hand. The entire system is powered by rechargeable NiMH batteries, allowing mobile testing for several hours. The GuideCane is thus fully autonomous in terms of power and computational resources.

While the current prototype consists of four PC/104-sized modules, only two of them are required for the final version. While the VGA module is very useful for visual verification and debugging, it is no longer needed after development. In addition, the hard-disk module can be eliminated in the final product, because the final software can be stored in an EPROM on the motherboard. This solid-state solution also eliminates potential problems with the moving parts of the hard-disk, which is sensitive to shocks and vibrations.

C. Software

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

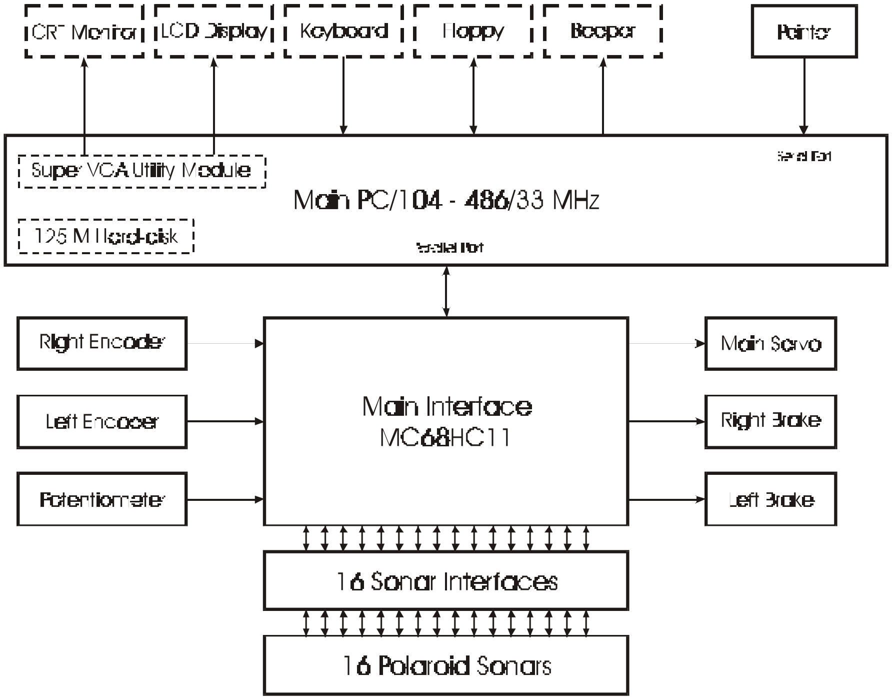

Figure 4: The GuideCane system. Dashed lines indicate components that are only required during the development stage.

localization). Combining the skills of a mobile robot with the existing skills of a visually impaired user makes this particular application feasible at the current stage of mobile robotics research. While reliable global navigation systems 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.

The main task of the GuideCane is to steer around obstacles and to proceed toward the desired direction of travel. To achieve safe travel at fast walking speed through cluttered and unknown environments, the GuideCane employs several mobile robot obstacle avoidance technologies that were developed earlier at the University of Michigan's Mobile Robotics Lab, as explained next.

The ultrasonic sensors are controlled by the *Error Eliminating Rapid Ultrasonic Firing* (EERUF) method [6]. 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 GuideCane 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 GuideCane's obstacle avoidance performance and is necessary for allowing safe travel at fast walking speed.

Based on the sensor data, the GuideCane uses *histogramic in-motion mapping* (HIMM) to build a local map of its immediate surroundings [4]. The map is represented by a two-dimensional array, called *histogram grid*, which is based on the concept of *certainty grids* pioneered by Moravec and Elfes [13]. HIMM produces high certainty values for cells that correspond to obstacles and keeps low certainty values for cells that were increased because of misreadings or moving objects. In the current implementation, the dimensions of the local map are 18 m × 18 m with a cell size of 10 cm × 10 cm. The map requires less than 32 kilobytes of memory. A discrete scrolling algorithm is implemented so that the finite dimensions of the local map do not limit the GuideCane's workspace.

Based on the information contained in the local map, the local obstacle avoidance algorithm determines an appropriate instantaneous direction of motion. Using the information in the local map instead of solely the current sonar readings, a better obstacle avoidance performance is achieved than with a purely reactive system. The task of the obstacle avoidance algorithm is to determine a suitable direction of motion, i.e., one that is free of obstacles but close to the user's desired direction of travel. This direction is then used to send the appropriate steering signal to the GuideCane's servomotor. Originally, the *vector field histogram* (VFH) obstacle avoidance method was implemented in the GuideCane [5]. During the GuideCane development, the original VFH method was successively improved, resulting in the VFH+ and VFH* algorithms [16; 17]. The improved algorithms are more robust by taking into account the width and the trajectory of the GuideCane, and less likely to direct the GuideCane into local dead-ends.

IV. EXPERIMENTAL RESULTS

A performance analysis of the experimental GuideCane prototype, shown in Figure 5, can be divided into two categories: 1) the usefulness of the concept and 2) the performance of the obstacle avoidance system.

The actual GuideCane prototype was tested throughout its development. In total, about 10 people tested the GuideCane. Their age ranged from 20 to 65 years. Three of the test subjects were blind, all of them users of the white cane. The others were sighted but blindfolded. Most of the tests were done indoors, mainly consisting of navigating through corridors and of traversing through cluttered areas. Each test lasted between 5 and 15 minutes.

The main result of our tests is that all test subjects only needed a few minutes of training to traverse cluttered environments at fast walking speed of up to 1 m/s. Blind subjects typically needed a few minutes to fully comprehend the GuideCane concept, as they could not visually observe how the device works. Blindfolded subjects needed some time to simply become accustomed to walking around without sight. In addition, blind and blindfolded subjects alike observed that walking with the GuideCane was very intuitive and required little conscious effort. The same tasks would have required hundreds of hours of training with the NavBelt, and would still result in a slower walking speed and require a substantial amount of conscious effort. The GuideCane concept thus fulfilled all our expectations and confirmed our initial hypothesis that following the GuideCane is a completely intuitive process.

The second category, the obstacle avoidance performance, is adequate in many indoor environments. The performance of the combined EERUF/HIMM/VFH* system is excellent as long as the obstacles are indeed detected by the sonars. 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, as well as potentially dangerous obstacles at head level, should easily be detected with the additional upward-looking sonars of the next prototype version. 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 GuideCane currently lacks the ability of detecting important features such as sidewalk borders. Overcoming this problem will be a necessary step to make the GuideCane a truly useful device for the visually impaired.

Dynamic obstacles are rarely a problem. The most commonly encountered dynamic obstacles are sighted people, who typically have enough courtesy to get out of the blind person’s path. For less accommodating but slowly moving obstacles, the GuideCane is capable of avoiding them.

Figure 5: Iwan Ulrich demonstrates the actual GuideCane prototype.

V. FUTURE IMPROVEMENTS

Sonars – The next version of the GuideCane prototype will be equipped with 13 sonars located in the front in a semi-circular fashion, covering 195° ahead of the GuideCane. Three additional sonars will be placed on top of the housing to detect overhanging obstacles.

Brakes – Both wheels can be equipped with brakes that can be activated by the onboard computer, for several purposes. In densely cluttered environments, the user can be slowed down if his/her speed is too fast. Or, when the user walks into a dead-end where no avoidance maneuver is possible, e.g., a closed door at the end of a corridor, the system can immediately signal this condition by fully applying the brakes. Brakes can be implemented using off-the-shelf, servo-actuated disk brakes used in model race cars. These brakes are powerful and their dimensions are suitable for the GuideCane.

Wheel Configuration – We have proposed a new wheelbase design that consists of a *tricycle* configuration with three unpowered wheels [18]. This new configuration, of which we built and tested a simple prototype, has significantly less inertia, is exposed to smaller mechanical shocks, and insures that the sonar inclination stays horizontal. This configuration is also much more comfortable to hold, and it automatically adapts to the height of the user as well as to vertical movements of his/her hand.

Speech output – Speech output could be a very helpful feature if used appropriately. It would allow the GuideCane to not only guide the user to a desired location, but also to provide additional information about the environment. One useful function could be the instant presentation of location and orientation data. Another useful function would be to warn a user if he/she gets too close to an obstacle, and even telling him/her on which side the obstacle is. Speech output could also be used instead of the brakes to ask the user to slow down or stop.

Global Navigation – Another promising improvement consists of adding a localization module to the GuideCane. This would allow the user to enter a desired target location to the system and then have the GuideCane automatically guide him/her to that location. Alternatively, the system could learn a desired path by recording path segments during an initial "lead-through" run with a sighted person.

Computer vision – The main problem of the current GuideCane prototype is its sensor performance outdoors. The sonars are unable to detect important features such as the borders of a sidewalk. Computer vision seems to be the most promising approach to solve this problem. Computer vision could also be used for other purposes, like localization.

VI. CONCLUSION

The GuideCane offers innovative solutions for the three fundamental shortcomings of conventional ETAs:

1. Because of the sensor array comprising of multiple sonars, the user no longer needs to actively scan the area ahead of him/her. Although not yet implemented in the experimental prototype described in this paper, upward-facing sonars should be relatively easy to implement to detect overhanging obstacles.

2. When the user approaches an obstacle, the GuideCane does not communicate everything it knows about the obstacle to the user. Instead, it analyzes the situation, determines an appropriate direction to avoid the obstacle, steers the wheels in that direction, and thus guides the user around the obstacle without requiring any conscious effort on his/her part. This is possible because a coarse representation of the obstacle's contour is formed in the GuideCane's local map.
3. The GuideCane does not use acoustic feedback, so that there is no masking of audio cues on which many blind persons rely heavily.

As a consequence of these advantages, the GuideCane is intuitive and easy to use. In addition, because the GuideCane takes care of the local navigation task, it allows the user to fully concentrate on the global navigation task.

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