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The NavBelt - A Computerized Multi-Sensor Travel Aid for Active Guidance of the Blind

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ABSTRACT

A new and sophisticated computerized *Electronic Travel Aid* (ETA) for blind and visually impaired individuals is under development at the University of Michigan. This device, called *NavBelt*, enables a blind user to quickly and safely walk through obstacle cluttered and unknown environments. The foremost innovation of this device is its ability to **actively guide** the user around obstacles in pursuit of a given target direction. Using a binaural feedback signal to indicate the suggested direction of travel, only a minimum of conscious effort is required from the user to follow the directional signal. A special *contour following* feature lets the system *automatically* determine the direction of travel when traveling alongside walls, sidewalks, etc.

Alternatively, the user may choose *image mode*. In this mode, the system presents the user with an acoustic image (120^{o} panorama) of the environment. Advanced statistical signal processing algorithms compensate for sensor inaccuracies and provide the user with a more accurate and intuitive image than existing ETAs do.

1. Introduction

The development of a sophisticated computerized *Electronic Travel Aid* (ETA) for blind and visually impaired individuals is under way at The University of Michigan. The device will consist of a belt with a small computer, ultrasonic and other sensors, and support electronics. Signals from the sensors will be processed by a unique algorithm and relayed to the user via headphones. This device, called *NavBelt*, will enable a blind user to quickly and safely walk through unknown, obstacle-cluttered environments.

The *NavBelt* system uses binaural feedback (acoustic stereo signals that create the impression of sound coming from different directions). This feedback signal provides *active guidance* a novel ETA concept for fast, safe travel. With *active guidance*, either the direction of travel or the target location is known to the system. A single binaural signal *actively guides* the user around obstacles in pursuit of the target direction. Preliminary experiments show that only a minimum of conscious effort is required by the user to follow this directional signal. If the direction of travel is not known to the system, two special features let the system *automatically* determine the direction of travel:

1. The *contour following feature* guides the user alongside walls, sidewalks, etc.

2. The *averaging feature* monitors an initial sequence of the user's steps and then determines a direction by extrapolation.

The underlying technology of the *NavBelt* is based on our previously developed *Obstacle Avoidance System* (OAS) for mobile robots a proven and mature technology considered by many experts to be the fastest mobile robot OAS in the nation.

The main advantages of the proposed *NavBelt* over existing ETAs are summarized below:

1. The *NavBelt* not only detects obstacles but **actively guides** the user around the obstacle.

2. The *NavBelt* can guide the user in a predefined direction or toward a predefined target both while actively guiding the user around an obstacle.
3. The *NavBelt* can automatically guide the user alongside walls.
4. The *NavBelt* does not require active scanning by the user (as is the case with hand held devices). It automatically scans a horizontal sector of 120^o in front of the user and protects the user vertically "from head to toe".

5. The *NavBelt* can provide the user with a 120^o-panorama of the environment (when operating in the *image mode*).

6. The *NavBelt* provides the user with full protection and serves as the primary travel aid. The *long cane* is used as a secondary device (e.g., after the *NavBelt* detects a step, to measure the size of the step).

The feasibility of the proposed system was demonstrated in experiments in which a blindfolded user is seated on top of a vehicle. The vehicle is equipped with an OAS, similar in principle to the one proposed here. Relying on the signals generated by the OAS, the user steers himself and the vehicle through an unknown, obstacle-cluttered environment.

2. Background

The most successful and widely used travel aid is the *long cane*. It is used to detect obstacles on the ground, uneven surfaces, holes, steps, and puddles. Blind pedestrians usually tap their cane on the ground, and the resulting vibrations indicate the nature of the surface. Tapping also produces sound, which is then reflected by nearby obstacles. Very skillful travelers are able to detect these echoes and their direction of origin. The foremost disadvantage of the cane, however, is its failure to detect obstacles outside of its reach. Such obstacles include branches, signs, or any other obstacle protruding into the path above the user's waist (Kumpf, 1987). Thus, the blind traveler is constantly in fear of collision and injury. *Dog guides* are considered the best travel aid available, but are very expensive, because of their extensive training. Thus, only a small percentage of blind people can benefit from dog guides (Shao, 1985).

Researchers have been developing *electronic travel aids* (ETAs), designed to help users detect obstacles in their way. The best-known among these devices are the *Russell Pathsounder* (Farmer, 1980), the *Laser Cane* (Benjamin, 1973), the *Binaural Sonic Aid (Sonicguide)* (Kay, 1974), the *Nottingham Obstacle Detector (NOD)* (Bissit and Heyes, 1980), and the *Mowat Sensor* (Wormald, 1989). However, none of these devices is widely used (Shao, 1985), and user-acceptance is relatively low (Blasch et al., 1989). One possible reason for the limited use of these ETAs may be their disappointing performance: All existing ETAs must be used as a secondary device (with the *long cane* as the primary one) (Shao, 1985). Furthermore, these devices must be used in a scanning function; a time-consuming task requiring a constant conscious effort by the user. Once an obstacle is detected, the *conscious and active effort* of the user is required to measure the relevant dimensions of the object and to plan a path around it; all the while scanning and looking out for additional obstacles. This procedure is timeconsuming and straining, and does not permit fast travel.

It may therefore be concluded that no truly useful and generally accepted ETA exists, although such a device would greatly enhance the mobility, as well as the productivity and confidence of blind or visually impaired people.

3. The NavBelt

We plan to remedy the shortcomings of existing ETAs by introducing a new and unique device, named *NavBelt*, designed to allow visually impaired users safe and fast travel through obstacle-cluttered environments. that *actively guides* the user through cluttered environments without demanding much conscious effort. This level of performance is made possible by a *transfer of technology from the field of mobile robotics*: In over six years of research in obstacle avoidance for mobile robots (Borenstein and Koren, 1985, 1987, 1988, 1989b), we have developed a reliable, fast, and robust *obstacle avoidance system* (OAS) that is considered by many experts to be the fastest OAS for mobile robots in the nation. This system scans the environment with many sensors simultaneously, while employing a unique real-time signal-processing algorithm that produces the *active guidance* signal. The strength of this OAS is based on its gradual reduction of data complexity (from multiple sensors) to a level suitable for real-time guidance of robots (or human beings).

The user wears the *NavBelt* around the waist like a "fanny pack," and shoulder straps support the weight of the device. Unlike a fanny pack, the *NavBelt* has a *rear pack* and a *front pack* (see Fig 1). The *rear pack* houses the battery, the computer, and a *solid state compass*. The ultrasonic sensor and a *doppler-effect distance sensor* are mounted on the *front pack*. Sixteen ultrasonic sensors are arranged in two horizontal arrays, called the upper and lower array. Each array covers a horizontal sector of 120°. However, the upper array is also tilted upward, making an angle of 15°-30° with the horizon (the final angle will be determined experimentally), while the lower array is tilted downward at the same angle.

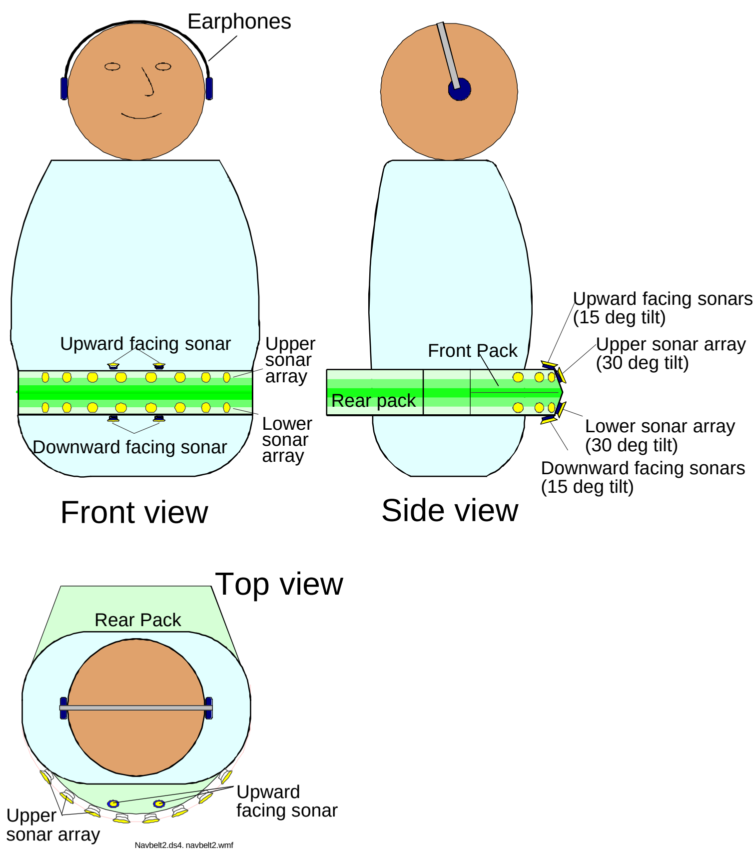


Figure 1: The NavBelt – a sophisticated travel aid for the blind

Each array comprises 8 sensors equally spaced at 15° intervals. Two additional ultrasonic sensors on the bottom of the *front pack* face downward (at an angle of 75°-85° with the horizon, so as not to detect the feet of the user) to detect steps, and two sensors are mounted on top of the *front pack*, facing upward, to protect the user's head from overhanging obstacles. The *doppler-effect distance sensor* is mounted in the center of the *front pack*.

4. The Obstacle Avoidance System

The computational heart of the *NavBelt* is the *obstacle avoidance system* (OAS), a computer program developed originally for mobile robots (see companion paper Borenstein, Levine, and Koren, 1990, in this volume). The OAS described in this section has been developed and implemented, and was successfully tested with mobile robots *and* sightless users. In the *NavBelt* application, the OAS reads the sensors and computes the feedback signal for the user. In its raw format, this feedback signal is the *suggested direction* for safe travel. In the absence of obstacles, this direction is simply the direction toward the predefined target. If, however, obstacles block the user's path in that direction, then the OAS will compute a safe direction around the obstacle. This feedback signal is recomputed every 35 msec, and fed back to the user via the *binaural feedback system* (explained below in Section 4). The present section briefly describes the OAS computer program; The method is described in greater detail in our recent paper (Borenstein and Koren, 1989c).

The OAS uses a two-dimensional Cartesian *histogram grid* as a world model. This world model is updated continuously and in real-time with range data sampled by the ultrasonic sensors. The *histogram grid* comprises of a large number of square cells, each representing a small square area of the "real" world. If a sensor detects an obstacle, the contents of the corresponding cell, its *certainty value* (CV), is incremented by '1'. Thus, in spite of the inherent inaccuracy of ultrasonic sensors, rapid sampling during motion causes high CVs in the *vicinity* of an obstacle.

During each sampling interval, the algorithm constructs a *polar histogram* **H** around the user's *momentary* location. **H** comprises n angular sectors of width α. α may be chosen arbitrarily but must be such that $n=360/\alpha$ is an integer (e.g., $\alpha=5^o$ and $n=72$). Each sector k corresponds to a discrete angle Φ quantized to multiples of α, such that $\Phi=k\alpha$, where $k = 0,1,2,...,n-1$. A transformation (described below) maps **C*** into **H** resulting in each sector k holding a value h_k which represents the *polar obstacle density* in the direction k.

In order to map the *active region* of the *histogram grid* **C*** into the *polar histogram* **H** the algorithm treats the *certainty value* of all *active cells* $c^*_{i,j}$ as an *obstacle vector*, the direction of which is determined by the direction $\beta_{i,j}$ from the cell to the *user center point* (UCP).

$$\beta_{i,j} = \tan^{-1}\frac{y_j-y_0}{x_i-x_0} \tag{1}$$

and the magnitude is given by

$$m_{i,j} = (c^*_{i,j})^2\,(a - b\,d_{i,j}) \tag{2}$$

where

a,b Positive constants.
$d_{i,j}$ Distance between *active cell* (i,j) and the UCP.
$c^*_{i,j}$ Certainty value of *active cell* (i,j).
$m_{i,j}$ Magnitude of the *obstacle vector* at cell (i,j).
x_0, y_0 Present coordinates of the UCP.
x_i, y_j Coordinates of *active cell* (i,j).
$\beta_{i,j}$ Direction from *active cell* (i,j) to the UCP.

Note that a and b are related by $a - bd_{max} = 0$, where $d_{max} = \sqrt{2}\,(w_s-1)/2$ is the distance between the farmost *active cell* and the UCP. This way $m_{i,j}=0$ for the farmost *active cell* and increases linearly for closer cells.

The *histogram grid* **C** is absolute and does not change with the user's momentary location. However, along with the user moves a virtual window of size $w_s\times w_s$, overlaying a square region of **C**. We will call this region the "*active region*" (denoted **C***), and cells that momentarily belong to the *active region* will be called "*active cells*" (denoted $c^*_{i,j}$). In our current implementation, the size of the *active region* is 33×33 cells. As will be discussed below, only *active cells* have immediate influence on the feedback signal.

Correspondence between $c^*_{i,j}$ and sector k is established through

$$k = \alpha\cdot\mathrm{INT}(\beta/\alpha) \tag{3}$$

For each sector k, the *polar obstacle density* h_k is calculated by

$$h_k = \sum_{i,j} m_{i,j} \tag{4}$$

Notice that

a. $m_{i,j}$ in Eq. (2) is proportional to $(c^*_{i,j})^2$. This expresses our confidence that *recurring* range reading represent actual obstacles, as opposed to single occurrences of range readings, which may be caused by noise.

b. $m_{i,j}$ in Eq. (2) is proportional to $-d$. Therefore, occupied cells produce large vector magnitudes when they are in the immediate vicinity of the robot, and smaller ones when they are further away.

Finally, a smoothing function is applied to **H**, which is defined by

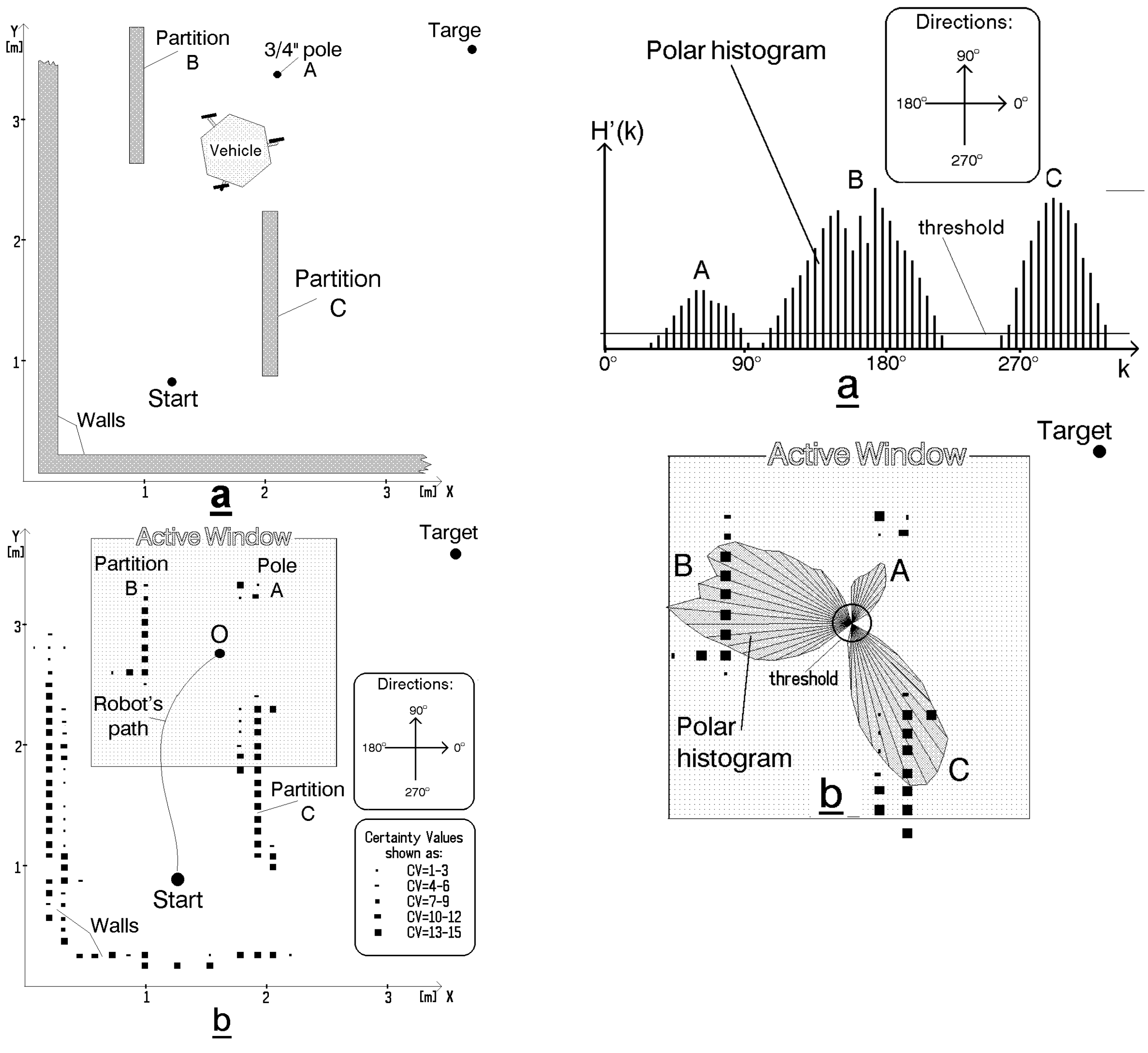
$$h'_k = \frac{h_{k-m}+2h_{k-m+1}+...+mh_k+...+2h_{k+m-1}+h_{k+m}}{2m+1} \tag{5}$$

In our current implementation, $m=5$ yields satisfactory smoothing results.

Fig. 2a shows a typical obstacle setup in our lab. Note that the gap between obstacles B and C is only 1.2 m and that A is a thin pole 3/4 inch in diameter. The actual *histogram grid* obtained after partially traversing this obstacle course is shown in Fig. 2b. The *polar histogram*, corresponding to the momentary position of the robot O is shown in Fig. 2c. The directions (in degrees) in the *polar histogram* correspond to directions measured counterclockwise from the positive x-axis of the *histogram grid*. The peaks A, B, and C in the *polar*

Figure 2:
Left pane:
a. Example obstacle course.
b. *Histogram grid* representation of the example obstacle course.

Right pane:
a. *Polar obstacle density h* is relative to the robot position O and represented in the *polar histogram* **H**(k).
b. Same as c. but **H**(k) is relative to the user's direction of travel Θ, such that 0° corresponds to Θ and -90° and +90° correspond to the travelers left and right side, respectively.



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histogram result from obstacle clusters A, B, and C in the *histogram grid*.

After constructing the *polar histogram* (we recall that a new *polar histogram* is computed at every sampling interval, i.e., every 35 msec), the algorithm determines the desired direction of travel, Θ_{free}: As can be seen in Fig. 2c, a *polar histogram* typically has peaks (sectors with high obstacle density), and valleys (sectors with low obstacle density). Any valley with obstacle densities below threshold is a candidate for travel. Since there are usually several candidate-valleys, the algorithm selects the one that most closely matches the direction to the target.

When the user approaches or travels between two or more closely spaced obstacles, only a very narrow valley is available for travel. In this case, Θ_{free} is chosen to be in the center of the valley, in order to maintain equal clearance on each side of the user. If the selected valley is very wide (e.g., when only one obstacle is close to the user) the algorithm chooses Θ_{free} several sectors "deep" into the valley, but not necessarily in its center.

Finally, the absolute direction Θ_{free} is transformed into a relative direction Θ_{rel}, with respect to the user's actual direction of travel Θ (which is measured by means of the *solid-state compass*). Then, using the *binaural feedback system* (BFS), this information is fed back to the user, as explained in Section 5.

5. Feedback for the Traveler

ETAs commonly use acoustic or tactile feedback devices to provide environmental information to the user. While the output signals of the *obstacle avoidance system* (OAS) are suitable for tactile feedback systems, we concentrate our research efforts on an acoustic system which permits a wider range of experimental possibilities.

An experimental prototype of the *binaural feedback system* (BFS) for the *NavBelt* has been developed and tested. This BFS uses a set of stereo earphones to create a *virtual direction* (i.e., an impression of directionality of virtual sound sources). Our *binaural feedback system* is based on the *interaural time difference* (i.e., the phase difference between the left and right ear) to create the impression of directionality. This system generates clicking sounds, the *virtual direction* of which is particularly easy to determine (Benson, 1988). In addition to the *virtual direction*, different amplitudes can be set with this system.

We have tested two binaural feedback modes that will be offered as user-selectable modes of operation in the *NavBelt*. A discussion on each of these modes follows.

5.1 Acoustic Guidance Mode

In this mode, the BFS *actively guides* the traveler around an obstacle and toward the original target. The amplitude *A* of this signal is proportional to a parameter that is unique to our OAS and that allows very efficient and fast travel: h_Θ, the *polar obstacle density* in the current *actual* direction of travel Θ (see Section 4). h_Θ is a function of the obstacle size, the distance to the obstacle and the certainty about the accuracy of the sensor measurements. Thus, h_Θ is most practical as a measure for the *anticipated change of direction*. At walking speed, h_Θ (and thus the amplitude of the feedback signal) changes 0.5-1.0 sec before a drastic avoidance maneuver is required. This *preview time* is extremely important for the blind traveler (Shingledecker, 1978; Clark-Carter et al., 1986), as it increases their confidence and ability to avoid obstacles. A traveler will react to an increase in amplitude by reducing their walking speed and by paying closer attention to the changing *virtual direction* clues during the avoidance maneuver.

Active guidance is extremely powerful when the *obstacle avoidance system* knows the destination of travel (e.g., in conjunction with a *global navigation aid* such as the one discussed in Section 7) or when a direction of travel is known. If the direction is not known, two special features will be available that let the system *automatically* determine the direction of travel. These features are discussed below.

1. The *contour following* feature guides the user alongside walls, parked cars, and possibly along suburban sidewalks (the latter possibility must be checked experimentally). Once the system has "locked in" on a wall, it will follow that wall even if it is curved or around corners. This feature is based on our previously developed *wall-following* algorithms (Borenstein and Koren, 1989a).
2. The task of the *averaging* feature is to determine automatically the desired direction of travel. For this purpose, the user resets the system and starts walking in the desired direction, using any of a number of

guidance techniques (e.g., a long cane or a human helper), while the system monitors the user's path. After a few yards of (possibly slow) travel, the system has accumulated enough data to determine the desired direction of travel τ by averaging the data. Naturally, this direction will not accurately correspond to the *actually* desired direction. For example, the user may wish to travel on a straight sidewalk. After the first few data points have been sampled, the system determines τ, but is off by 10^o, in the direction of the street. However, parked cars and the curb are recognized as obstacles, and the OAS guides the user alongside these obstacles in the true direction of the sidewalk. All the while, the system continues to monitor the user's path, updating (and thus improving the accuracy of) the initial average. The difference of this feature as compared to *contour following* is subtle but relevant: When a sidestreet was reached, the system would suggest a sharp turn in the direction of the sidestreet if *contour following* was active. However, with the *averaging* feature active, the user would follow the initial direction and cross the sidestreet.

Since these two features are new and their approach has not been tested yet, we expect some difficulties and limitations to become apparent upon experimentation. However, this approach of *automatic learning* and *real-time adaptation* promises great flexibility and improved machine/user interaction.

5.2 Acoustic Image Mode

At each sampling interval, the OAS generates a *polar histogram* (PH) that represents the momentary *polar obstacle density* (POD) around the user (PH and POD are explained in Sec. 4). The PH looks somewhat similar to the panoramic view of a mountainous landscape: "*Mountains*" indicate the presence of obstacles, while "*valleys*" indicate directions free of obstacles. Fig. 2d shows a 180^o sector of the PH in *user-coordinates*, i.e., the center of the PH always corresponds to the current direction of travel, and the left and right side of thePH (-90^o and $+90^o$) correspond to the left and right side of the user. This panoramic view can be fed back to the user via an *acoustic image generator* (AIG). The AIG uses the same binaural feedback hardware that is used in the *guidance mode*. The AIG is designed to invoke the impression of a virtual sound source moving from one side of the listener to the other (called a sweep). This is done in 37 discrete steps (i=-18,...,0,...,18), corresponding to discrete virtual direction steps (each of $\alpha=5^o$), from -90^o (left side) to $+90^o$ (right side). At each step i, the amplitude A of the binaural signal is set proportional to the POD in the corresponding *virtual direction* Φ:

$$\Phi(i) = \alpha i, \quad i = -18,...,0,...,18 \qquad (6)$$

and

$$A = h_{\Phi(i)} \qquad (7)$$

where

i Sweep index.
$\Phi(i)$ Virtual direction in [degrees].
$h_{\Phi(i)}$ *Polar obstacle density* in direction $\Phi(i)$.
A Output amplitude.

This method yields the following effect: If no obstacles are present (the panoramic view is flat), the virtual sound source is of a low amplitude and barely audible. If, however, obstacles are present, the amplitude of the virtual sound source increases proportionally to the height of the "mountain" and corresponding to the momentary sweep position. This way, the user's mind creates a mental picture of the environment that adequately describes the *obstacle density* around the user.

The technique of creating an acoustic image of the environment has been investigated by Fish (1976). In his work, he linearized 2-D images by sweeping over each horizontal line with sounds of different frequencies. Fish's research showed that a sweep-time of only 0.8 sec is sufficient to *imprint* a linearized acoustic 2-D image in the mind of the listener. However, it would then take the listener several seconds to *comprehend* the perceived image. Our acoustic imaging mode, on the other hand, models a one-dimensional image (the PH) and, therefore, is significantly easier to comprehend.

6. Experimental Results

We performed several experiments in order to assess the feasibility of our system. Our main concern in these experiments was the user interface, the *binaural feedback system* (BFS), and the user's ability to react quickly to such input. For our experiments, we implemented the BFS described in Section 5.

We used a mobile robot with onboard computer and a ultrasonic sensors as the testbed for our experiments. A blindfolded test-person seated on the mobile robot was able to steer himself quickly (with the aid of a joystick) through a difficult obstacle course. The average speed of the vehicle in a typical experiment was 0.51 m/sec, and the maximum speed was 0.78 m/sec (this is the maximum speed of the vehicle). While this speed is slower than the walking speed of a sighted person, it should be noted that most of the difficulty in this experiment stems from steering the vehicle with a joystick: With this experimental setup the test-person was completely unaware of how far he had driven and how much he had turned information considered crucial for efficient travel.

Another experiment aimed at evaluating the *acoustic image mode* (described in Section 5.2). In this experiment, the test-person had to steer a simulated vehicle through a difficult obstacle course. Obstacles were represented in this run by actual sensor data (gathered in previous mobile robot runs). *Acoustic images* of the *polar histogram* where created continuously, with a sweep-time of 0.55 sec. After 20 hours of training on this system, the test-person could drive the simulated vehicle at an average speed of 30 cm/sec through difficult obstacle courses. This result clearly shows the real-time feasibility of the *acoustic image mode*.

7. Future Developments

The proposed *NavBelt* system encourages a great variety of future developments. The most obvious and immediate expansion of the system would aim at incorporating a *global navigation aid* (GNA) into the ETA. An integrated GNA/ETA system would work as follows: First, the user specifies his or her present location, as well as the target location (e.g., the grocery store on Main street). Next, the GNA computes an optimal path between the starting position of the user and a known target location. The path comprises a list of *via-points*, typically vertices of straight line segments. This way, the OAS always receives a new target location (namely, the next GNA-generated *via-point*), and the *guidance mode* can be used. This is desirable, since the *guidance mode* is easy to follow and allows for fast travel.

In order to generate a path, a *map* of the environment must be known to the system. In urban environments, regular street maps would be used. Computerized versions of such maps are already commercially available. For indoor applications, such map would comprise data on corridors, walls, doorways, etc. In the future, public buildings like hospitals, schools, government agencies, etc., may offer electronic map information at their entrances. This information can than be downloaded into the user's *NavBelt* computer.

A GNA for optimal path planning has been one focus of our mobile robotics research (Borenstein and Koren, 1986, Zhao et al., 1989) and is implemented on our mobile robot CARMEL.

8. Conclusions

We present the concept for a sophisticated travel aid for the blind. This system, called *NavBelt*, is based on technology originally developed for mobile robots. To show the feasibility of this transfer of technology, we have designed and tested an acoustic feedback system suitable for real-time guidance of blind travelers. Results of this experiment are shown in a video clip.

We have also investigated the commercial availability of components required for a *portable system*. We have further analyzed the electrical power requirements and weight and size constraints of these components. It was determined that the total power consumption of all necessary components is 18 W. The total weight of the portable system, including rechargeable batteries for 2.5 hours of continuous operation, is 3.4 Kg. All components can be packaged into a volume of 12"x6"x4".

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