Mobile Robot Obstacle Avoidance in a Computerized Travel Aid for the Blind

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Abstract

A blind traveler walking through an unfamiliar environment, and a mobile robot navigating through a cluttered environment have an important feature in common: both have the kinematic ability to perform the motion, but are depended on a sensory system to detect and avoid obstacles. This paper describes the use of a mobile robot obstacle avoidance system as a guidance device for blind and visually impaired people. Just like electronic signals are sent to a mobile robot's motor controllers, auditory signals can guide the blind traveler around obstacles, or alternatively, they can provide an "acoustic image" of the surroundings. The concept has been implemented and tested in a new traveling aid for the blind, called the Navbelt. Experimental results of subjects traveling with the Navbelt in different surroundings are presented.

1. Introduction

The motion of a blind traveler in an unfamiliar environment is somewhat similar to that of a mobile robot. Both have the physical ability to perform the motion, but aredepended on a sensory system to detect obstacles in the surroundings, and to relay the information to the control system (human brain or motion control computer). In both cases, reliable obstacle system is mandatory for fast and safe motion.

In order for a blind person to follow a particular route, the person must have some concept or plan of that route. Sometimes, the traveler can learn the plan while being guided by a sighted escort. At other times, the traveler has only verbal instructions to go by. Once a route has been learned, successful travel requires the individual to be able to: (1) detect and avoid obstacles and (2) follow the route precisely (i.e., to know their position and orientation and, if necessary, make corrections). The performance of both tasks can be enhanced through electronic devices, called *electronic travel aids* (ETAs). Among the common ETAs are the C5 Laser Cane, the *Mowat Sensor*, the *Nottingham Obstacle detector*, the *Binaural Sonic Aid*, the *Talking Signs*, and the *Sona System*.

Existing ETAs are not widely used, because of four major shortcomings:

1. The user must actively scan the environment to detect obstacles. 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 isdetected, in order to determine the dimensions of the object. A path must then be planned around the obstacle; again, a time consuming effort that reduces the walking speed.

3. Only a portion of the required mobility information is acquired or transferred to the user.
   The information gathered by the sensors is inaccurate and subject to external noise.

Applying a mobile robot obstacle avoidance system in a travel aid for the blind eliminates several of the shortcomings found in existing devices. Using multiple ultrasonic sensors that face in different directions frees the user from the need to scan the surroundings manually. Furthermore, no additional measurement is required when an obstacle is detected, since its relevant dimensions are determined simultaneously by the multi sensor system. In addition, the obstacle avoidance system can guide the blind traveler toward a target while avoiding obstacles along the path.

2. The *Navbelt*

Based on our experience with obstacle avoidance for mobile robot, we have developed a new travel aid for the blind, called the *Navbelt* [Borenstein, 1990; Shoval et al. 1993a]. The *Navbelt* consists of a belt, a portable computer, and ultrasonic sensors. In this system, the computer processes the signals that arrive from the sensors, and applies the obstacle avoidance algorithm. The resulting signals are relayed to the user by stereophonic headphones, using a stereo imaging technique. The similarity between this approach and the original mobile robot application is illustrated in Fig. 1. The electrical signals which originally guided the robot around obstacles are replaced by acoustic (or tactile) signals.

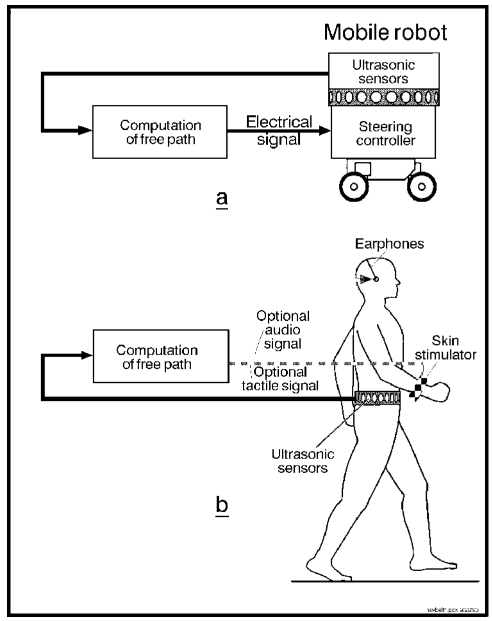

Figure 1: Transfer of technology: mobile robot obstacle avoidance applied as a mobility aid for the blind.

The *Navbelt* was originally designed for two operational modes:

1) ***Guidance* Mode** - The acoustic signals actively guide the user around obstacles in pursuit of the target direction. The signals carry information regarding the recommended direction and speed of travel, and information about the proximity to obstacles.

2) ***Image* Mode** - This mode presents the user with an *acoustic panoramic image* of the environment by using stereophonic effects: sound signals appear to *sweep* through the user's head from the right ear to the left. The direction to an obstacle is indicated by the perceived spatial direction of the signal, and the distance is represented by the signal's volume.

The *Guidance* mode is very similar to the control of a mobile robot. However, this mode of operation requires constantly updated information about the traveler's position. In a mobile robot this information is easily obtained from encoders attached to the vehicle wheels (Odometry). However, the *Navbelt* is currently not equipped with any positioning feedback device. Possible feedback systems for the *Navbelt* might comprise of a pedometer and an electronic compass, but it is not clear if this system would be accurate enough. To overcome this problem, we introduced a third operating mode - the ***directional guidance* mode**. This mode is based on the tele-autonomous mode of operation, which was also originally developed for mobile robots [Borenstein and Koren, 1990]. In this mode the system actively guides the user toward a *temporary* target, the location of which is determined by the user. The user can prescribe the direction of the temporary target with a joystick; or when a joystick is not used, the target is assumed to be straight ahead of the user. In case an obstacle is detected, the *Navbelt* guides the user around the object with minimal deviation from the target direction. This mode is particularly efficient for wall following or detecting corners, door ways etc.

3. The obstacle avoidance system in the *Navbelt*

The obstacle avoidance system in the *Navbelt* is based on a polar map, which is divided into eight sectors (for the eight ultrasonic sensors of the *Navbelt*). Existence of an obstacle is represented as an arc in the sector (Fig. 2).

To reduce the occurrence of erroneous readings due to noise, specular reflection or crosstalk, we have integrated a powerful noise reduction algorithm, known as EERUF [Borenstein and Koren, 1992]. EERUF allows the sonars to fire at rates which are five to ten times faster than those attained with conventional ultrasonic firing methods. At the same time EERUF reduces the number of erroneous readings by one to two orders of magnitude. In addition, a low pass filter is applied to further reduce the affect of inaccurate sonar readings. Implementing the EERUF method in the *Navbelt* is done as follows:

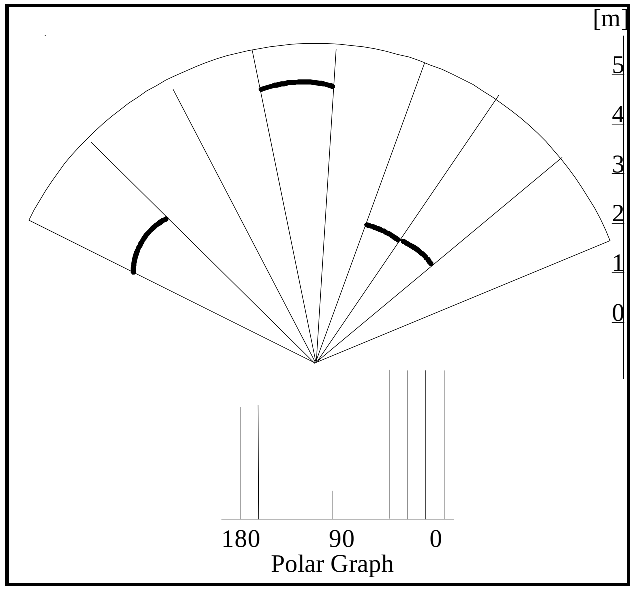

Figure 2: The obstacle avoidance system in the *Navbelt* based on EERUF

1) EERUF controls the ultrasonic sensors and filters erroneous readings before they are processed by the obstacle avoidance algorithm.
2) The world model is divided into eight sectors, each representing one sonar. The width of the sectors is similar to the span of the ultrasonic ray fired by the sonar (approximately 15°). Based on the sonar's reading, the corresponding sector is filled with the range to an obstacle. The sector range is updated as soon as a reliable reading is accepted by the EERUF control.
3) A polar graph is than constructed from the sectorial map. The value of each sector in the graph is inversely p

roportional to the distance of the object of the corresponding sector in the polar map.

The recommended travel direction is computed from the polar graph. The polar graph has "peaks," which represent obstacles in that direction, and "valleys," representing obstacles far away from the traveler, or no obstacles at all (see Figs. 2 and 3b). A threshold determines the margin of safety. Polar sectors with values higher than the threshold are considered unsafe directions as they represent obstacles in close proximity to the traveler. Similarly, sectors with a lower value than the threshold are considered safe directions since no obstacles are immediately threatening the traveler. Valleys comprised of polar sectors lower than the threshold are called candidate valleys. Usually there are two or more candidate valleys, and the obstacle avoidance algorithm selects the one that most closely matches the direction of the target. The width of the selected valley (the number of consecutive sectors in the polar graph below the threshold) determines the required travel direction. If the valley is narrow (i.e. the number of sectors below the threshold is smaller than a certain value) then the required direction is at the center of the valley. In such a case, the recommended direction is centered between closely spaced obstacles. When the valley is wide, the algorithm selects a travel direction at a safe distance from obstacles, but with minimal deviation from the target direction. Figure 3 illustrates the selection of the candidate valleys and the required travel direction. Note that this method is identical to the one that was introduced in the VFH obstacle avoidance method for mobile robots [Borenstein and Koren, 1991].

The recommended travel speed is determined according to the size of the valley, the distance from the obstacles, and the user's capabilities (age, motoric skills etc.). A narrow valley or close distance to an obstacle require more cautious motion, thus the recommended speed is reduced proportionally according to Eq. (1).

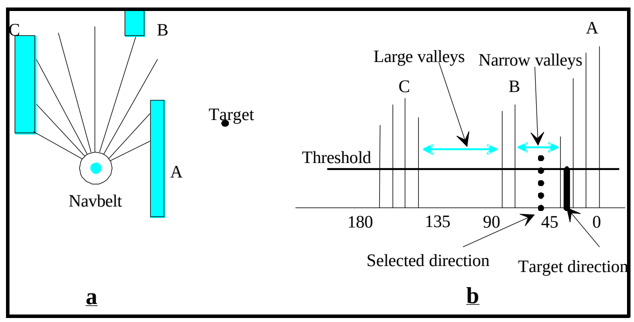

Figure 3:
Selection of travel direction in *guidance* mode

$$V = \frac{V_{max}}{2} \left[\left(\frac{d}{d_{max}}\right) + \left(\frac{w}{w_{max}}\right) \right] \quad (1)$$

where:
d_{max}, w_{max} - maximum distance (5 meters) and maximum valley's width (35°)
d, w - actual distance and valley's width
V_{max} - maximum travel speed

4. Implementation of auditory image signals

The *image* mode provides the user with a panoramic auditory image of the surroundings. The principle is similar to the operation of a radar system (used in air traffic control, submarines etc.). An imaginary beam travels from the right side of the user to the left through the sectors covered by the *Navbelt*'s sonars (a span of 120° and 5 m radius). A 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. At each step, the amplitude of the signal is set proportionally to the distance to the object in that virtual direction. If no obstacles are detected by the beam, the virtual sound source is of a low amplitude and barely audible. If, on the other hand, obstacles are present, then the amplitude of the virtual sound source is louder. The amplitude increases for close objects, and decreases if objects are further away.

Figure 4 demonstrates the principle of the *image* mode. Obstacles are detected by the ultrasonic sensors (Fig 4a), and are projected onto the polar graph (Fig. 4b). Based on the polar graph, the binaural feedback system generates the *sweep*, which comprises of 12 steps (Fig. 4c). Each step "covers" a sector of 15^o, thus the whole *sweep* covers a panorama of 180^o. Each of the eight sectors in the center of the panorama (covering the sectors between 30^o and 150^o) is directly proportional to the corresponding sensor. The remaining four sectors (two at each side of the panorama) represent sectors which are not covered by the sonars. The value of these sectors is calculated basedon the values of adjoining sectors. For example, if the third sector(representing the first sonar) contains an object, than the first and second sectors are automatically assigned the same value. This way, the sides of the traveler which are not covered by the sensors are blocked, therefore eliminating the possibility of turning into an unchecked area.

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 image. Many meaningful combinations of these parameters are possible. For example, because of the *short term memory* capability of the human ear, a *sweep* may be as short as 0.5 sec. Given enough cognition time T_c, the user will comprehend the image. Alternatively, the *sweep* time may be as long as one second, combined with a very short cognition time. Notice that each *sweep* starts with an anchor signal. This signal has a unique pitch, thus providing the user with a convenient identification of the start of a *sweep*.

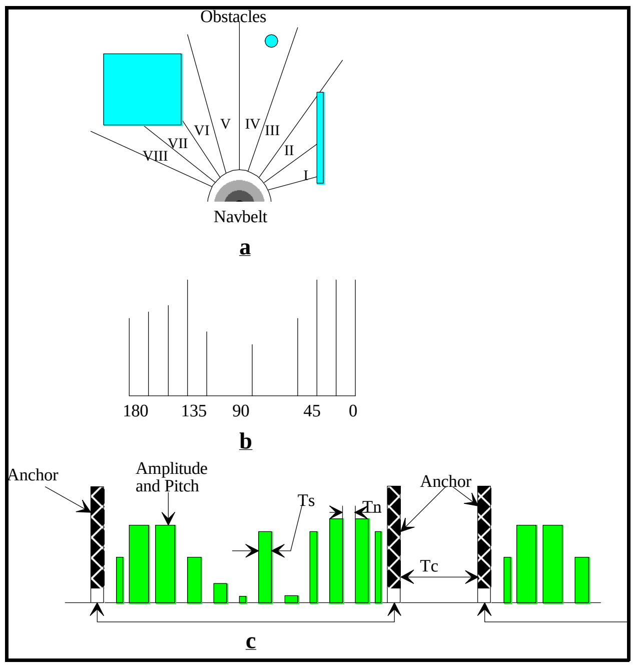

Figure 4: The *image* mode. obstacle are detected by the ultrasonic sensors (a), projected onto the polar graph (b), and an acoustic *sweep* is generated (c).

5. Implementation of auditory *guidance* signals

Implementing the *guidance* mode in the *Navbelt* is simpler than the *image* mode, as the amount of transferred information is far smaller. In the *guidance* mode the computer provides the user only with the recommended travel speed and direction, based on the obstacle avoidance algorithm.

The travel speed and direction are relayed to the user by a single stereophonic signal. The virtual direction of the signal is the direction the obstacle avoidance system has selected for travel. The pitch and amplitude are proportional to the recommended travel speed. Higher pitch and amplitude attract more human attention, thus the traveler intuitively reduces the walking speed and concentrate on the stereophonic signal.

A special low pitch signal (250 Hz) is transmitted when the direction of motion coincides (within +/- 5^o) with the required direction. This special tone serves two purposes:

1) The low pitch tone is an efficient and simple feedback signal for the user, indicating that the travel direction is correct.
2) Low pitch tones occlude external sound from the environment less than medium and high pitch tones. One of the main concerns of potential users of the *Navbelt* is that the stereophonic signals may occlude the perception of important external sounds. However, when the user is traveling in the right direction, less external sound is occluded by the low pitch tone. 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 is the rate in which signals are transmitted. Although a low transmission rate causes less occlusion of external sounds, it may also be too slow for alerting the traveler to hazards. An adaptive information transfer system [Shoval et. al., 1993b] adjusts the transmission rate according to changes in the process and the user's requirements. For example, when the user is traveling in an unfamiliar environment cluttered with a large number of obstacles, the transmission rate increases to 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 seconds.

6. The *Navbelt* simulator

To investigate the *Navbelt* concept under different situations, a simulator was developed. The simulator is based on the same hardware as the *Navbelt*, and the same acoustic signals that guide the user in the real *Navbelt* are used in the simulator. The user's response to these signals is relayed to the computer by a joystick. Several maps are stored in the computer's memory, representing different types of environments with different levels of travel complexity. In the experiments with the simulator, subjects "traveled" through the different maps while listening to the sounds generated by the computer.

In the experiments with the *image* mode, the position of the subject and the location of the target were shown on the computer screen. When subjects "collided" with an obstacle, a verbal message informed the subject about the collision, and no forward travel was permitted. The subject then turned or backed up to continue traveling toward the target. After reaching the target, the full map was superimposed on the traveling path so that the subject's performance during the run could be evaluated.

In the experiment with the *guidance* mode, only the traveler's simulated position was shown on the screen while the target position was unknown to the subject. This is the equivalent of traveling in an unfamiliar environment, where the traveler depends entirely on the guiding signals from the *Navbelt*. As with the *image* mode, when subjects "collided" with an obstacle, a verbal message informed about the collision, and no forward travel was permitted.

7. Experiments with the *Image* mode

Experiments with the *image* mode included three stages. In the first stage subjects listened to different *sweep*s and drew a map of the environment based on the auditory information. Several combinations of the *sweep* parameters were examined. The aim was to determine a good combination for perception and fast comprehension of the transmitted signals. Good results from these experiments were obtained with the following parameters:

Signal transmission time T_s varies between 20-40 msec, where 20 msec is used for the longest distance from an object (5 meters) and 40 msec for very close objects (0.5 meter).

Space time T_n between signals is kept constant through the whole *sweep* with T_n = 10 msec.

The amplitude A varies inversely with the range reading from the corresponding sonar sector. Sixteen discrete amplitudes can be selected, where the lowest value represents no threat to the traveler and is not audible at all, while the maximum value represents high risk from that direction. Twelve signals per each *sweep* (not including the anchoring signals) are sufficient for safe travel, and they require less than 0.5 seconds for the transmission of the whole *sweep*.

Cognition time T_c between *sweeps* varies according the user's capabilities and the complexity of the *sweep*. The complexity of the *sweep* is calculated before the *sweep* is transmitted based on the polar graph. The complexity is defined as the sum of the number of non- zero signals in the polar graph, the difference between the signals within the graph, and the rate at which signals are changed in time. Eq. 2 describes the calculation of the *sweep*'s complexity.

$$C = \sum_{i=0}^{12} A_1(t) + \sum_{i=0}^{12} \{A_1(t) - A_{i-1}(t)\} + \sum_{i=0}^{12} \partial(A_1)/\partial t \qquad (2)$$

where $A_i(t)$ is the value of sector i in the polar graph at time t.

The second stage in the experiments included the *Navbelt* simulator. 100 maps were selected randomly by the computer from a list of 10 maps. The average travel speed was 0.52 m/sec from all 100 runs with the *image* mode. An important conclusion from this experiment was that the complexity of the environment has a major affect on the traveling speed. A more complex environment requires more conscious efforts from the user, thus causing a reduction in the travel speed. Another important element which affects the travel speed, is the user's experience with the *Navbelt*. Those with less experience or reduced auditory perception capabilities travel slower than highly skilled people.

An adaptive auditory information transfer (AAIT) method [Shoval et. al., 1993b] can improve the traveling speed by continuously adjusting the information flow from the computer to the person. This adjustment is based on changes in the environment as well as on the person's skills, which are represented in a performance model. In a simulator experiment, the AAIT method improved the travel speed by an average of 30% compared with non adjustable information transfer.

Finally, experiments with the actual *Navbelt* prototype were conducted. Subjects traveled through the controlled environment of the laboratory, relying only on the *Navbelt*'s audio signals in the *image* mode. Obstacles were randomly positioned in the laboratory, and the blindfolded subject were asked to travel from one side of the laboratory to the other. Travel speed in these experiments was slower than with the *Navbelt* simulator, mainly because subjects were more cautious. However, after a training period of several hours they traveled safely through the controlled environment of the laboratory with an average speed of 0.4 m/sec.

8. Experiments with the *Guidance* mode

The experiments with the *guidance* mode were conducted only with the *Navbelt* simulator. A performance index was introduced for the evaluation of human travel in the *guidance* modes. The evaluation of the performance is based on a continuous comparison of the traveler's actual trajectory to the recommended trajectory by Eq. 3:

$$P = [\ (V_a - V_r)\ dt + \ |D_a - D_r|\ dt]/t \qquad (3)$$

where

P - Human accumulated performance

V_r, V_a - Recommended and actual traveling speed

D_r, D_a - Recommended and actual traveling direction

t - Total travel time

V_r and D_r of Eq. 3 are calculated by the obstacle avoidance system. V_a and D_a are measured according to the joystick position. Since the obstacle avoidance system eliminates the possibility of collision with obstacles, any deviation of the traveler from the recommended direction is undesirable and results in a reduction in performance evaluation.

Experiments with the *Guidance* mode on the *Navbelt* simulator included 200 tests. Averaging the results from all tests shows a travel speed of 0.76 m/sec, with an average directional deviation (deviation from the recommended travel direction) of 7.7°. The results naturally vary with the level of difficulty of each map, with the best results reaching a travel speed of 0.95 m/sec and directional deviation of 0.9°, while the worst result was 0.55 m/sec and 16.7°.

The experiments with the *directional guidance* mode were conducted with the *Navbelt* prototype. In the first series of experiments, subjects were asked to travel from one side of the laboratory to the other side (12 meters). They were blindfolded, and obstacles were positioned randomly in the room. The average traveling speed achieved in this experiments was 0.45 m/sec. The next experiment took place in a more realistic environment. The subjects were asked to travel along a standard office building corridor, with which they were familiar. The length of the path was 25 meters and included several corners. No obstacles were initially positioned along the corridor, but passer-by were walking through the corridor during the tests. Average speed in this experiment was 0.6 m/sec. Since no positioning feedback was available, no measurements of the directional accuracy were taken. However, during most of the experiments, subjects were able to detects obstacles, and avoid them safely, with no additional detection aid being used.

9. Conclusions

A mobile robot obstacle avoidance system has been converted successfully to a navigation aid for the blind. Instead of transmitting electronic signals to the robot motion controllers, the obstacle avoidance system relays information to the user by transmitting stereophonic signals. These signals provide spatial information about the location of objects in space, or guiding information for the recommended travel direction and speed.

The method is implemented in a new travel aid for the blind, the *Navbelt*. Average traveling speed on the *Navbelt* simulator in the *guidance* mode was 0.76 m/sec. The average traveling speed of blindfolded subjects traveling with the *Navbelt* prototype was 0.45 m/sec, and 0.6 m/sec along a typical office building corridor. Future developments of the Navbelt will include additional ultrasonic sensors for detecting overhanging obstacles, halls, steps etc.

10. References

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Here is a photo of the Navbelt. This photo was not part of the paper. The NavBelt testing device is worn by PhD. student (now Dr.) Shraga Shoval in 1994.