Watch Your Head: A Wearable Collision Warning System for the Blind

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***Abstract*— We describe work in progress towards the development of a miniaturized, wearable sensor device to enhance safety during ambulation for persons who are blind. This system warns the blind user when they are about to hit an obstacle at head level, in time to avoid a collision. With respect to existing Electronic Travel Aids, this device is "minimalistic": rather than attempting to provide rich information about the environment, the proposed system simply emits a warning signal (in acoustic and/or tactile form) when a hazard is detected. The sensor, which uses two ultrasonic transducers for obstacle localization, can be mounted on one's shirt pocket or disguised as a brooch. Special care is devoted to optimizing the devices' performance (in terms of range accuracy and detection / false alarm rate) and to minimizing form factor and power consumption.**

I. Introduction

It is estimated that more than 250,000 Americans are totally blind or have only some light perception [1]. Vision loss can be devastating for a number of reasons. In particular, one's ability to move about independently may be seriously affected.

The long cane is by far the most popular mobility device for the blind, with about 130,000 users in the U.S. [2]. A much smaller number of persons with vision loss use dog guides to get around (just over 7000 according to a 1995 survey [3]). Unfortunately, *the long cane cannot protect against collision with a head-level obstacle*, such as a tree branch, an exposed shelf, or even a propped-open window. A recent survey of about 300 blind or legally blind people [4] showed that even expert long cane users experience head-level collisions from time to time. The same can be said for guide dog users, when the guide dog misjudges if the handler has sufficient clearance from head-level obstacles. About 40% of the respondents to the survey stated that they experience head-level collisions at least once a year, and 15% more often than once a month. These traumatic events, even when they do not result in serious physical consequences, often affect one's self-confidence and self-reliance.

This contribution reports on work in progress towards the development of a miniaturized sensor that warns a user when he or she is about to hit on obstacle at head level, in time to avoid a collision. This device can be worn at chest level (for example, clipped to one's lapel or shirt pocket) or on the user's sunglasses. As opposed to existing Electronic Travel Aids (ETAs), the proposed device provides "minimalistic" feedback - just enough to ensure that the user can avoid a potentially painful collision. Our approach is guided by the observation that "information rich" feedback can overwhelm, distract or annoy the user, who is already busy with other mobility and orientation tasks (avoiding ground-level obstacles, keeping track of his or her position in the environment, and tracking other environmental cues such as landmarks, people or moving cars).

Our sensor uses two ultrasonic transducers in a bilateration scheme. The geometry of the system allows for "shaping" the receptive field to just the portion of space that is important for head-level protection. This avoids annoying false alarms from surfaces that do not pose an hazard. Range measurement is obtained by correlating the echo signal with a prototype waveform. Bilateration imposes strict constraints on the tolerance of the range measured by each transducer. Thus, accurate measurements of the range error variance as well as of the correct detection/false alarm statistics have been conducted to prove the feasibility of this system. One peculiar problem with this type of range sensor is the "ringdown" effect, a type of self-interference that is characteristic of narrowband transducers used in mono-static mode. Ringdown can occlude echoes from nearby surfaces, and needs to be dealt with via suitable signal processing. Fast mechanisms for echo correlation using bandpass sampling are utilized, enabling implementation in a low-power DSP. An activity detector, calibrated to switch off the sensor when the user is not walking, and an appropriate user interface, complete the system.

II. Related Work

ETAs for the blind can be broadly classified into two categories: clear-path indicators and environmental descriptors. Clear-path indicators are devices that warn the user of hazards or obstacles which pose some sort of collision threat. Environmental descriptors convey rich information about nearby objects through sensory substitution (via auditory or tactile feedback). Our work fits squarely in the category of clear-path indicators.

Most commercially available clear-path indicator ETAs are hand-held or head-worn ultrasonic devices. Examples include the Mowat and the Polaron (now discontinued); the Miniguide; the Mini-Radar; the Palmsonar; the Ultra-Body-Guard; and the Hand Guide Obstacle Detector [5]. These devices provide simple tactile (and in some case, aural) feedback that conveys information about the presence and distance of an obstacle. They would not work well (and are not intended) for continuous monitoring of the region in front of the user's head when the user is walking and maneuvering a cane or holding a dog. Cane-mounted sensors include the Nurion Laser Cane (no longer in production) and the Laser Long Cane produced by Vistac [6], which use three laser beams to detect (via triangulation) obstacles at head–height level [7]. The UltraCane (formerly BatCane) produced by Sound Foresight [8], [9] uses sonars on a regular cane to detect obstacles up to head level. Information about the distance and elevation angle of detected obstacles is provided to the user by means of vibrating buttons on the cane's handle.

In addition to the commercially available devices, several academic prototype ETAs have been designed and tested. These include the NavBelt [10], GuideCane [11], Ultrasonic Long Cane [12] and People Detector [13]. While most of these devices have provided innovations over their commercial counterparts, none of them have made it into the market.

None of the products or prototypes listed above has reached a high level of acceptance by the blind community [14]. Indeed, according to various surveys, the rate of abandonment of Assistive Technology devices is generally high, especially within the first year of acquisition (ranging from 8% to 75% [15]). Mobility aids are more frequently abandoned than other devices [16]. Appearance, convenience, performance and cost are critical factors to acceptance. Devices that attract undesired attention to the user should be avoided. Poor performance, in terms of missed detections or false alarms, degrades a user's confidence in an ETA. Frequent maintenance, which can occur with fragile or power-hungry devices, can be difficult, or at best annoying. Expensive devices are not accessible to the majority of the blind population. All of these issues have been known to prevent acceptance, or lead to early abandonment of ETAs. These concerns must be addressed by any new system, and are critical to its acceptance within the blind community.

III. Specific Requirements

Our ETA is meant as a safeguard for a blind person during ambulation. More precisely, it warns the user when he or she is about to hit a surface with their head, in time to avoid a collision. Thus, this system can be considered as a secondary electronic travel aid, complementing the use of a long cane or a guide dog. The presence of a nearby surface should trigger a warning mechanism only when it is detected within a precisely defined volume of space, which must include the space in front of the user's head. The maximum distance at which a surface should trigger an alarm is a function of the user's typical walking speed and expected reaction time. For example, for a person walking at 1 meter/second and with a reaction time is of 1.5 seconds (from the time the alarm is produced till the time the user is able to reach a full stop), the maximum distance for detection should be of at least 1.5 meters (see Fig. 1). A much larger detection range may be counterproductive, due to the risk of false alarms from far away surfaces.

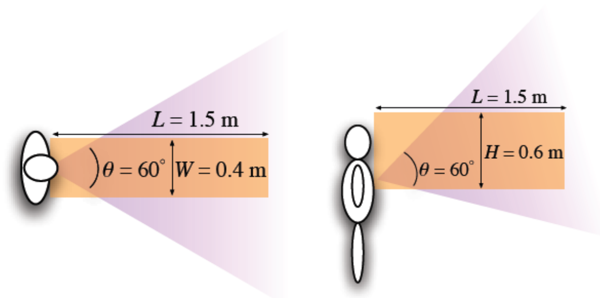

Fig. 1: Illustration of the placement of the described ETA. The coverage area of the typical ultrasound sensor (purple) is shown along with the ideal hazard detection area (orange).

Ideally, the device should be "wearable", meaning that it can be easily placed on one's garment, without cosmetic concerns that may hamper its adoption. This places hard constraints on the device's size and weight. In addition, it is highly desirable that all components of the system fit within a single piece. Informal conversation with blind persons and Orientation and Mobility (O&M) instructors has evidenced that some persons may be comfortable with a small device placed on one's hat visor or even on one's sunglasses. Other potential users, however, may not want to wear a hat or specialized glasses at all times while walking, and may prefer attaching the system on their clothing in an inconspicuous place, for example clipped on one's shirt pocket or disguised as a brooch. In either case, the user should be able to correctly position the sensor without much effort. The user should not be required to change batteries more often than once every several weeks of "regular" daily usage. The interface to the user should be effective enough to enable prompt reaction (and thus avoid collision), yet not so intrusive as to be annoying or generate embarrassment. The nature of this device as a warning system requires a very high level of performance in terms of missed detection and false alarm rates. Due to the high mental attention required while walking without sight, especially in unfamiliar environments, it is imperative that the false alarm rate be kept at a minimum to avoid distraction. On the other hand, any missed detections would affect the user's confidence in the system. Finally, the design choices should facilitate future production and marketing at affordable cost.

IV. Range Sensing

Our ETA performs range measurement by means of ultrasonic echolocation. In the following we discuss some important aspect of the system.

A. Correlation Based Detection

Most available ultrasound systems, such as the Senscomp 6500 ranging module, and most commercially available ETAs, detect and range objects by thresholding the envelope of the echo signal. The performance of these sensors degrades rapidly with decreasing SNR, resulting in false alarms, missed detections and erroneous range measurements It is well known that optimal detection and range estimation involves correlation with the transmitted signal (sometimes referred to as matched filtering [17], [18]). However, until recently, the complexity associated with this operation inhibited the use of matched filtering for ETA sensors. The advent of miniaturized DSPs and micro-controllers with the processing power, form factor and power consumption required to meet the processing specifications, has enabled new miniaturized ultrasonic ETAs capable of real-time matched filtering [12].

B. Bandpass Sampling

Digital matched filtering requires sampling of the received echo signal. The sampling rate is usually chosen to be equal to or larger than the Nyquist rate to avoid spectral aliasing. Unfortunately, for the bandpass signals of interest, this yields a high data rate which requires relatively high speed DACs, ADCs and powerful DSP. For example, the ultrasonic ETA described in [12] uses a sampling rate of 110 kHz. In order to reduce the sampling rate, one may exploit the fact that the received echo is typically a bandpass signal. One popular solution is quadrature demodulation, which needs an analogue device to bring down the spectrum to baseband. Bandpass sampling [19], [20], [21] is a technique that allows for reduced sampling rate and does not require additional analog components.

Bandpass sampling relies on the fact that, as long as the spectral repetitions formed by sampling do not overlap, distortion of the sampled signal is avoided and the original continuous time signal can be fully recovered from its discrete time counterpart. It can be shown that, if the signal is bandlimited with a bandwidth of W and a center frequency of f_0, intervals of alias-free sampling rates exist larger than $(2f_0 - W)/K$ with $K = \lfloor(2f_0 - W)/(2W)\rfloor$ but smaller than the Nyquist rate $(2f_0 + W)$. For example, a signal whose spectrum is contained between $F_1 = 36$ kHz and $F_2 = 44$ kHz could be sampled at 22.5 kHz, about four times less than the Nyquist frequency (88 kHz), without aliasing. This allows us to reduce the computational cost associated with correlation dramatically.

Our ETA uses a transducer with a center frequency of 40 kHz and is bandlimited to range of frequencies from approximately 36 kHz to 44 kHz. Laboratory experiments have confirmed that correlation processing can be effectively implemented for this system using a sampling rate of just 32 kHz.

C. Ringing Noise

An active Time of Flight (TOF) system may operate in one of two modes: bi-static, in which one transducer is used for transmission and another for reception; and mono-static, in which the same transducer is used for both transmission and reception. In order to minimize cost and size, our system works in mono-static mode.

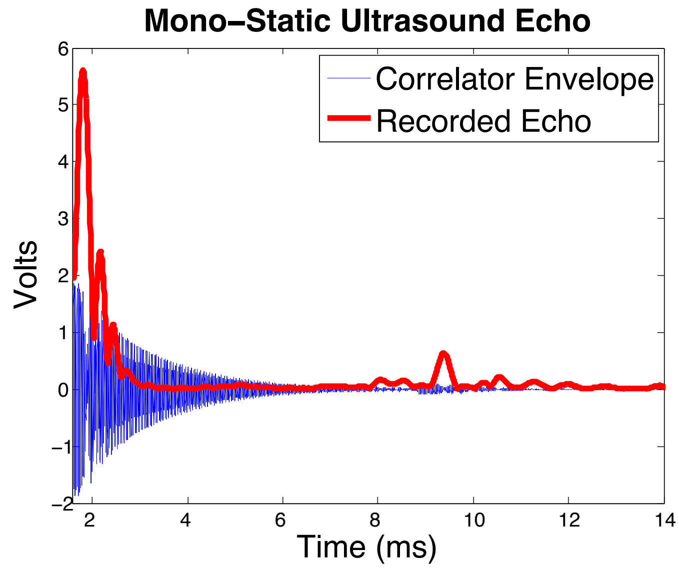

Fig. 2: Example of an echo signal captured by the laboratory test system. The recorded signal (blue) and the envelope of the correlator output (red) are shown. Ringing noise is present in the initial 6 ms. A target placed at approximately 150 cm, the return from which is barely discernable in the unprocessed signal but clearly visible at the output of the correlator.

Virtually all low-cost, commericially available ultrasound transducers are narrowband, piezo-electric devices [22]. The implementation of a mono-static system using a narrowband transducer results in a phenomenon known as *ringdown* or *ringing noise*. This is a type of self-interference which occludes echoes from nearby targets. The ringing noise results from the storage of the stimulus signal's energy in the reactive component of the transducer. After transmission is complete, and the transducer is no longer stimulated, the stored energy begins to decay, and some residual component of this signal is recorded as a part of the received echo (see Fig. 2). Increasing the signal energy, which is desirable for the detection performance of correlation processors [23], results in a more energetic ringdown, and consequently, poorer detection performance at short distances. In order to deal with ringing noise, and thus measure even short distances (up to 0.5 m), we developed and tested a novel CFAR (Constant False Alarm Rate) processor, which is shown to provide good detection performance in the presence of ringdown [24].

D. Multilateration

Our ETA needs to monitor a specific volume of space in front of the user. In order to re-shape the approximately cone-shaped receptive field of the sensor to the desired field (shown in Fig. 1), one may use phased-array beam forming or multilateration [25]. Phased-array beam forming requires a large number of sensors spaced closely together to be effective, which results in a prohibitively large, complex system. For our device we chose a bilateration scheme, which uses range

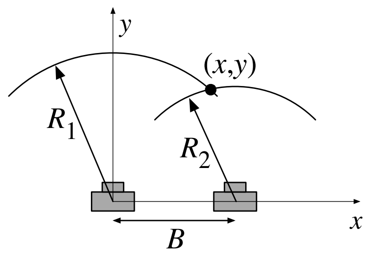

Fig. 3: The geometry of bilateration.

estimates from two different sensors to triangulate an obstacle in free space (see Fig. 3). Note that a bi-lateration system is capable of resolving a target's range and bearing, but not its elevation. Additional sensors could be used to estimate the object's position in free space, and thus better shape the receptive field, but would increase the cost, size and power requirements of the system.

E. Performance

Accuracy of range estimation is essential for reliable bilateration. We experimentally evaluated the performance of our sensor over a large dataset collected in our laboratory. The experimental system consists of two custom circuit boards which contain the necessary analog circuitry: transmit amplifiers, pre-amplifiers, programmable gain amplifiers (PGA) and a single pole double throw (SPDT) switch which is used to select between transmit and receive modes for the ultrasound transducer (used in mono-static mode). These circuit boards are physically separated from each other to simulate the bilateration layout of the sensor, with the transducers on the two boards separated by 4.1 cm. The circuit boards are connected to a National Instruments USB-6259 Data Acquisition System (DAS) which is in turn connected to a laboratory PC which controls the experiments and stores the acquired datasets.

Datasets were collected for two separate targets: a 0.75 inch diameter wooden dowel and a 1 inch diameter wooden ball. These targets were placed at a variety of positions of interest with respect to the test system. Datasets for radial ranges of 30, 40, 50, 75, 100, 150 and 200 cm were taken at angles of 0, 15, 30 and 45 degrees (a total of 28 target placements). For each target placement 500 echoes were collected. Datasets were built for three different pulse shapes(Barker, Sinusoid and Linear FM) with three different transmit durations (400 μs, 1000 μs and 1400 μs). The sampling rate for these data sets was of 160 kHz, with a pulse repetition rate of 50Hz. The stored data was then used to evaluate the detection and estimation performance for several different signal processing schemes. Reference echoes to be used for matched filtering were collected from a high SNR target (a wall at direct incidence) at a distance of 1.25 m. Two types of error statistics were measured: the measured range error standard deviation σ_r , and the correct detection rate P_D versus false alarm rate P_{FA}. Sample results are shown in Figs. 4 and 5 for different values of the signal SNR (estimated as the ratio of echo signal

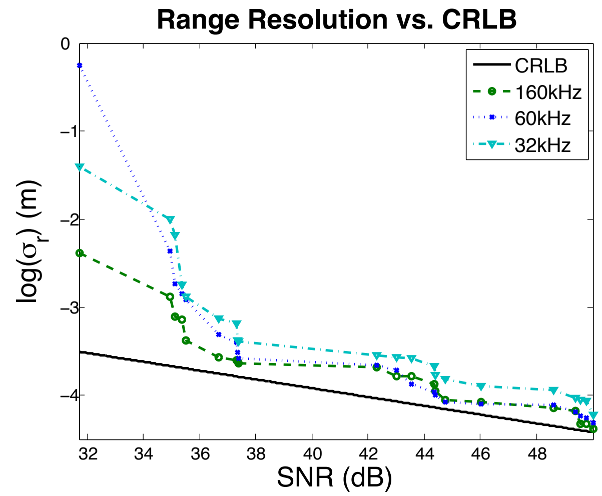

Fig. 4: Range estimation performance of our laboratory prototype utilizing a 1000 μs Barker encoded sinusoid (length 5 code with a sinusoid center frequency of 40 kHz). The Cramer-Rao Lower Bound (CRLB) and the standard deviation of range estimates for several different sampling frequencies (red: 160 kHz; green: 60 kHz; blue: 32 kHz) are plotted against the SNR. Note that the test system is capable of sub-millimeter range resolution.

energy and noise variance). P_D is generated using a dataset in which a target is present, while the P_{FA} datasets have been captured with no target in the sensor's field of view.

V. System Integration

A. Activity Detector

This ETA is designed to be used during ambulation, warning the user of collision threats he/she is approaching. Thus, detection of hazards, and warnings thereof, should only occur while the user is walking. Knowledge of the user's activities allows for energy conservation by turning off the ultrasonic transducers and digital controller when they are not needed. In addition, annoying false alarms can be avoided, for example when the user is standing and talking with another person who finds themselves within the monitored area. We are planning to include a low-power, 3-axis accelerometer to the system. Analysis of the accelerometric data can be used to detect whether the user is walking or not [26], [27].

B. User Interface

The user interface is a commonly overlooked component of an assistive technology device. Our ETA is intended to provide simplistic feedback to the user regarding the presence or absence of a possible hazard. There are two possible modes of communication with a blind the user: aural and haptic. Some users may prefer one or the other, and others may desire a combination of the two. For example, one may use tactile modality (via a small vibrator placed near the device, close to the user's skin) when an obstacle is detected at a

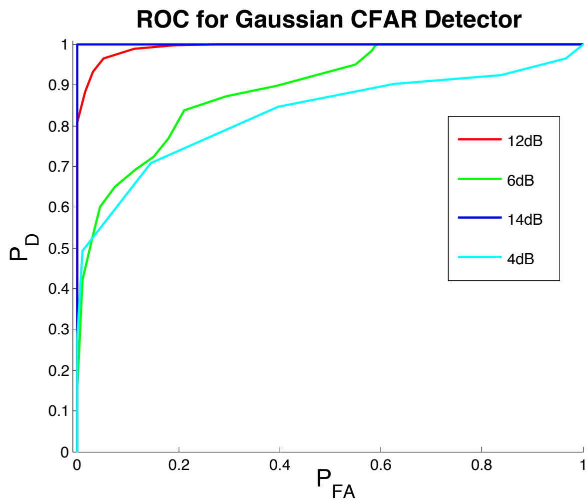

Fig. 5: Detection performance (correct detection rate, P_D, versus false alarm rate, P_{FA}) of the laboratory prototype for several values of SNR, using the same pulse as in the case of Fig. 4. P_D and P_{FA} are defined as the percentage of echoes in a dataset in which a peak in the correlator output exceeds a prescribed threshold. Each point in the figure is generated with a specific threshold. 500 echoes were captured for each dataset and 500 thresholds were used to evaluate the ROC (Receiver Operating Curve) in the plot.

certain distance, and use an acoustic signal when the collision is imminent.

C. Hardware Implementation

Technological innovation within the hearing aid and consumer electronics industries has resulted in a number of low-power, small form factor DSPs which contain nearly all the required peripherals for our system. These chips present a System on a Chip (SoC) hardware solution, which is desirable as it minimizes the size and power consumption of the final product. For example, the BelaSigna® manufactured by On Semiconductors® contains all of the analog peripherals required for the system design, save for the pre-amplifiers and anti-aliasing filters (which require custom circuits), in a single package. In addition to the reduction in size and power such a chip enables, the use of off the shelf components minimizes the cost and development time for the final product.

The average power consumption of the overall system is expected to be less than 50 mW, enabling a battery life of over 90 hours under continuous usage (assuming a standard 9 Volt battery at 500 mAh battery charge or comparable energy storage system). Combined with the power saving strategy enabled by activity detection, and assuming that the user walks for an average of 2 hours per day, this system would have more than six weeks of battery autonomy.

VI. Conclusion

This project aims to design and prototype a wearable, miniaturized ultrasonic clear-path indicator for the blind. This system utilizes state of the art signal processing and off-the-shelf hardware components. The main requirements for this ETA are that is should be discreet, affordable, ergonomic and effective. In this paper, we presented some challenges, solutions and early results towards the development of the desired system.

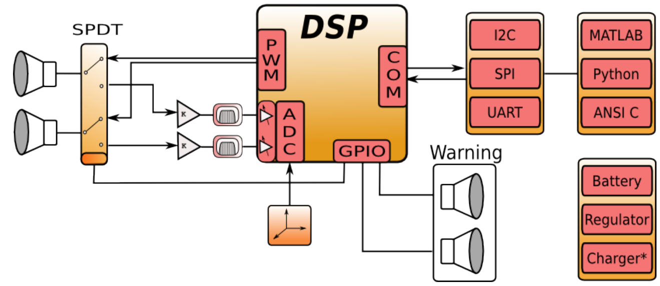

Fig. 6: A block diagram of the planned ETA hardware implementation. The ultrasound transducers and associated circuitry (pre-amplifier, switch and bandpass filters), shown to the left, connect to the the prospective DSP's (Belasigna®250/300) ADC, which includes a built-in PGA. Synthesis of the transmit signal is accomplished using the DSP's onboard PWM (Pulse Width Modulation). The accelerometer is shown below the DSP. A number of serial communication protocols will allow the device to interface with a laboratory PC or another embedded system (such as a robot), and to be re-programmed or re-purposed. The power supply, which includes a battery, a regulator and an optional charge controller is shown at the bottom right hand corner.

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