Perceiving A Corridor With CTFM Ultrasonic Sensing

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Abstract—

When deprived of sight humans adapt and use other senses for navigation. Most rely on touch (long cane), but some use auditory perception. We have observed a blind teenager echolocating using sounds (clicks) he makes with his mouth. More commonly, an ultrasonic sensor is used as a navigational aid to scan the path and environment. The echoes blind people perceive are interpreted by each individual to form an auditory scene where clear paths and obstacles are identified. With this information, the blind user threads his/her way safely through the space scanned. The work we describe here seeks to mimic a blind person using a sonar navigational aid to traverse a path or corridor. We are using a commercially available ultrasonic mobility aid to isonify and capture echoes from a corridor, we then attempt to correlate these to the geometric features of the corridor, as we perceive them. Our aim is to develop a perception system, which is capable of interpreting, in real time the echoes to discern the geometric features of the environment, so that this data can be used to navigate a robot through it.

1. INTRODUCTION

A teacher of blind children pitches softball towards a blind boy. The blind boy hits it with a baseball bat. After the game, the blind boy hops onto his bicycle and rides home along a path lined with cherry trees [Bay Advanced Technology, 2007]. He is using a **C**ontinuously **T**ransmitted **F**requency **M**odulated "CTFM" ultrasonic mobility aid to sense his environment. He has learned to navigate using echolocation. We are surprised by the ability of blind people to learn to use mobility aids based on ultrasonic sensing. They have demonstrated far superior navigation abilities with CTFM ultrasonic sensing than with any other technology.

Blind people who have learned to use CTFM ultrasonic mobility aids provide a model of what is achievable. We aim to develop a conceptual model of navigating down a corridor. The model contains a description of the task, the objects in the environment, the locus of motion of the sensor, the components of the echo (features) from which the objects are perceived, and the appropriate navigational response.

We can analyse and learn from blind people interacting with and using ultrasonic sensors for navigation. A recorded training course on the use of a commercial CTFM mobility aid comprising ultrasonic echo audio samples, and training commentary on what is heard has enabled us to develop an ultrasonic scanning methodology of the environment for navigating a corridor.

To understand this methodology and its use for navigation, we are attempting to reproduce the navigation ability of a blind person using an ultrasonic mobility aid on an autonomous mobile robot. The mobile robot is equipped with the ultrasonic mobility aid as its primary sensor, and it will mimic the blind person's scanning motion and echo analysis techniques.

2. ULTRASONIC SENSING

Early attempts at using simple time-of-flight ultrasonic sensors produced inconsistent results due to the limitations of the sensors that were compounded by poor understanding of acoustics by the researchers. Studies of ultrasonic sensing in air over the past two decades solved some of the inherent problems that confront its users, and led to the development of reliable sensing systems. Since 1995, CTFM has been used it to navigate an outdoor mobile robot [Ratner and McKerrow, 2003]. Other research demonstrated 99.73% classification of 12 surfaces using 5 features representing roughness, extracted from echoes recorded by a moving CTFM sensor [McKerrow and Kristiansen, 2005]. That research demonstrated that CTFM ultrasonic sensing is a reliable and robust system for classification of surfaces.

A single receiver measures the range to reflecting objects. Because the sensor transmits a beam, these objects can be located anywhere on a sector of a spherical shell defined by that beam. As the frequency response of a transducer varies with angle relative to the axis of the transducer, the angle to an object can be measured by matching the echo to a set frequency response templates [Yata, et Al 1998]. This

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reduces the uncertainty in location from the whole sector to a circular annulus at that range. Therefore, with a single sensor, it is possible to measure range and angle to sensor axis.

Finding the horizontal and vertical components of this angle requires the use of multiple sensors in both 2D and 3D [Kleeman, 2002]. These systems solve the stereo correspondence problem with echo-matching algorithms. They are only robust for isolated targets, most require identification of target type, all require strong echoes, and their computation time is quite long. An alternate approach is to detect objects at the side of the beam. As the frequency is swept down, the beam broadens and objects at the side become audible [Krammer and Schweinzer, 2006].

Ultrasonic research has concentrated on measuring location [Kao, and Probert Smith 2000], recognizing objects [Krammer and Schweinzer, 2006; McKerrow and Harper, 2001], and using both for mapping and mobile robot navigation [Kay, 1974; Tardos, et Al 2002] in static environments. This research differs by monitoring how humans navigate and then developing sensing strategies to mimic human navigation. It also differs in using directed sensing by physically scanning a monaural sensor to determine angle to objects as well as their range.

Enabling a mobile robot to navigate like a human is a major goal of our research. We believe that human-like navigation abilities can be achieved with CTFM ultrasonic sensing. Our hypothesis is that humans do not need precise geometric information to navigate because of their ability to accurately perceive and track landmarks. In this paper, we look at the first step towards this goal, that of modelling how a human perceives and navigates a corridor.

3. CTFM

In this research, we are using the K-sonar CTFM (Continuously Transmitted Frequency Modulated) sensor developed by BAT [Bay Advanced Technology, 2007; Gough and Cusdin, 1984; Kay, 2000; Kleeman, 1996] as a mobility aid for blind people (Fig. 1.). One transducer is used for transmission and one for reception.

Fig. 1. K-Sonar ultrasonic sensor is designed with a mount point to fit on a blind person's cane.

A single 19mm diameter transducer has a theoretical beam angle of 19.32˚ from axis to first minima (Fig. 2.). Combining two transducers to form a transmitter and receiver, the vertical diameter is 47mm and the theoretical horizontal beam angle is 7.6˚.

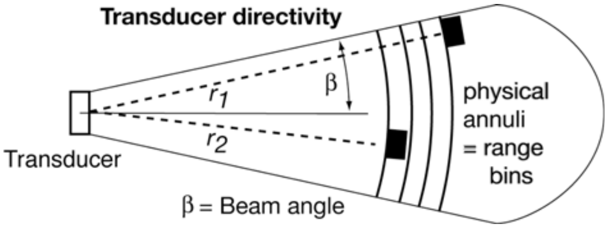

Fig. 2. An ultrasonic transducer emits a beam of energy. *r* = range to

The CTFM system is set to transmit a downward swept sine wave (f_{sweep} is 100kHz to 50kHz) every 100msec (sweep period t_s). The ultrasound energy reflects from objects and returns to the receiver as an echo. The echo is a delayed and filtered version of the transmitted signal. A demodulation sweep, derived from the transmitted sweep, is multiplied with the received echo in the time domain. The outputs of this multiplication are sum and difference frequencies (Fig. 3.).

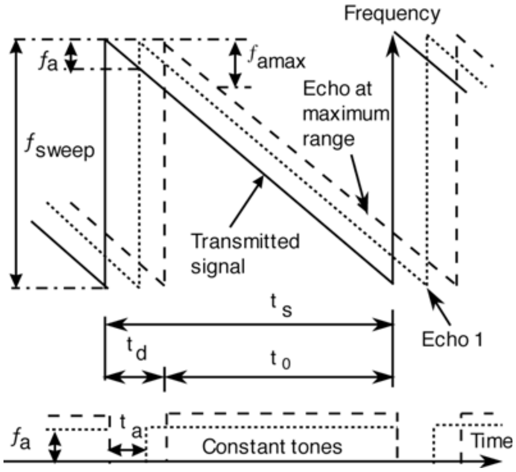

Fig. 3. CTFM demodulation – multiplying the echo by the transmitted signal produces a set of different tones where frequency is proportional to range to object.

The distance of flight information is contained in the difference frequencies (*fa* is 0 to 5kHz), where frequency is proportional to range (Fig. 3. & 4.) and amplitude is

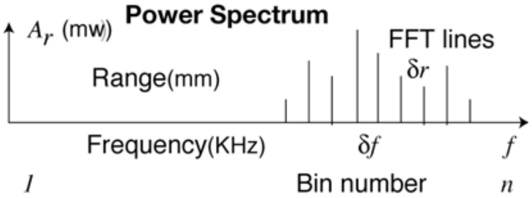

Fig. 4. Power spectrum of echo – frequency (bin number) is proportional to range and amplitude to echo energy at that range

proportional to surface area. This time domain signal is converted to a power spectrum with an FFT to give a range-energy echo (Fig. 4.). The amplitude in frequency-bin i is the energy reflected from surfaces in a spherical annulus at range r_i (Fig. 2.)

4. TEACHING A BLIND HUMAN

> *"If I, as a thirty-six-year-old blind person, am able to thread my way through heavy pedestrian traffic smoothly, gracefully, and without collision, and can find an empty seat on the bus, an empty desk in a classroom, or an empty booth or table in a restaurant…"* Gissoni, 1966 [Gissoni, 1966].

Emeritus Professor Leslie Kay has developed and commercialised 4 different sensing systems over a period of 40 years [Kay, 2000; Kleeman, 1996]. The first system, released in 1966, was a torch that the user held in his hand and scanned the environment with steady purposeful movement. Fred Gissoni [Gissoni, 1966] made a set of 10 audio training lessons for the Hadley School of the Blind [Hadley 2007], in Illinois, on how to use the sonic torch to navigate.

Detecting A Corridor

Gissoni's tutorials cover a myriad of day-to-day navigation challenges. He identified the task of following a path or corridor as being very important in navigation. Gissoni's tutorials describe scanning techniques, expected echoes, their meaning, and their use for navigational purposes. He interleaves the verbal explanations with audio samples of the echoes, captured from the ultrasonic aid, relevant to that explanation.

To detect the edges of a path or the walls of a corridor, he uses a horizontal scan of the environment in front of himself. The scan should be a horizontal sweep from left to right counter synchronized to the movement of the feet to explore the space that will be occupied next. Path sensing seeks to validate the assumption that the path exists and is clear.

When held horizontally the sensor does this for the area of space that is being scanned. When held horizontally at thigh height, information about the space at thigh height is fedback. The signal includes no information about the floor.

Tilting the sensor down below the horizontal brings the scanned region closer to the ground. When walking forward, the blind person seeks assurance that the ground persists (down steps are dangerous), so he seeks echoes from the ground. The more acute the tilt angle below the horizon the more dominant the ground echo will become. When set to short range the K-sonar will render the ground as a gentle swish sound at 20° below the horizon.

The sweep motion is dictated by the scan objective. A clear path for walking requires only a sweep wide enough to accommodate the user. A sweep of ±15° every 2 seconds explores a path that is wide enough. To sweep the full width of a corridor a more acute sweep angle is required. This angle depends on the width of the corridor.

For information on the geometry of an obstacle, a different sweep motion is used. At a range equal to the outer limit of the short range scan (first contact with wall or path edge) a vertical sweep of ±20° about the horizontal plain explores a vertical space equivalent the height of the user (2 meters approximately). The nature of the echo will vary depending on the surface being isonified. A specular (glass pane) object will reflect a crisp smooth echo, while a rough textured surface will reflect an echo with a varying tone (A surface with a rough texture may sound like "musical sandpaper").

Table 1. Taxonomy of scanning sweeps (path/corridor navigation) relative to the user's body. Scanner is held thigh high in either right or left hand.

	Horizontal Tilt Angle	Horizontal Scan Angle / Sweep Period	Vertical Scan motion (About the Horizon)	Oval scan
Narrow Path	-20°	± 15° / 2sec	+ 0° to +5°	
Path to edges	-20°	± 25° / 3sec		
Door (contact to entry)	-20°	±15° to ±90° / 3 sec		
Low obstacle	-20°	± 15° / 3sec		
Low obstacle height			-15° to -20°	
Overhanging Obstacles (stationary)		± 15°	+15° to -20°	Full Sweep
Overhanging /tall Obstacles			+15° to -20°	

The speed of the sweep across the surface will impact on the amount of data that can be gleaned from the echo. A slow sweep can detect slight variations from cracks in the plasterwork or gaps between a closed door and the doorframe. Table 1. describes the scanning sweeps appropriate for the different targets that may be encountered on a path or in a corridor.

In summary, the way a blind person navigates a corridor is to pan the sensor so that he hears weak yet distinct echoes from different directions. At the left extremity of the pan, he hears the left wall. At the centre of the pan, he hears the floor. At the right end of the pan, he hears the right wall. When either walls shifts away from him he hears a change in the echo from that wall. When the path in front of him is blocked, he can hear a strong distinct echo from the object. He can also hear the approach of the object from the decreasing frequency of its echo.

5. BLIND PERSON NAVIGATION MODEL

Does either a sighted or blind person need to know what an obstacle is to walk around it or does he simply need to identify a clear path around it? Scanning for safe translation (distinct from scanning for navigation) for a blind person or any user is a case of the later. The user needs to detect a clear path to travel on, to that end, minimal information is required about a short distance ahead of the current location, the scanning range (ahead) correlates to the translation speed: the faster the movement the farther the range explored needs to be.

Research into the navigation of sighted people indicates that they update their view of the world 10 times per second to walk at normal rate (4.5Km/h or 1.2 meters per second). For a robot moving at 1.2 meters per second a sensor update every 100 mill-sec is equivalent to 120 mm of translation. Likewise a blind person performs a full pan cycle (right left right) for every step cycle (left right left) at 800mm per step he completes 2 steps per cycle, and covers 1.6 meters taking at least 4 distinct sensor readings (Fig. 5.)

Thus, he listens to an echo every 400 mm or every 400 mill-sec. Therefore, the blind person updates his view less often than the sighted person. For a mobile robot travelling at the same speed it would have to match the pan time and echo capture rate of (400 mill-sec) to achieve just in time perception for the equivalent speed of translation.

Navigation by blind people is not a case of simple translation with safety; a blind person has a plan, objectives, and milestones (in this case landmarks) to mark her successful progress [Lee et Al, 1992]. A blind person's navigation goal is to travel from her current location along a planned path to a destination. To that end she needs to successfully carry out the following 5 tasks. In the text that follows we describe each task and develop algorithms to achieve it.

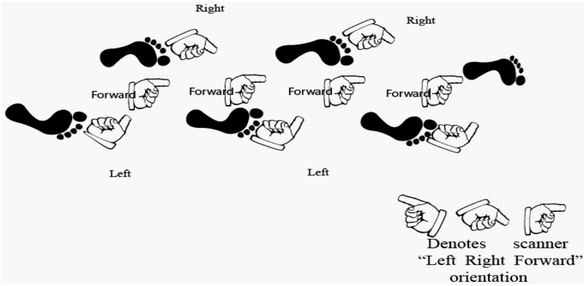

Fig. 5. Scanning one step ahead in contra-synchronicity to the forward progress of the feet

Task A **Walk safely to his her destination**

A blind person has to plan and follow a course to walk, through empty space, and use the ultrasonic aid to scan ahead for features and obstacles. The echoes she hears and interprets as known features [McKerrow and Antoun, 2007] serve to confirm he is on the correct path. While echoes that are unknown or unexpected warn him of obstacles or deviation from the planned path. The scanning technique employed determines what is being observed. An unexpected echo from a left/right sweep of the floor indicates an obstacle, a step, or an oncoming person. The absence of an echo at the far end of a sweep (left or right) may alert to an open door or an intersecting corridor (We assume competent use of ultrasonic mobility aid). The following 3 algorithms are required to implement this task.

Algorithm 1. Navigate a course from present location to goal

```
Determine destination
    Determine known paths to destination
        Select paths sequence to reach destination
        Determine landmarks for each sector
            For each sector Proceed while seeking landmarks
```

Algorithm 2. Calibrate

```
Scan horizontal pan left to right twice ±10˚ about dead
centre to listen for obstacles and the floor to become
familiar with echoes in current environment
Adjust tilt angle to contact the floor such that the sound of
the floor is just audible to alert the user if the floor
becomes inaudible (step down / hole in the floor).
IF corridor is wide
THEN
    Decide which side wall to follow and increase pan
    angle to the desired side to contact it on every sweep
    (may choose to walk closer to a given wall rather than
    centre of a very wide corridor).
```

Algorithm 3. Proceed while seeking landmarks

```
Confirm beginning of sector
IF at sector start
THEN
    Orient self to travel direction Walk Safely (4)
ELSE
    Lost Localise (5)
```

Walk on firm level ground

To confirm that the ground continues ahead, it is swept with the beam from the ultrasonic aid (the aid held at thigh level angled to the ground at about 25˚ depression) in a rhythmic manner from left to right in contra-synch to the forward progress of the feet. The user initially scans 2 or 3 times while stationary to establish a reference echo for ground with no obstacles. While walking constant echoes are perceived, whereas a fade to no echo indicates it is unsafe to proceed.

Detect and evade stationary obstacles

Variations in the tone and pitch of the echoes signal a change in the ground characteristics. Depending on the nature of the variation a conclusion can be reached as to nature of the change, such as a step up, a step down, a stationary obstacle, or an oncoming mobile obstacle.

Detect and evade mobile obstacles

If the user comes to halt an oncoming mobile obstacle will present a descending pitch from one scan to the next. The lower the pitch the closer the obstacle. The changing pitch serves to indicate a mobile obstacle and in response to the situation a blind user will change course to evade the mobile obstacle.

Confirm a hypothesis as to the nature of each detected obstacle or Landmark.

When a change in the echo is detected the user in reacting to the change forms a hypothesis as to the reason for the change, then seeks to confirm the hypothesis by further sensing. If she expects a landmark on the planned path, a sensor scans will serve to confirm the presence of the landmark, otherwise the extra scans will render information about the nature of the obstacle (size, shape, height, etc..).

Algorithm 4. Walk Safely

```
While still stationary Calibrate (2)
    Identify echoes from ground
    Identify path edge/corridor wall to follow
    Confirm obstacle free space ahead
    Advance foot start walk and in contra-synchronicity to
    feet progress scan left right
IF Unknown obstacle detected (unexpected echo)
THEN
    Stop, scan obstacle left right
    IF obstacle is mobile Converging (decreasing echo
    pitch)
    THEN
        Determine which side of obstacle has space and step
        to that side (evade obstacle)
    ELSE IF mobile obstacle diverging (Increasing echo
    pitch)
    THEN
        continue on unchanged course
    ELSE IF obstacle Stationary
    THEN
        Determine which side of obstacle has space and step
        to that side (circumnavigate obstacle)
        Resume course
ELSE
    Stop
    Confirm Landmark (extra scans)
```

Algorithm 5. Lost Localize

```
Scan locale while stationary
Compare echoes to known locations
Determine match(es) between known locations echoscape
to echoes detected
Compare travel course from last known & confirmed
location to matching location
When a concurrence is found, scan location to validate
concurring location as physical location
Navigate a course from present location to goal
```

6. ECHOLOCATION

Echolocation is the perception of objects and their location from the echoes of chirps of ultrasonic energy off those objects. Bats use it to navigate in the dark and in restricted spaces, such as in caves and inside buildings [Lee et Al, 1992]. It is a sense of perception that human's don't normally possess. If God had not made echo-locating bats, we would not believe it possible to recognize objects and navigate using ultrasonic sound waves.

In order to use echolocation, we have to convert the auditory information in the echo into range and area information representing the geometry of the scene. The working range of the K-sonar is 2 or 5 meters, selectable with buttons on its side. The user interprets the data presented to her as audio tones. It is the user who perceives the nature of the object detected, and who decides what action to take.

A mobile robot that mimics a human also has to interpret the echo data and determine its course of action. Thus, the focus of echolocation is the detection of natural beacons, and the characterization of shape, distance and size of obstacles.

Geometric modelling of objects in the environment is necessary as a theoretical basis for the algorithms that process the information in the echo to recognise those objects. Echolocation becomes a useful sensing mechanism for mobile robots navigation when it can both detect an recognise objects. For successful recognition of objects by analysing the echoes scattered back off them, a model that captures the geometry (and other echo modifying features) of those objects is required [McKerrow and Kristiansen, 2005].

7. GEOMETRIC MODEL OF A CORRIDOR

We chose the corridor outside the intelligent robotics laboratory as our initial echo capture site. Different sections of the corridor have differing geometric features that should

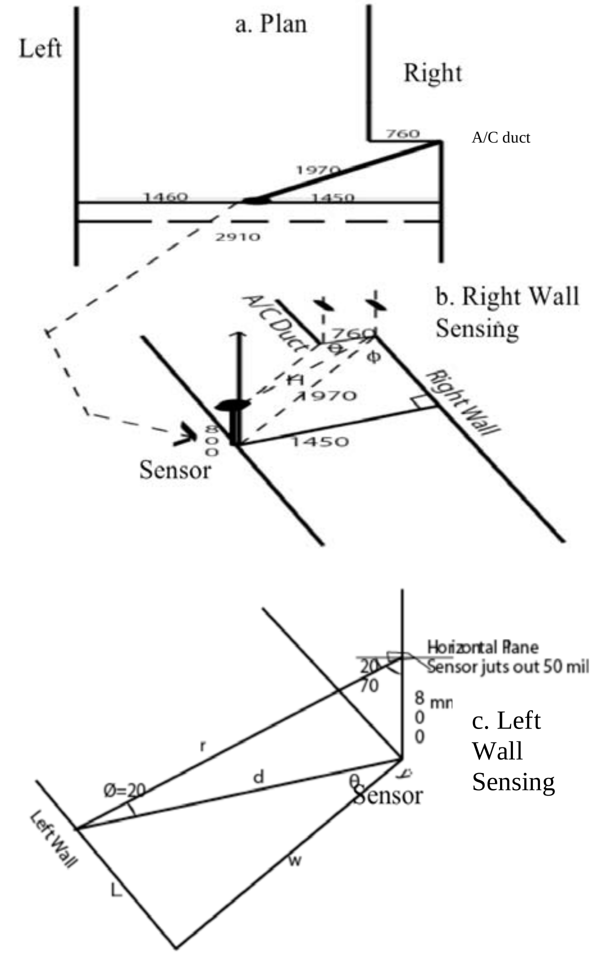

Fig. 6 Geometry of the corridor where echo capture experiment were conducted at station b. a. plan of corridor b. sensor relationship to right wall c. sensor relationship to left wall

give different echo information as scanned. Fig. 6. is a geometric map of the section of the corridor at station B, middle photo in Fig. 7.

Moving from "Station A" to "Station C" along the left wall (Fig. 6.) we note initially a featureless plaster wall, then glazed picture frames with doorways at irregular intervals, then 2 almost adjacent doors. Moving from "Station A" to "Station C" the floor is carpeted with no other visible features. Moving from "Station A" to "Station C" along the right wall, we note a steel cabinet, a building pylon, a door of an air-conditioning duct, another door, and mailboxes abutting a building pylon.


Fig. 7. Photographs of corridor at stations A, B, C

Using the sweep technique described in section IV at station B, we would expect to discern a sharp low pitched echo from the plaster wall on the left end of the sweep, followed by a low swishing echo from the carpet floor, thence another low pitched echo, not as sharp at the right from air conditioning enclosure at the right of the sweep. We used a sweep angle broad enough to isonify both left and right walls of the corridor. We tilted the sensor -20˚ below the horizontal plain to detect the floor.

With the sensor mounted on a tripod at 800 millimetres high, and panned left to detect the wall, we calculated the geometry of the sensing location (Fig. 6.). We note the sensor juts forward 50 millimetres from the origin of rotation. From the lengths measured with a tape measure we can calculate the point of reflection on the left wall.

$\sin ø = 800/(r+50) = \text{height of sensor/ultrasonic range} \quad (1)$

$\therefore r = 800/\sin 20^\circ = 2344.043$

$\cos ø = d/2344.043 \quad (2)$

$\therefore d = 2202.679$

$\text{Also, } d = r * \cos ø = 2202.679 \quad (3)$

$\text{And } \cos \theta = w/d = 1460/2202.679 = 0.66 \quad (4)$

$\therefore \theta = \cos^{-1} w/d = 48.48 = \text{left most scan angle.}$

$\text{By Pythagoras } L^2 = d^2 - w^2 \quad (5)$

$= 4{,}848{,}804 - 2{,}131{,}600 = 2{,}717{,}204$

$\therefore L = 1648.39$

Likewise we can calculate the geometry of the right wall.

$(\underline{H}\text{ypotenuse}+50)^2 = 800^2 + 1970^2 \quad (6)$

$\therefore H = 2126.25$

$\cos \theta = 1450/1970 \quad (7)$

$\therefore \theta = 42.6^\circ = \text{right most scan angle}$

$\therefore ø = 47.4^\circ$

In this experiment the scanning sequence was:

1 Empty space horizontal tilt angle = 0
2 Floor at tilt depression of 30˚ then 20˚
3 Left wall at pan angle 70˚ and tilt depression 20˚
4 Right wall at pan angle 70˚ and tilt depression 25˚

We geometrically modelled the corridor for three reasons

a. To correlate the echoes we captures with the features of the physical environment.
b. To verify the accuracy of the sensor by mathematically calculating distances from objects based on echoes observed and verifying the calculations against physical measurements (Fig. 6 and Equations 1 to 7)
c. To achieve experimental rigor so that we can reliably use ultrasonic echo data for landmark recognition, navigation, and obstacle avoidance in future work [Antoun and McKerrow, 2006].

8. STANDING IN A CORRIDOR

We scanned the corridor leading to the intelligent robotics laboratory at "station B" in Fig. 6. The scan was carried out by mounting the ultrasonic sensor on a tripod at 800 millimetres above the floor. In each of the figures (7 to 11), 64 echoes were recorded and their mean calculated to produce the PSD graph. In Fig.8. the echo from empty space shows a spike at FFT bin 230 of 10 nanovolts. However, as this spike was inaudible in the earphones connected to the mobility aid we suspected electronic noise.

In order to confirm this, we moved a strong reflector above, below, to the left, to the right, and in front of the sensor but we were unable to eliminate it, or to identify an

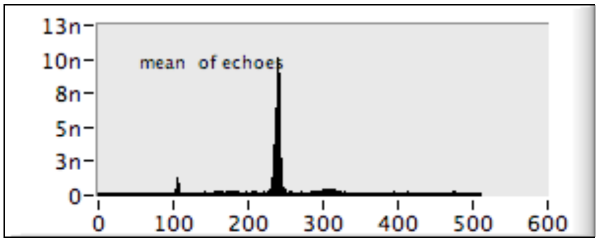

Fig. 8. Mean of PSD of echo from the free space in the corridor at station B sensor depression = 0˚ (horizontal) vs FFT bin number.

object at that range that could have caused it. We also found that moving the sensor up and down did not affect the spike. Changing the ADC card resulted in different noise spikes one at bin 20-(80mm) and one at bin 490-(1900mm) in Figs 12 to 17.

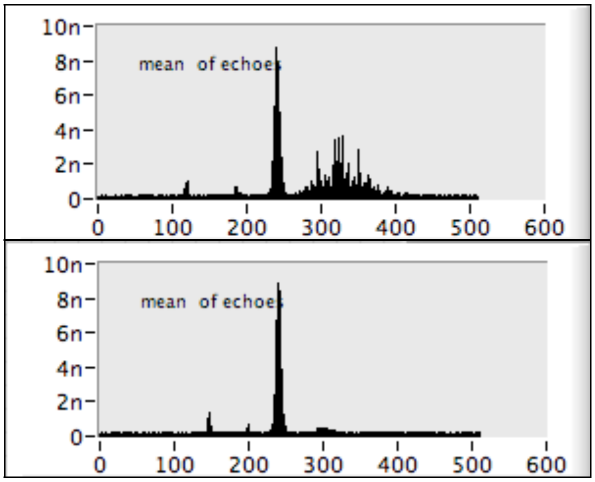

Fig. 9. Echo from floor of corridor at station B. Top: depression = 30° , Bottom: depression = 20°. NOTE: spike at bin 250 is noise

We then vertically tilted the sensor to detect the floor. At 30° below the horizontal plane (Fig.9.), we observe a distinct set of echoes from the floor between bins 260 and 400. We know from previous research [McKerrow and Kristiansen, 2005] that this is sufficient to classify the floor as carpet. When we look closely at Fig. 8. the echo from free space we can see a slight hump around bin 300. This echo from the floor was not audible in the earphones.

Next, we changed the angle of the sensor to 20° below the horizontal plane we were still able to observe the echo at bin 300 FFT (Fig.9.) and it was barely audible in the earphones. We then panned the sensor to the left by ≈ 50° where we observed at FFT bin 300 the echo off the floor and to the right of that a strong echo off the wall (Fig. 10.).

Finally, we panned the sensor to the right to point into the concave corner caused by the air conditioning duct (Fig. 6.). We can see in (Fig. 11.) multiple echoes from various features. The highest is from the 2 D concave corner at sensor height, the next strongest is from the 3D concave (corner on the floor) where three orthogonal surfaces form a strong reflector. The two echoes to the left are from the convex corner at sensor height and from the point where the convex corner intersects the floor.

In these experiments, the sensor was on short range (2m). As a result, the right corner's echo and the left wall's echo are from near the end of the range. This is why we needed to pan the sensor so far to detect the walls.

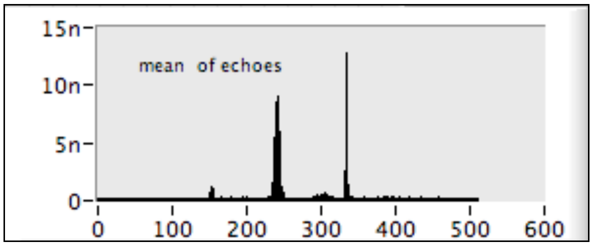

Fig. 10. Echo from the left wall of corridor at station B with sensor at 70° left pan, depression = 20° (below horizontal plane)

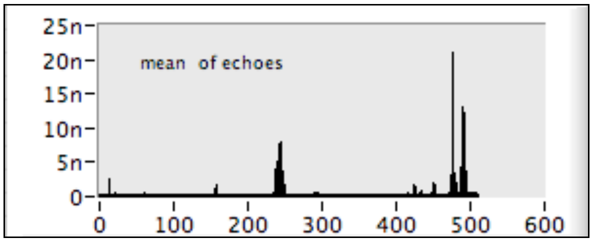

Fig. 11. FFT corridor at station B right wall, at 70° right pan, depression = 25° (below horizontal plane)

9. ECHO STRENGTH

In previous research to classify objects [McKerrow and Harper, 2001; McKerrow and Kristiansen, 2005; McKerrow and Yoong, 2007] we aimed the sensor to get the best signal to noise ratios while isonifying the whole object. As a result, we got very strong echoes (microvolts). During the current experiments, we observed that we could hear tones that are barely distinguishable from the noise in the PSD. This low volume of the tones explains why blind people can use the sensor and not be annoyed by the sound or lose their hearing of environmental sounds. So it seems that in this project we will have to work with much lower signal to noise ratios. Stronger echoes can be obtained from the walls and floor by increasing the scanning angles.

In previous research electronic noise was not problematic as we worked with strong signals (hundreds of nanovolts or microvolts) and 12 bit ADCs. We have observed that blind humans use very week signals, unless they want to peer at something to confirm its identity. The use of week signals enables them to scan faster, because they make decisions on minimal information, and reduces the interference with their hearing.

In this research, we are using a 14-bit ADC that enables us to detect weaker echoes. However, we found that audible echoes are often weaker than the above noise spikes. In the measurements shown in the following figures for these experiment we have deliberately panned and tilted a bit further to lift the signal above the noise level for observation purpose despite the fact that we could physically hear them at a lower level.

The level of signal that we desire has an impact on the motion of the scanning. When the sensor is depressed by 30° we can just hear the echoes from the floor and from the walls. We can increase the strength of the echoes from the floor by depressing to 40° (McKerrow and Kristiansen, 2005) but loose the wall all together. The strongest signals from the walls at 0°, however depressing the sensor by 10° ensonifies the wall/floor interface giving us more information. A consequence of this is that the scanning motion should include changes in vertical angle (tilt) as well as change in horizontal angle (pan).

10. A STEP IN TIME

Having observed the echoes when stationary, the next stage is to observe the echoes when walking. The following experiment includes one step and a person walking towards the sensor and then passing to the right.

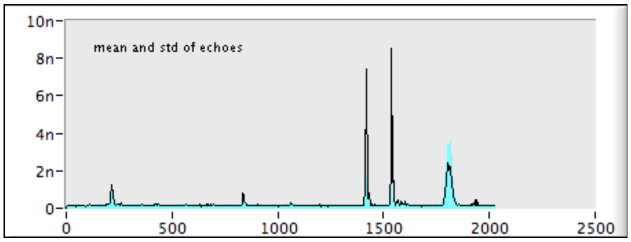

Fig. 12. Right wall, at 60˚ right pan, depression10˚ for a measured distance of 1450mm (c/f) first spike vs range.

We took a calibration reading at the beginning of the experiment by placing a specular surface in front of the sensor at 0˚ depression and physically measured the distance to the sensor. We divided the distance in millimetres by the echo FFT bin number to obtain distance per bin of 3.957 mm per bin used to calculate the range in Figs. 12, 15, and 17.

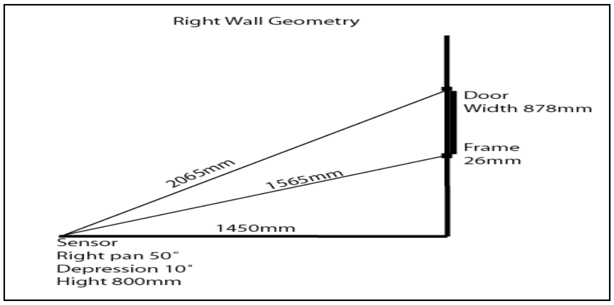

Fig.13. Right wall geometry notably the wall at 1450mm and the doorframe at 1565mm.

To move one step forward (Fig. 5.) we panned right to detect the right edge of the corridor (Fig.12.). We note 2 distinct echoes at 1450mm and 1600mm approx, which corresponded to the geometry of the right wall (Fig. 13.). Next we panned the sensor to scan forward (Fig. 14.) where we perceived an oncoming person and observed echoes from his front and back legs (Fig. 15.).

Having detected an obstacle one metre away in the forward direction, the blind person has to decide what to do with the next step (left foot). He could stop, or move to the left. He also has to choose where to sense; to the left where the left foot will go or straight ahead to track the obstacles.

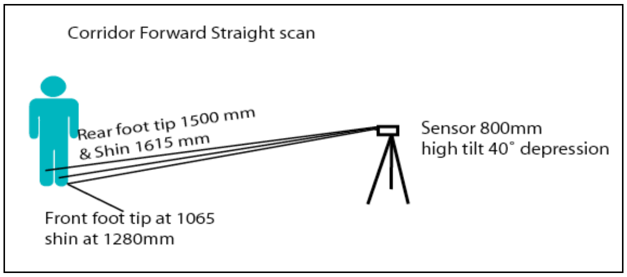

Fig.14. Forward scans geometry notably the oncoming person at 1045mm and 3 distinct echo points at 40˚ depression.

As the obstacle is 1 meter away he has time to sense twice (at 400 mm between scans - Sec. 5) so he can scan left and then forward. But by the time he has the echo data from the forward scan he is only 265mm from the object if it is stationary.

If it is moving towards him at the same velocity, as he is moving he will collide with it after he has travelled 600mm. So we have to revisit the calculations in Section 5. They showed that a blind person could navigate with a sensor update of 400 msec in a stationary environment. In a dynamic environment, a faster echo-sampling rate is required; in this case at least every 200 msec. Also, a change in scanning strategy is needed to deal with the changed navigation situation.

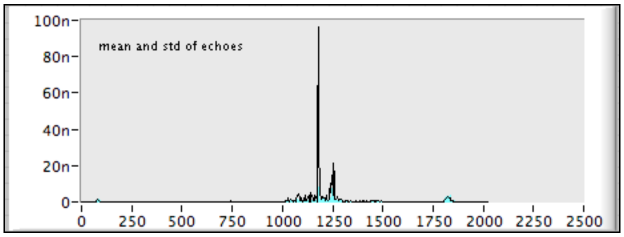

Fig.15. Forward scan echo notably oncoming person at 1045mm front foot 100n, back foot at 1250mm at 20n.

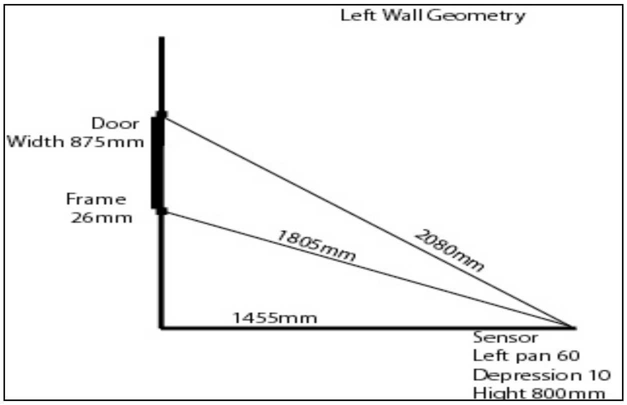

Fig.16. Left wall geometry notably distance to wall is 1455mm, and to the door 1805mm

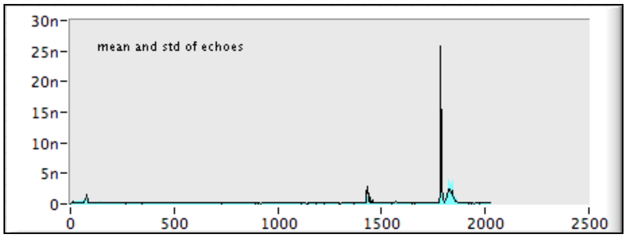

Fig.17.Left wall 60˚ pan 10˚ depression spike (4n) at approx 1455mm and a spike at approx 1800mm from metal doorframe we also note that the far end of the doorframe is beyond the scan range of 2000mm

If the blind person decides to step towards his left, then the scan of the left edge of the corridor (blind person's perspective) shows that there is space for him to step left (Fig. 17.). We note that the above figures show close correlation between corridor features as measured for the geometric model and the echoes captured.

11. CONCLUSION FUTURE WORK

We are just starting to understand the information in the echoes from the corridor. Combining echo information with a knowledge sensor motion helped to identify where the echoes are from. In this paper we have demonstrated an accurate correspondence between physical features and echoes by comparing the ranges measured with the echoes to those measured of the physical geometry with a tape measure. Also, we have shown a correlation between expected navigation trajectory and sensor direction commands.

In addition, it appears that the tilt angle required to get a strong echo from the floor results in a weak echo from the walls. Therefore, a blind person may be changing the tilt angle during the horizontal pan to get stronger echoes, or due to the high dynamic range of human hearing, may be able to select an angle where both the floor and wall echoes are strong enough. The solution to this problem may vary with the width of the corridor and the roughness of the surfaces.

We observed that the human ear can detect very low energy tones and the human brain can identify those tones. Identification of the object may be possible by correlating energy level changes with scanning, although frequency content can tell us more about the object including how far away it is.

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