THE APPLICATION OF VIRTUAL ACOUSTIC TECHNIQUES FOR THE DEVELOPMENT OF AN AUDITORY NAVIGATION BEACON USED IN BUILDING EMERGENCY EGRESS

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ABSTRACT

This paper will address the issues surrounding the use of real-time virtual auditory auralization techniques in order to develop real-world acoustic applications. A primary application is described, notably the development of an audition based navigation beacon to aid emergency egress from buildings, ships, oil exploration platforms and aeroplanes.

1. INTRODUCTION

April 1990. A fire rages through the Scandinavian Star passenger ferry as it courses through Norwegian waters on an overnight voyage from Oslo to Copenhagen. The crew for the voyage had been hastily assembled from all over the world, language was a problem and no fire drills were carried out. Of the 500 passengers and crew on board, 158 died, including 29 children. Bodies were found piled up in the corridors close to emergency exits, in cabins, even in showers, where they had attempted either to escape the fire or protect themselves in their rooms waiting for someone to collect them. The fire had overwhelmed the ship in a matter of minutes, and the authorities launched the biggest marine investigation ever held in Scandinavia.

Part of the investigation concentrated on why people died where they stood….why they never made it on deck even though they were so close to the emergency exits. Many survivors claimed that it was impossible to see the emergency exit signs in the corridors when these were full of smoke. This led to the Research Council of Norway's programme for fires, explosions and major disasters commissioning SINTEF NBL – the Norwegian fire research laboratory to perform a series of evacuation trials on a reconstructed section of the Scandinavian Star. Using existing emergency signage provision, it was found that "*40% [of test subjects] could not find the emergency exit. They either passed it, or tried to get out through the wrong door, and some turned round on the way out….The tests showed that the standard sign that points to the emergency exits are difficult to see and interpret. We know that many of the subjects saw the signs, but could not understand them properly. It was disturbing to realize that so many people managed to make a mess of the evacuation process in spite of the fact that they know that they were taking part in an experiment, and that the corridor we had built up was relatively simple in comparison with many hotel or ship corridors*."[1]

In their summary, the researchers at SINTEF stated "*….we do know that emergency lighting and marking signs do not help to distribute people among the evacuation routes available. People try to get out the same way as they came in, and this can easily cause overcrowding. Our suspicion that signs do not live up to expectations has been reinforced by a major study that only 8% of the people noticed signs when they were fleeing from a fire.*"

Figure 1. *The Scandinavian Star rescue operation.*

August 1995: 06:12hrs, flight G-BGJL, carrying 131 passengers and 6 crew on a charter flight to Corfu, began its take-off from runway 24 at Manchester. About 36 seconds later as the airspeed passed 125 knots, the left engine suffered an uncontained failure, puncturing a wing fuel tank access panel. Fuel leaking from the wing ignited and burnt as a large plume of fire directly behind the engine. The crew abandoned take-off immediately, having no idea that a severe fire was taking place. After an exchange with Air Traffic Control, during which the fire was confirmed, the commander warned his crew of an evacuation, bringing the aircraft to a halt. As the aircraft turned off the runway, a crosswind carried the fire onto and around the rear fuselage, penetrating the hull rapidly. Smoke and some flame transients entered the cabin through the aft right door which was opened shortly before the aircraft came to a halt and fire took hold within the cabin. Despite the prompt attendance of the airport fire service, the aircraft was destroyed and 55 persons on board lost their lives.

The major cause of the fatalities was rapid incapacitation due to the inhalation of the dense toxic/irritant smoke atmosphere within the cabin. Many survivors from the front six rows of seats described a roll of thick black smoke clinging to the ceiling and moving rapidly forwards along the cabin. On reaching the forward bulkheads it curled down, began moving aft, lowering and filling the cabin. Some of these passengers were engulfed by the smoke despite their close proximity to the forward exits. All described a single breath as burning and painful, immediately causing choking. They experienced drowsiness and disorientation, and were forced to feel their way along the seat rows towards the exits, whilst being jostled and pushed. Some stated that "*the smoke generated an immediate sense of panic*."

Although many aspects of the disaster were criticised by the Air Traffic Investigation Branch, one key factor came to light and is documented in the report:

"*4:30 Research should be undertaken to assess the viability of 'audio attraction' and other techniques designed to attract passengers towards viable exits when speech and vision is impaired in smoke and toxic/irritant gases*."[2]

Figure 2. *Smoke plume from flight G-BGJL.*

2. WHAT IS THE PROBLEM?

These harrowing accounts of two severe disasters illustrate the fragility of human life in emergency situations. Familiarity with a building or structure is a key determinant to evacuation success, but takes time to form and is built up in many different ways [3]. One such way is through experiencing and interacting with the space, but this rarely occurs in structures such as hotels and ferries which are generally for short-term occupation. The problem in acquiring the spatial knowledge needed to facilitate navigation is compounded by the autonomous nature of many building interiors (as highlighted by the Scandinavian Star disaster). Additionally, the ambiguity of being in a smoke filled enclosure coupled with not knowing the location of the fire facilitates disorientation. Disorientated and blinded, a victim begins to rely on their other senses, for example touch; trying to 'feel' their way out. A very simple preliminary experiment conducted within a (non-toxic) smoke filled TV studio here at Leeds University showed that an individual would take some 3 min 50 secs to find a conventional emergency exit sign relying on touch and on their memory of the immediate environment. If this was a real fire, the individual would have been overcome by smoke within a minute or so and dead within 4 minutes. Since we have negated the efficiency of two of our senses (and also considering that there are over 750,000 people in the UK who are registered blind) in such circumstances, the only other option is to use sound to navigate our way out.

3. CAN WE USE OUR EARS TO NAVIGATE?

In the 1950s research was undertaken to investigate the way in which blind people use sound waves as tools, or sense extenders for exploring their surroundings. The original work was centred around obstacle perception [4] [5], or how blind people detect obstacles before touching them. It was thought for a long time that the blind had an augmented tactile sense, or 'facial vision' as it was termed, allowing them to orientate themselves to obstacles too far away to feel or touch. However the problem was eventually solved by a group of psychologists and biophysicists, Professor Karl M. Dallenbach of Cornell University, and two graduate students, Michael Supa and Milton Cotzin. Supa was himself congenitally blind, whilst Cotzin and subsequent experimental subjects wore blindfolds in order to participate in the experiments. Their research took the form of individually eliminating each possible channel of sensory communication to discover the sense which allowed for obstacle detection. In order to remove the influence of tactile communication, either from electromagnetic radiation, air currents, heat or cold, they used a long veil of thick felt which covered the entire bodies of the subjects. It was found that subjects had no problems in detecting the presence of the objects (which was in the region of 2.1 metres) effectively leaving only the auditory system in the equation. By completely plugging the ears, the subjects' auditory sensitivity was reduced considerably and upon the obstacle detection task, they all failed. To conclusively prove that the auditory system was the only sense in the detection task, the experimenters set up a remote listener / explorer experiment, with the explorer placed in the obstacle environment holding a microphone and the listener in a soundproof room. Using this, the subject could hear, nearly exactly, what the environment sounded like, being able to detect the comb-filtering of the room. Surprisingly, the detection rate was only 5 to 10% less than when the subject had actually been in the environment.

Further research [6] investigated the basis of the auditory signal which the subjects were extracting from the environment. Footsteps were an obvious possibility and after experimentation by making the subjects walk barefooted, their detection success rate fell by over 50% (to 1 metre). Further experiments, using a cart equipped with a loudspeaker as a remote rig with the subject in a soundproof room were carried out. A variety of sounds, from pure-tones to hissing (white) noise were presented and the detection distance measured. In summary, it was found that the hissing noise gave the best detection distance of the artificially generated stimuli at around 1.4 metres. Other sounds were tried but the experiments had to be concluded before the optimum signal was found.

What was interesting about these experiments was the fact that there is a strong indication that certain signal types are better than others for object location tasks. Although these tasks were echolocation based, it is obvious that if the auditory system is acute enough to discriminate distance and direction of obstacles, then it can surely be used as an aid to navigation.

Numerous studies since then have proven the acuity of the auditory system for performing localization tasks under both binaural and monaural conditions within free-field environments, all supporting the hypothesis that a navigation beacon can be designed and used to support building evacuation.

Going back to the previous experiment in the TV studio, a very simple white noise generator with loudspeaker was added to the emergency exit sign with the same individual completing the search task in 15 seconds. This was navigation at its most elemental level, using the sound as a perimeter marker.

4. RESEARCH AIMS

The aim of this research therefore is to design, develop, and test a navigation beacon that requires a single acoustic transducer placed at strategic points within a "building" emitting predefined pulses of sound. In essence, all the victim of a fire situation need do is follow these auditory beacons until they reach a safe exit (akin to the concept of Ariadne's silken thread in Greek mythology, or the Hansel and Grettle breadcrumb approach).

In order to develop such a system however, there are several factors that must be investigated. From a psychoacoustics perspective, there is an optimum signal that would be presented by the beacon which would help in the clear formulation of directional decisions. From an architectural and subjective acoustic perspective, any signal presented would be adversely affected in terms of localization performance by the enclosure itself. From a human perspective, how would people react to such a system; would they actually be able to use it?

Although simple in concept, these factors are difficult to investigate in real life. First of all there are high financial and time costs involved in gaining access to the different building types needed to develop such a system. Secondly because they are smoke based experiments, each building would have to be filled with artificial smoke which is not only unpleasant to breathe, but also leaves a slimy residue on any surface it condenses on. And finally, there are the issues of ethics approval and insurance to cover injury, which are almost impossible to obtain for such research.

As a result, an experimental methodology has been developed around real-time predictive virtual acoustic techniques. Using binaural room simulation techniques, we can authentically expose a person to a series of different acoustic environments in order to evaluate their performance. These simulation techniques have been developed to such a state of maturity that they represent some of the best ways of understanding the exact processes and problems associated with room acoustics, providing a sound basis for many auditory experimentation applications. When combined with a real-time auralization system, and linked to a high performance graphics engine, their power really begins to unfold, being able to reproduce with great accuracy the auditory percepts of the space under investigation.

5. THE SYSTEM

A fully immersion based virtual acoustics laboratory has been created at Leeds to act as an arena for development and testing of the navigation beacons. The graphics system is based around a Silicon Graphics Visual Workstation running Sense8's Virtual Reality development software WorldToolKit. Navigation is by means of either a Spacetec 6DoF Spaceball or mouse with a Polhemus IsotrakII head mounted tracker and pointing stylus. Visual images are projected monoscopically onto an I-glasses2 head mounted display.

Acoustic models are created using CATT acoustic, with its impulse response files exported to a 16 DSP Lake Huron20 real-time audio convolution workstation. These sounds are rendered in a pipelined process, paralleling the image rendering process using TCP/IP communications protocols, sending X,Y and Z coordinates in addition to Pitch, Yaw and Roll. Both the navigation beacons and listener are rendered in this manner. The auralized sound is presented to the listener using a pair of Sennheiser HD565 headphones. Software platforms include both C and Visual Basic.

In addition to being able to navigate the environment, the software includes a real-time people animation module (RTAM). Using the RTAM, a finite number of people can be inserted into the simulation, adding to its authenticity (i.e. shouting, screaming), these sounds sourced from either a multi-track soundcard or DAT / tape array. One advantage of the real-time animation module is that it can easily import data from pre-calculated fire behaviour models (given the correct conversion format) therefore applying real-world behavioural data to its characters.

To confound navigation and increase realism, smoke effects have been implemented into the simulation. This has the effect of increasing disorientation due to the way in which it is rendered. Although the smoke is static, visibility changes dynamically through the rendered scene.

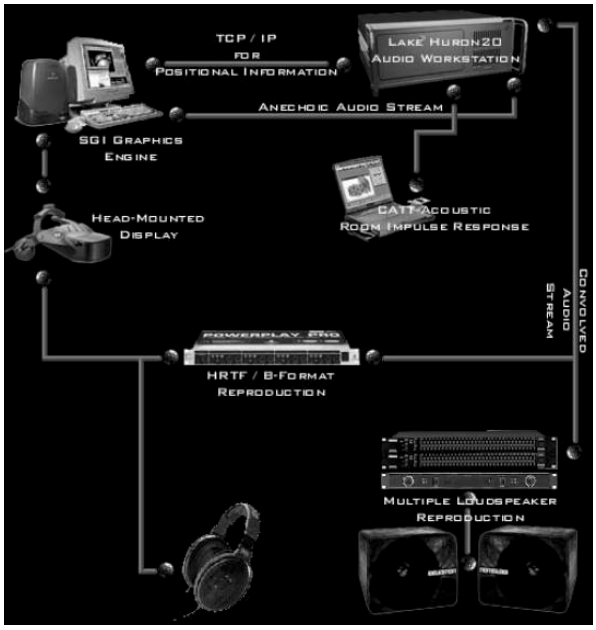

Figure 3. *The visual / audio rendering pipeline.*

6. SYSTEM INTEGRATION ISSUES

As is usually the case, system integration was not as transparent as it was deemed to be by both hardware and software sellers. The first integration issue concerned Windows NT and its TCP/IP protocol. Whilst the code supplied by Lake (for Unix) worked perfectly well on an SGI O2, its translation across to NT was not quite as successful. It appears that NT is very unforgiving when it comes to TCP/IP streaming, necessitating a complete re-write of the communications protocols to the Lake hardware. As a result, a complete Unix / NT protocol has been developed which allows for trouble free communications.

The second integration issue concerns one of definition. More specifically, it is the varying definition of coordinate and angular space used between different packages for different applications. For example, WorldToolKit describes 3D space in the following manner, Z looks straight ahead, X points to the right and Y points down. However, the Lake hardware and CATT acoustic use a different convention whereby Z points upwards, X points to the right and Y looks straight ahead.

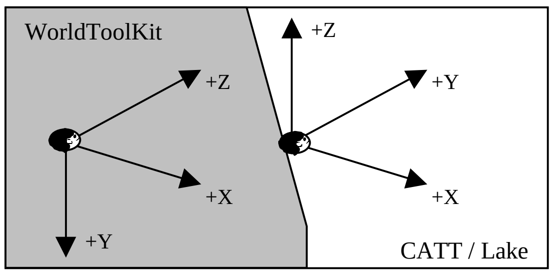

Figure 4. *Coordinate systems.*

Similarly, angular conventions also differ. For example, WorldToolKit extracts its angles using quaternions and provides functions for converting these quaternions into euler angles. The Lake hardware expects its angles to be in the form of eulers (converted into degrees) so it was assumed that this would be a relatively simple conversion. How wrong we were! The quaternion conversion from WorldToolKit does not give the current angle, it only appears to describe how you got there. For example, consider the following. If we yaw 89 degrees to the right and pitch up 10 degrees, we would expect that these angles would be expressed in this way. Unfortunately this was not the case. WorldToolKit would report that we had yawed 87.xx degrees, pitched up 45 degrees, rolled 45 degrees, and this was the same for other angles. Making matters worse, when turning into the rear hemisphere (i.e. surpassing 90 degrees yaw), the angles would invert, confusing the system entirely.

As a result, a new angular conversion function had to be written using vector maths to return the angles in their correct form. Additionally, the orientation rotations described by WorldToolKit are expressed differently (whereby a +ve yaw in WorldToolKit represents a –ve yaw in the Lake system), so the new vector code had to include conversion factors for these as well. All in all, it was a very difficult task and has pushed the project at least 8 months behind schedule.

Other minor difficulties include the implementation of sufficiently fast collision detection (which has now been achieved using simple bounding box intersection testing) and animated characters having no inverse kinematics modelling. Applying kinematics modelling to limb movement slows the simulation to the point whereby it turns step-time as opposed to real-time.

7. PREVIOUS WORK

Between 1995 and 1997, Rutherford [7] investigated the possibility of using static simulation tools to develop an auditory navigation beacon. The principal hurdle at the time was the availability of tools powerful enough to do the required simulations in real-time. Although he used sound spatialization hardware to do many of his localization experiments, technology restricted him into using non real-time simulation techniques. As a result, several problems evolved.

Firstly, many subjects found that the sound image stayed *inside the head* and did not externalise effectively. Although the implementation of such auralization techniques helped minimise such effects by providing environmental cues (such as reverberation [8]), the ability to use some form of head tracking would have vastly improved such externalisation. According to Durlach et al. [9], externalisation is maximised when (a) head movements occur, such as rotations and translations and (b) when the binaural stimulus is altered in a *natural* way as a function of these head movements (i.e. the sound follows the motion precisely, as would be experienced in the natural world). In a similar vein, the researcher found that when subjects were trying to locate these static sound stimuli, they often experienced problems determining whether the sound was originating from the front or back. In everyday life this is rarely a problem as we resolve this ability by turning our head, aligning our ears towards the source. In brief, the results of the experiments, although highly conclusive in their own right, were disappointing, being directly limited by the technology available at the time.

Lokki et al. [10] took this one stage further allowing real-time movement in virtual space to study navigation. Using the arrow keys on the keyboard, subjects could move forwards, backwards and turn their heads. Using simple acoustic environments, varying signal types and different panning techniques, they found that in most cases, subjects did find the target area. Pink noise was clearly the best stimulus used in the navigation task with reverberation tending to increase search times and error rates.

It is from here that a description of our planned experiments, their methodologies and preliminary results will be discussed.

8. EXPERIMENT LAYERS

The experiments for this research have been split into several parts, each tackling issues which might affect navigation. The following will describe these experiments:

8.1. Experiment 1 – Auditory Attention

Adaptation to a sound source or its location over time is critical to the success or failure of any audition based navigation device. As a result, a series of experiments are currently being developed.

The fundamental question to be addressed here is do we adapt to sound sources and begin to 'tune them out' (desensitise). If so, what are the influencing factors? Is it the spectrum of the sound source, its duration, its location or a combination of all three? Whilst this has been extensively investigated for the visual system, the auditory system has largely been left alone.

A series of recordings are currently being made to investigate this phenomenon. Several different signal types such as pure tones, filtered noise and broadband noise have been generated for the experiments. These signals are sent through several different auralization devices, including a Neumann dummy head (in an anechoic chamber) from which its impulse response at various locations has been measured, a CATT acoustic room model and a standard Lake Aniscape model. From these models, different acoustic environments are simulated (i.e. the CATT model can either be made anechoic by rejecting all reflections except direct sound, or fully rendered for any given space). To avoid cross-hemisphere effects, all sounds are constrained to a single hemisphere (i.e. all sounds are to the left of the listener).

In essence, each experiment consists of two stimuli. A 'cue' stimulus is presented followed by a 'target' stimulus. If we want to look at whether attention adaptation is stimulus based then the cue and target will be presented from exactly the same location, but the signal types will differ between them. The interstimulus interval will be varied to see whether it has any effects, and a reaction time will be taken based on the target stimulus. If attention is location based, then the cue – target stimuli will be presented from different locations, and once again a reaction time will be taken on the target stimulus.

By presenting stimuli in different acoustic environments, we can investigate whether the environment has any effect on attention (such as influences from the precedence effect). It is hoped that this series of simple experiments will give us some clue as to the basis for auditory attention.

8.2. Experiment 2 – Critical Localization

As previously discussed, localization performance is adversely affected by both signal type and propagation medium. In this experiment therefore, the task set is for subjects to determine the location of an auditory object within an acoustic environment using dynamic head movement.

Calculating a complete and detailed room impulse response for every single position and orientation of all sound sources and receivers is an exceptionally time consuming and computationally expensive process. As a result, some simplifications must be introduced. However, with a certain degree of pre-calculation, high realism can be achieved. As this experiment is primarily interested in exploring the early response of a room (where localization judgement is extracted), we have decided to use a real-time model which calculates the direct sound and early reflections of the source's propagation with a randomised late reverberation tail. For this critical evaluation experiment, room models are created using CATT acoustic, generating 128 different listener head orientation impulse responses (with direct sound and early reflections). These early impulse responses are dumped into the Lake DSP hardware (occupying some 5Mb data and 4 DSPs) to which the reverberation tail is added (also from CATT). This provides a highly accurate simulation of the listening environment, and the listener is free to dynamically orient themselves to any position (with the 128 impulse responses switching in real-time).

The listener's task is to indicate the direction of the different signal types, which similar to the previous experiment include tones, filtered noise, noise in isolation and various combinations of the above. By altering the dimensions of the space and signal type it is hoped that an optimum signal type(s) can be found that would aid as opposed to hinder navigation.

Listeners indicate sound object location using a Polhemus Stylus which is similar to the head tracker except that it passes both positional and orientation information to the simulation from the pointing device. In effect, holding the stylus like a pen, they 'point' to where they think the sound is originating which is subsequently recorded by the researcher. Such a technique has been found to be most accurate for subjects expressing the apparent location of a sound source [11].

One concern with this experiment was the criticality associated with compounded system latency. A considerable quantity of information is passed between hardware and software components in this simulation, therefore a degradation in both task performance and presence can be expected if there is a sufficiently large temporal lag in the device used to track head motion [12]. Complete sensory equivalence is needed between the tracker and visual and acoustic display mediums; i.e. their interaction must appear seamless to the user. Repercussions of an unsynchronised display include an internalisation of the sound source leading to conflicts between the auditory and visual channels thus decreasing the perceptual validity of the environment. Fortunately this issue proved to be an easy one to overcome. The head tracker has an update rate of 50Hz and there is a total convolution delay of some 3 or 4 milliseconds which was well within the capabilities of the rewritten TCP/IP protocols.

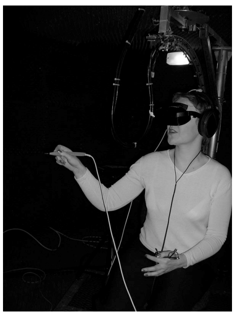

Figure 5. *A subject locating a sound source.*

8.3. Experiment 3 – Complex Navigation

Having provided a theoretical framework for the development of the beacon, the final stage in the project is to test subject's responses to such a device. A series of complex environments have been created in CATT acoustic and exported to the Lake hardware. Although the room impulse response and head related transfer function sets for this exploration task are simplified, the purpose of this experiment is not to test the fine details of the beacon (this is done in experiment 2), but to test whether subjects understand the task at hand and gain their feedback on the device. For example, as well as measuring travel times and navigation success, questions such as whether they think the device is a good idea, whether they find it useful, whether they would be confident in using it in an emergency situation etc.. are to be asked. For those without visual impairment, visual depth can be constrained (for example implementing smoke or just completely removing the head mounted display) in order to elicit some kind of reaction as to how difficult it is to navigate out of these spaces in an emergency situation without the use of sound. Although we acknowledge the fact that these are sensory deprived environments and that in a real situation people would additionally search with touch, the purpose is in effect to gauge a reaction and get people thinking about just how difficult it is to navigate in a real fire.

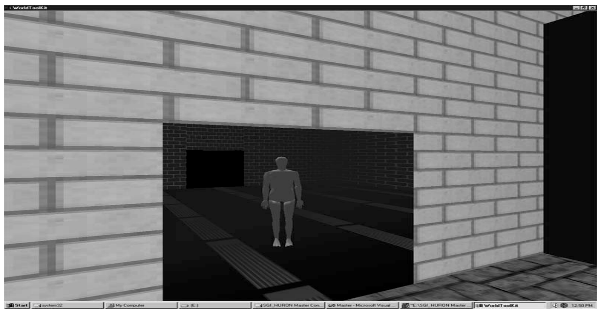

Figure 6. *A prototype virtual acoustic environment.*

In essence, the task is simple. Navigate through the environment until they reach their destination. Environments have been created that include 1 and more than 1 beacon. For example, a complex navigation route might include several beacons to be passed under.

One concern was the interface technologies used for navigating these environments (i.e. the link between the HMD, the mouse or Spaceball etc.. for movement). To facilitate navigation, motion constraints are imposed to the horizontal plane, i.e. subjects can not fly off into space using the system, simplifying the use of the peripherals. Additionally, the question of analysing the data from this experiment is an interesting one. Since the purpose is also to look at ease of use and quality issues, all subject's movements are dynamically recorded to a file allowing the researchers to examine their movements from their perspective, post experiments. Combined with videotaped records of their actions (and frustrations), both subjective and objective results can be obtained.

9. PRELIMINARY RESULTS

It must be noted here that this research is in its very early stages and as explained, behind schedule, and we apologise for the obvious lack of experimental data However, the following results and experiences hope to give an indication as to what we are to expect over the next year of this work.

9.1. Interface Technologies

- System latency tests are showing no detriment to subject's performance, so system integration appears to be working well.
- Using a pointing system is far superior to using a rotating dial or announcing the apparent location of the source using a clock face paradigm.
- Navigating using the interface peripherals is strange to many users in the beginning but after a brief period of hands-on training, they have few problems. Subjects are actively searching the environments and using their ears to locate the source.

9.2. Experimental Observations

- No work has yet been commenced on the attention experiments but this should be complete by the time of the conference.
- The critical localization experiments are showing some interesting phenomena, but these have yet to be analysed fully (only 5 subjects so far). In line with the hypothesis set out in the project, it appears that the acoustic environment in which the sound is propagating tends to delocalize the location of the sound source. However this delocalisation is very much dependent upon the spectrum of the sound source. For example, using spectra containing only ITD information (below 1.6kHz), localization performance decreases rapidly. Tonal stimuli give very clear locatable events, but to the detriment of localization accuracy, especially in the front / rear hemisphere. The perception of the location of the sound can be changed by utilising certain narrow-band stimuli (i.e. we can get it to move about across the median plane).
- Users are generally enthusiastic about the possibilities of the system, exclaiming that they would feel more comfortable in a building knowing that they had an additional device that would allow them to escape.

10. CONCLUSIONS

Although the results are somewhat tentative at the moment, the researchers believe that the developed system is more than adequate to help in the development of the navigation beacon. Although the development time has been long and frustrating, it is at a stage now whereby an acoustic model can be created, implemented and tested within a matter of a few days so the number of acoustic environments and stimuli tested will be large. In addition, interest has been expressed in using the system for two further projects. One project is to develop a train-door location device for blind and visually impaired users. The second project which is about to commence will look at the effects of which restorative surgery might have on people with unilateral hearing loss. Looking at localization pre and post surgery, it is hoped that an indication as to the improvement in these people's quality of life can be gauged.

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