3D Spatial Audio Extraction and Demonstration System for Augmented/Mixed Reality Simulations

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ABSTRACT

The U.S. Army Research Laboratory-Human Research and Engineering Directorate, Advanced Simulation Technology Division (ARL-HRED-ATSD) performs research and development in the field of augmented/mixed reality training technology. As part of this continuing research, 3D spatial audio concepts previously developed have been further matured culminating in a desktop demonstration system and a set of novel real-time approximations for sound propagation in a true 3D environment. While much attention has been given to the visual representations in augmented/mixed reality systems, true 3D spatial audio has generally been overlooked. The 3D spatial audio simulation has tremendous utility in immersive environments used for augmented/mixed reality training. This technical challenge has been thoroughly researched for many years and many approaches have been designed, developed and studied over the years but yet still a viable system is lacking which exploits the availability of high fidelity and low-cost gaming engines. The basis of these studies is that while immersed into an augmented/mixed reality training environment, a soldier must be able to sense the direction and distance of sound sources from virtual components as he moves through the augmented world. The developed concept is based on true 3D geometry computations and virtual mixers which preserve the sound source implementations. Representation of the 3D spatial audio field is demonstrated using a discrete transducer desktop system which fully supports all six primary sound field directions; up, down, left, right, front, and back. This paper describes the implementation of real-time approximations to sound propagation in realistic dismounted environments, a novel demonstration system to produce the 3D sound, and presents the remaining challenges to be overcome. Designs for the next phase of experimentation are also discussed along with the remaining challenges required to provide 3D spatial representation in real-time to immersed humans on the move in augmented/mixed reality training systems.

ABOUT THE AUTHORS

Jay Saffold is the Chief Scientist for RNI and has over 35 years engineering experience in both military and industry research in game-based training, immersive systems, RF tags, virtual reality, digital databases, soldier tracking systems, millimeter wavelength (MMW) radar, multimode (MMW and optical) sensor fusion, fire-control radar, electronic warfare, survivability, signal processing, and strategic defense architecture. Mr. Saffold is the Program Manager of the Dismounted Augmented Reality Environment (DARE), Game Distributed Interactive System (GDIS), Hitbox Haptics, and Man Machine Interfaces for Simulation and Training (MMIST) systems. He lectures annually for GTRI on remote sensing and signal processing. He holds a B.S.E.E. degree from Auburn University.

Tovar Shoaf is the Lead Software Engineer for RNI with 6 years of experience in the military simulation industry. At RNI he works on research and integration of hardware and software for man-worn tracking systems, smart sensor fusion, game engine interfaces, game-based trainers, mobile applications, multiplayer servers, pose estimation, simulation data recording and analysis, abstracted architectures, and SLAM components for Augmented Reality. Mr. Shoaf is the Lead Developer of the Dismounted Augmented Reality Environment (DARE). Prior to working at RNI he worked on flight reconstruction and analysis from both live and simulated flights. He holds a BS in Game Development from Full Sail University (2011) which focuses on efficient, real-time input and processing.

Pat Garrity is a Chief Engineer at the U.S. Army Research Laboratory-Human Research and Engineering Directorate, Advanced Simulation Technology Division (ARL-HRED-ATSD). He currently works in Dismounted Soldier Simulation Technologies conducting research and development in the area of dismounted soldier training and simulation where he is the Army's Science and Technology Manager for the Augmented Reality for Training

Science and Technology Objective (STO). His current interests include Human-In-The-Loop (HITL) networked simulators, virtual and augmented reality, and immersive dismounted training applications. He earned his B.S. in Computer Engineering from the University of South Florida in 1985 and his M.S. in Simulation Systems from the University of Central Florida in 1994.

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INTRODUCTION

This paper describes research performed into the creation, extraction, and demonstration of three-dimension audio information for use in immersed training systems and extends the principles and concepts from previous work (Saffold and Roberts, 2011). The U.S. Army Research Laboratory's Simulation and Training Technology Center (ARL STTC) Ground Simulation Branch has a deep interest in this technology as most dismounted Soldier virtual-immersive simulations currently use sound sent through a personal computer or through headphones to allow Soldiers the ability to perform communications uses sound in the environment for situational awareness. The issue in training simulations and hardware is that the sound is not directional and immersed Soldiers cannot tell the direction or distance of another Soldier when communicating. This is inherently not as it is in the real world as buildings and other objects can obstruct the view of Soldiers immersed in a virtual environment. When Soldiers are inside buildings, they can still communicate with their fellow squad mates, but they do not know where their squad mates are as there is no directional or distance to the sound they hear. So if a Soldier has an issue and calls on his fellow Soldiers to help, come "here", in this case, the word "here" has no meaning as they do not get direction and distance in what they hear as they would normally in a live training event. In order to further increase the immersive experience and training of Soldiers immersed in virtual reality environments, this problem must be solved. The ARL STTC has been researching this problem for years looking for a way to solve this inherent issue with using virtual reality environments.

Under a sponsored Phase II effort with the US Army, RNI focused on developing an ability to demonstrate the utility of 3D spatial audio. This included (a) building a true 3D speaker system, (b) implementing the impact of obstacles and boundaries on sound propagation, (c) defining bidirectional reflection and transmission coefficients for boundary materials, (d) implementing metadata to preserve propagation path acoustical transformation information, (e) performing optimizations to allow large amounts of sound data to be processed in real-time using a commercial gaming engine, and (f) developing scenarios to verify and demonstrate 3D spatial audio concepts previously developed. (Saffold and Roberts, 2011)

In the research and demonstration system each audio source was "paired" with a listener; which creates a single propagation geometry. Of course, there can be many listeners for any source in a training environment. Both sources (transmitters) and listeners (receivers) could be moving simultaneously. The source and listener data along with several other propagation parameters were preserved in the metadata for each successful path. These data were then filtered and processed by a spatial mixer and 3D spatial audio mapper which provided the appropriate conversion into the true 3D speaker system. The speaker system was designed to allow a direct relationship to sound angle of arrival information in the real world thus removing a need for complex Head-Related Transfer Function (HRTF) approximations typically employed on stereo headsets or speakers (Begault and Durand, 1990) (Burgess, 1992).

APPROACH

The approach was based on the fundamental assumption that all audio sources originate from a point (transmitter) in the three-dimensional (3D) field defined by specific transmission and motion properties. The source emissions then propagated (transformed) through a potential perilous environment and must then be properly referenced to a listener or receiver; which is also defined by specific reception and motion properties.

For dereferencing the point sound source emissions to the receiver, the acoustic wave's spatial diversity was sampled according to "ray tracing" methods. (Okada and Onoye, 2011) When each of the emitted rays reach the receiver point, the distance, source properties, propagation transformations, along with relative vector motion and obstacle/boundary properties are preserved as metadata. These metadata are used to provide the proper resultant sound field to the 3D listener spectrum, the demonstration system apparatus, and subsequently the human ear(s).

3D SPATIAL AUDIO SPEAKER APPARATUS

RNI initially researched current "spatial audio" specifications and speaker systems (headphones) to determine if all six cardinal directions (up, down, left, right, front, and back) could be supported by existing technology (see Figure 1). The two most prevalent "spatial audio" specifications are based on "virtual surround" concepts often called Surround Sound.

The Surround Sound specification nomenclature is based loosely on the number of discrete channels encoded in the original signal and the number of channels reproduced for playback. Channel identification is also loosely based on standards from the Consumer Electronics Association (Consumer Electronics Association, 2011).

In the current consumer and military market the most prevalent Surround Sound implementations are 5.1 and 7.1. [1] It is interesting to note that the channel specification does not include an "up" or "down" directional equivalent.

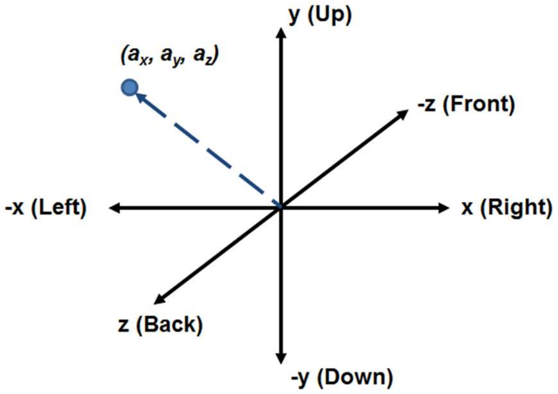

Figure 1. 3D Spatial Audio Cardinal Geometry

To verify the capability of 7.1 surround implementations two headphone configurations were tested: (a) a 7.1 virtual surround sound (one speaker per ear – Turtle Beach Stealth 450) and (b) a 7.1 true surround sound (5 drivers per ear - ASUS STRIX 7.1). A simple scenario was developed in Unity3D which provided a constant (or triggered) sound source moving around a listener in all directions and playing back through the appropriate 7.1 sound driver which accompanied the headsets. The sound source volume was also adjustable. RNI then created a custom audio system in Unity3D that can address discrete channels of the 7.1 Surround Sound specifications individually. These playback channels were then remapped into the proper cardinal directions of the 3D Spatial Audio geometry.

For both headsets, there was no distinction between up and down and the front/back difference was small and hard to pinpoint. This is not surprising as the 7.1 specification has no provision for up or down directionality encoding. The 7.1 specification does however provide for 8 discrete audio channels designated (Front Left, Front Right, Center, Sub, Left, Right, Back Left, Back Right) which can be used to produce the required directionality to the playback system with a simple channel remap (see Table 1).

Table 1. 7.1 Sound Specification Channel Mapping

7.1 Sound Card Channel	Speaker
FL (Front Left)	LEFT
FR (Front Right)	RIGHT
C (Center)	FRONT
S (Subwoofer)	DOWN
RL (Rear Left)	UP
RR (Rear Right)	BACK

To stimulate the 3D playback system a scenario was created where a single sound source could be rotated at any angle around a stationary listener. The audio amplitude from the sound source location was then

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[1] Note that in the ANSI/CEA/CEDIA-2030-A nomenclature the ".1" denotes a low frequency effects or LFE channel existence. Thus "7.1" means 8 total channels (7+1) with one of the channels used for LFE.

mapped into each speaker channel in accordance with the projection of the source-to-listener unit vector on the cardinal direction unit vector of the speaker location.

$$a \,.\, b = a_x b_x + a_y b_y + a_z b_z \qquad (1)$$

Where a is the unit vector from the listener at (0, 0, 0) to the source at (x, y, z), and b is the unit vector in the speaker's cardinal direction in the 3D Spatial Audio Cardinal Geometry.

The developed channel verification scenario allowed the user to rotate a number of different sound sources (wav files) including (a) Gunshot, (b) 60 Hz Hum, (c) White Noise, (d) Hand Claps, (e) Voice Dialog, and (f) Footsteps around the listener at different rates and intervals. The different sound types were also used to verify frequency response of the channel remapping in the 3D speaker apparatus (see Figure 2).

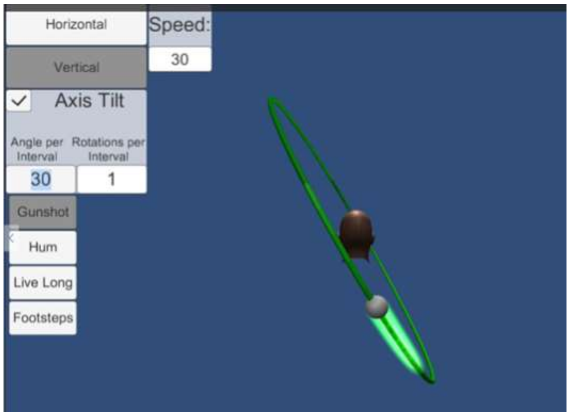

Figure 2. 3D Spatial Audio Verification Scenario

To support the speakers a simple apparatus was developed which would place each speaker at an equidistant point from a centered listener location (head), with one speaker in each of the cardinal directions. The volume of each of the speakers was matched to produce the same amplitude at the center of apparatus given the same sound source level.

The wired 3D Audio desk apparatus was made of light weight PVC and six discrete speaker attachment points were located at the 6 cardinal direction points around the head. A counter balance system was also made of "sand filled" PVC bars at the bottom to allow the apparatus to remain stable when placed upright on a surface in front of a desktop computer (see Figure 3).

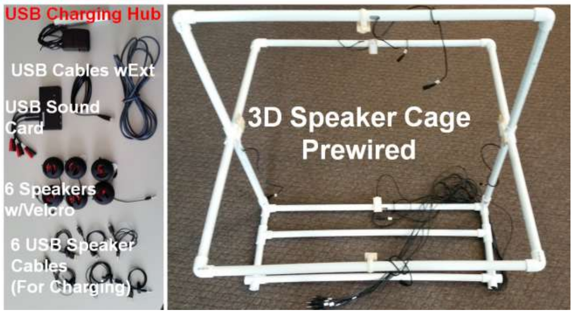

Figure 3. 3D Spatial Audio Apparatus

The user could then easily move into the center while still maintaining full ability to operate a mouse and keyboard while sitting normally in a desk chair.

Users were then asked to close their eyes and vocalize the direction of the sound source while an engineer operated the scenario moving the sound source around the head in all directions. In all cases, the user correctly detected the sound location during the scenario when asked.

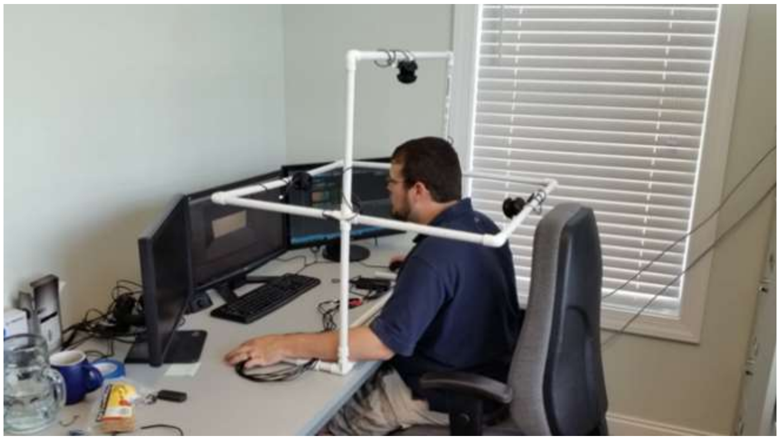

Figure 4. User Operating 3D Spatial Audio Apparatus

SOUND PROPAGATION AND MATERIALS MODELS

For the simulation RNI used a parameter based model to assess the transformations to emitted sound information due to the propagation environment between source and listener. This parameter model was also used to define the specific metadata for each ray propagation path.

In free space, sound propagates as waves according to the Friis transmission equation. For each point sound source in the environment, the received sound wave amplitude can be expressed as:

$$P_{r(i)} = P_{t(i)}\left(\frac{1}{4\pi R_{(i)}^{2}}\right) A_E \qquad (2)$$

Where $P_{r(i)}$ is the received acoustic wave from source "*i*", P_t is the transmitted acoustic wave, $R_{(i)}$ is the distance traveled in meters from source "*i*", and A_E is the effective transformation of the sound in amplitude, frequency, and time along the path due to obstacles, weather, ground, turbulence, and any other effects (see Figure 5).

For time delay, the speed of sound can also vary with air temperature. For a standard temperature, the speed of sound is presumed to be 343.2 meters per second which when multiplied by the distance *R*, provides the delay in seconds. Frequency transformations of the sound can be produced by the harmonics of the obstacle(s), resonances in the environment, damping characteristics of boundaries, and Doppler when the geometry has a radial velocity.

Frequency (and time) components of sound modified by materials or boundaries are typically characterized by the "impulse response" of these materials.

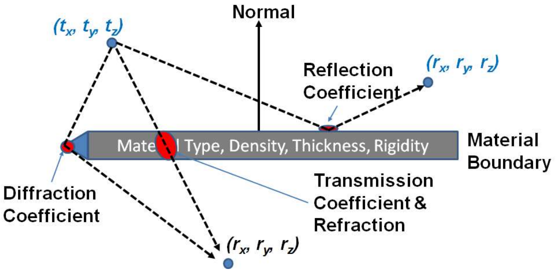

Figure 5. Propagation Geometry on a Material Boundary

For typical indoor military scenarios, a suite of common construction materials was needed to simulate operations inside a building. These materials can include concrete, carpet, drywall, wood, dirt, tile, and many variations of each type. Most of the literature contains only limited information on sound absorption or sound proofing properties associated with materials. Sound waves (depending of frequency and geometry) can reflect from, transmit through, refract through, or diffract around boundaries in the path on the way from a source *t* to a listener at *r*. In order to properly convolve the incident sound with an obstacle in the path the reflection, transmission, and diffraction (where applicable) coefficient of the obstacle's material must be known. These coefficients are also frequency dependent and a strong function of incident and reflection / transmission angle along with other physical properties such as thickness, rigidity, surface roughness, density, and shape.

For the parameter model, the reflection and transmission properties of material boundaries to sound were expressed according to "sound absorption" and "sound proofing" characteristics gleaned from the literature. In order to support the required metadata for a material boundary the following were defined in the simulation:

- *Material Type* – a name for the material
- *Transmission (T) dB Down* – ratio of the transmitted to incident wave at the boundary.
- *Transmission Angle Variance* – angle from material normal to transmission angle before a cosine function further attenuated the wave.
- *Transmission High Pass Cutoff (Hz)* – frequency by which additional attenuation (10 db/decade) applied to the wave's lower frequency components.
- *Transmission Low Pass Cutoff (Hz)* – frequency by which additional attenuation (10 db/decade) applied to the wave's higher frequency components.
- *Reflection (R) dB Down* - ratio of the reflected to incident wave at the boundary.

- *Reflection Angle Variance* – angle from material normal to reflection angle before a cosine function further attenuated the wave.
- *Reflection High Pass Cutoff (Hz)* – frequency by which additional attenuation (10 dB/decade) applied to the wave's lower frequency components.
- *Reflection Low Pass Cutoff (Hz)* – frequency by which additional attenuation (10 dB/decade) applied to the wave's higher frequency components.

Sound absorption data are typically measured when sound energy is absorbed by 'acoustically soft' materials that sound waves encounter, as opposed to being reflected by 'acoustically hard' materials. Absorption may also include sound energy that becomes "trapped" inside the medium or transmitted into another medium (McGrory 2012). Thus sound absorption coefficients (α) may be reasonably mapped into an equivalent reflection coefficient according to 1 – α. Sound proofing can be defined as both minimizing reflections and reducing sound propagation into other locations. In the literature RNI focused on any information based on the ratio of the transmitted sound energy on the other side of the boundary to the incident energy (Kimura 2014).

While there is a plethora of work published on sound absorbing materials, the time, frequency, and amplitude transformations associated with the audible spectrum (especially transmission) does not exist in large amounts (Smith, 1993). There is very little quantitative information on sound proofing characteristics of materials other than techniques to improve it. Further, what little data there is on sound transmission properties is only available in controlled measurements and at only normal incidence (Bolton 2007, Han 1977, Masateru 2014).

In order to develop the 3D Spatial Audio scenarios for demonstration, RNI compiled a list of required and available materials properties from a number of online resources to estimate the parameters needed for the boundary materials in the simulation (Watson 1927, Foster 1991). These parameters are summarized in Figure 6.

Table 2 summarizes the values used in the simulation where R is reflection and T is transmission data. The framework was defined primarily to illustrate what is needed to accurately determine the correct sound field for a true 3D spatial audio implementation.

Where frequency, reradiating pattern, and time characteristics were also not available in the literature the filter and angle variance metadata were set to defaults (no impact).

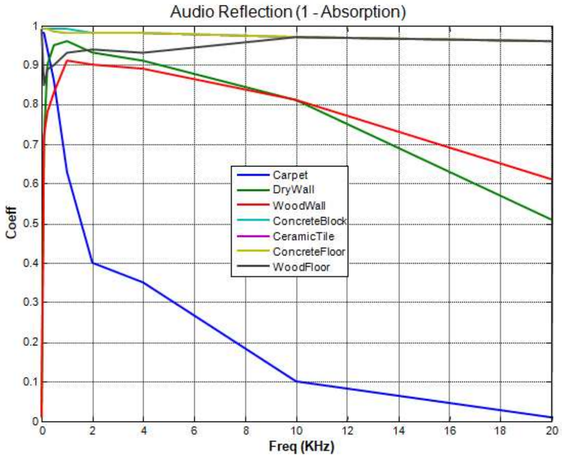

Figure 6. Estimated Reflection Coefficients for Construction Materials

Table 2. 3D Audio Simulation Materials and Sound Source Properties

Material	**R (dB)**	**T (dB)**		**Available Source Sounds**	**Volume (dB)**
Floor Concrete	5	60		White Noise	60
Floor Dirt	35	140		60 Hz Hum	60
Floor Wood	20	30		Gun Shot	140
Floor Carpet	30	70		Hand Clap	70
Floor Metal	5	70		Human Dialog	60
Floor Ceramic Tile	5	60		Foot Steps	40
Wall Drywall	20	20			
Wall Concrete Block	5	60			
Wall Metal	5	20			
Wall Wood	10	20			
Sound Absorber	∞	∞			
Sound Reflector	0	∞			

Of course when better data are either measured or located, these coefficients can be replaced in the materials model incorporating the propagation framework developed for more realistic sound effects; including those at specific military training sites. All physical objects in the simulation were considered homogeneous of the dimension of their applications (walls, floors, ceilings, etc.).

PATH METADATA

In even the simplest environment sound can propagate over many paths between a source and a listener. In order to accumulate all the 3D sound data at any listener RNI implemented a suite of metadata on every propagation path that ultimately could reach the listener location. Each valid path was then sorted according to (a) resultant amplitude, (b) 3D angle to the listener, and resultant path length (delay) relative to the direct path (if one existed). Since the sound sources were modeled as "omni directional" all paths were initially "shot" between the source and the listener.[2] As each ray reached a boundary, a new set of rays were shot. This was repeated until either a measurable number of rays from the source reached the listener or either (a) the number of boundaries exceeds a maximum allowed value or the number of rays became prohibitive for real-time performance.

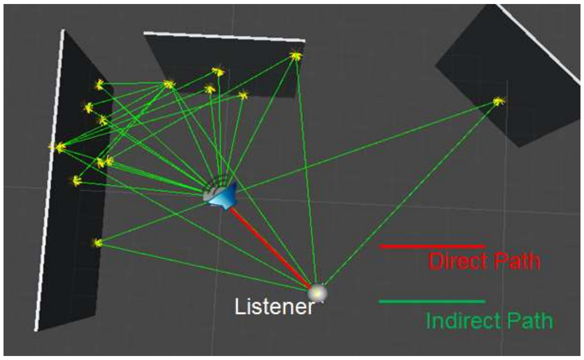

Figure 7. Propagation Paths From Source to Listener

The data accumulated for each path included the following information.

- *Source Type* – the ID of the source.
- *Source Volume* – the signal level at the source in dB.
- *Resultant Unit Vector to Listener* – the final path unit vector to the 3D spatial audio listener reference.
- *Path Length* – the total path length traveled (no material thickness included).
- *Materials List* – a list of materials hit during the path and associated material property for transmission or reflection along with other metadata and distance traveled inside the material.

In each frame, this list was then analyzed to present the proper sound transforms to the virtual mixer which was used to drive the appropriate 3D spatial audio speaker channels in the apparatus. When multiple sources were present, multiple virtual mixers were used to produce the combined sound with proper delays to the listener 3D spatial audio channels. Any paths which produced a resultant sound that was below a human ear audible threshold of 10 dB (Jones 2014) were discarded before summing in the mixer.

The resultant sound was then normalized based on the sum of the path results and multiple versions of it were played at incremental delays associated with the histogram of the path lengths relative to the shortest one. Due to the substantial number of resultant sounds and path transfer functions or $H_i(t,f)$ these delays were parsed in to 10 ms bins (equivalent to about 3.4 m of range difference). The starting sample for the sound was also delayed based on the path length of the shortest path (see Figure 8).

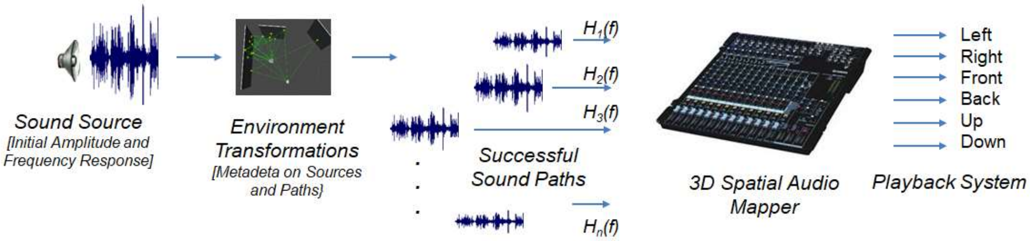

Figure 8. Reproduction of Sound Path Metadata into 3D Spatial Audio Mapper

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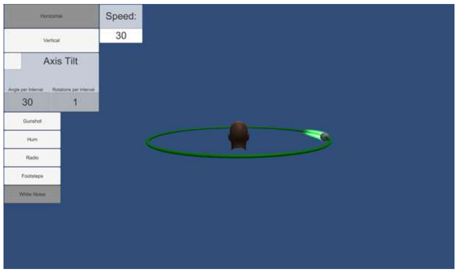
[2] For complex geometries these paths were further pruned according to number of bounces in order to allow real-time performance in Unity3D.

The 3D spatial audio mapper effectively mixed the composite sound results, scaled the composite audio data into the dynamic range of the output amplifier(s) and applied the appropriate channelization based the angle of arrival information provided by the component path metadata.

SCENARIO DEVELOPMENT

In order to perform demonstration of the 3D Spatial Audio model discussed three specific demonstration scenarios were developed as follows:

- *Calibration Demo:* To verify user can localize and set up volumes.



Speed: 30

Angle per Interval: 30

Rotations per Interval: 1

Figure 9. Calibration Demo

This scenario provides introduction to the different sound types and allows the user to get used to positioning his or her head in the 3D "cage". The sound sources used in the demonstrations have a large dynamic range related to the human ear so the user is encouraged to verify even the quietest sounds are still audible when setting overall volume levels of the system.

- *Single Room Demo:* To verify user familiarity with navigation controls and different sound types as they reflect off a basic suite of materials.

This scenario illustrates UI for changing materials in the room (walls, ceiling, and floor) and the impact each type has on audio. It also illustrates (using and editor) the ray tracing codes and the methods used to "cull" different sound reflections.

Figure 10. Single Room Demo

- *Three Story Building Demo:* To verify user can localize with navigation controls, pointing angles, and ability to discriminate multiple sound sources from different locations at once.

This scenario illustrates the impact of multiple materials inside a single multi-story environment on different source types. At the start, the listener is located on the second (middle) floor with the following sound objects either stationary or moving throughout the building:

- Footsteps on the floor above.
- Gunshots on the floor below.
- Talking behind a wall on the same floor.

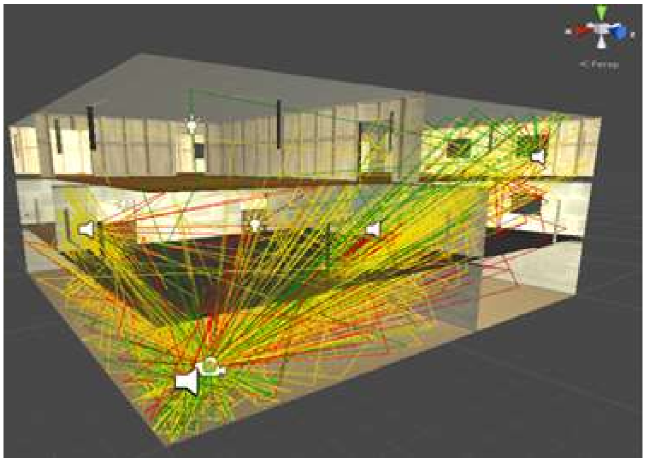


Figure 11. Three Story Building Demo

In all the scenarios, the user has the ability to select sound sources and set their initial volumes. Sound sources can also be set to trigger manually (by a key press) or play randomly with different delays. In the Single Room and Three Story Building scenarios, the user is free to move the listener (position and rotation) around the level along with configuring the sound sources to either be stationary or move randomly throughout all the navigable paths.

LIMITED EXPERIMENTATION

In order to perform limited verification of the 3D Spatial Audio demonstration system, personnel at RNI and the ARL compared the simulation results to some actual location results subjectively using human speech sound sources. One of the more interesting (and simple) experiments was a scenario where one person attempts to call out to another positioned in another room where there is an open door between the two. The walls were made of standard dry wall / wood stud / internal insulation construction found in many office buildings (see Figure 12).

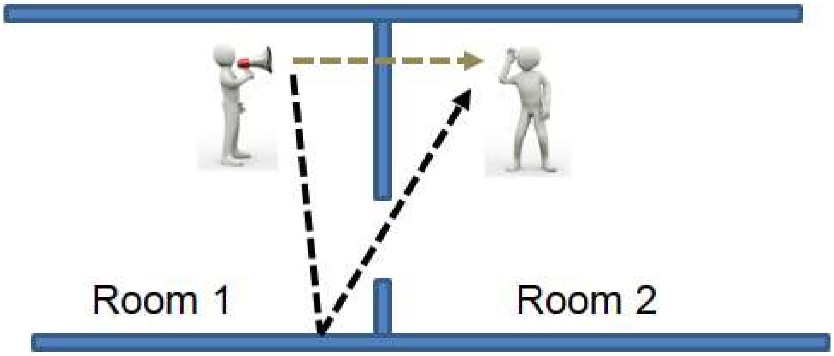


Figure 12. Example of Simple Experiment Geometry

When the speaker spoke, the listener (with eyes closed) perceived the sound – and thus the sound source location – as emanating in the direction of the doorway, and not directly in front. The 3D Spatial Audio system produced the same results illustrating the need and potential challenges associated with localizing sounds in complex environments when using virtual systems.

SUMMARY AND CONCLUSIONS

In this paper, we have focused on the information needed to accurately reproduce 3D spatial sound from hemispherical geometry which surrounds the human ears along with the development of a real-time simulation and playback system capable of producing and demonstrating the concepts. The authors recognize that many immersive training simulation systems often focus their resources on rendering, and sound is usually only reproduced using low-cost stereo headsets. But isn't true 3D sound part of immersion and realism? For augmented or mixed reality there can be both real and virtual entities emitting sounds, if the virtual entities do not sound like real entities it could lead to negative training for solders. The sources of key sounds (gun shots, footsteps, speech, etc.) are often used by our Soldiers to provide situational awareness inputs for the mission and decisions to take the next action to reach their goal.

Future activity related to 3D spatial audio should include accommodation of all the potential propagation mechanics for sound in a dismounted environment not simulated (refraction, diffraction, etc) along with developing a man-wearable device and framework to deliver accurate 3D spatial sound information (Saffold 2011). This activity should also include more experiments to quantify the effective benefits of 3D Spatial Audio to military training effectiveness and the impacts on trainee learning.

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