ISS Radiation Shielding and Acoustic Simulation Using an Immersive Environment

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Abstract

The International Space Station Environment Simulator (ISSES) is a virtual reality application that uses high-performance computing, graphics, and audio rendering to simulate the radiation and acoustic environments of the International Space Station (ISS). This CAVE application allows the user to maneuver to different locations inside or outside of the ISS and interactively compute and display the radiation dose at a point. The directional dose data is displayed as a color-mapped sphere that indicates the relative levels of radiation from all directions about the center of the sphere. The noise environment is rendered in real time over headphones or speakers and includes non-spatial background noise, such as air-handling equipment, and spatial sounds associated with specific equipment racks, such as compressors or fans. Changes can be made to equipment rack locations that produce changes in both the radiation shielding and system noise. The ISSES application allows for interactive investigation and collaborative trade studies between radiation shielding and noise for crew safety and comfort.

1. Introduction

Engineering problems are often complex and extend into multiple disciplines. The ability to adequately collaborate with every discipline involved is an essential component to the solution of such problems. Immersive virtual environments such as the Cave Automated Virtual Environment (CAVE) represent a relatively new technology that facilitates such collaboration [1].

Many of the early immersive applications, such as Crayoland [2] and CAVEQuake [3], were developed to learn about the interface and to demonstrate the capabilities of CAVE-like facilities. Other early applications, like Crumbs [4] and CAVE5D [5], took advantage of the 3D visualization capabilities of these facilities by allowing a user to visualize complex, 3D data sets, but few immersive applications attempt to solve real engineering problems. However, as researchers and engineers become aware of this technology they search for ways to utilize the new technologies to help solve current engineering problems. One engineering example is an application created by researchers at the Argonne National Laboratory that allows scientists and engineers to collaborate on design of injective emission control systems for commercial boilers. This immersive application allows scientists and engineers to more quickly interpret/evaluate numerical CFD data and to more efficiently optimize injector locations [6]. Another example is an application that facilitates the design of spherical spatial mechanisms that would otherwise be too complex to visualize and accomplish [7]. Other, more natural examples, where human factors play an important role, include architectural/plant layout and cockpit/cabin design of vehicles.

This paper presents the development of an interactive simulation and analysis environment that can be used to reduce high ionizing radiation and acoustic noise levels within the International Space Station (ISS). Motivation for this application stems from high projected ionizing radiation levels [8], the recent lowering of allowable radiation exposure limits [9,10], and high noise levels in the ISS, along with the difficulty in objectively assessing the coupled simulation and the need for better analysis tools. Design tools incorporated in the application allow the user to alter and intuitively experience the changes in both the radiation and acoustic environments. The objective of the application is to simulate the radiation and acoustic environments in the ISS so that scientists and engineers can perform trade studies between radiation shielding and interior noise.

There are two possible methods for minimizing radiation and noise levels: (1) the arrangement of discrete components and (2) the insertion of efficient radiation and acoustic absorbing materials. The first method can be accomplished in the ISS through the arrangement of standard, interchangeable, equipment racks located throughout the station. The functions of these racks are defined by their contents and range from storage and refrigeration units to electronic instrumentation and scientific experiments. Since their contents typically provide inherent radiation shielding properties and generate noise, rearranging the racks alters both the radiation and acoustic environments. The second method for minimizing radiation and acoustic levels in ISS can be achieved by analyzing the radiation and acoustic environments to determine locations to insert efficient radiation and acoustic absorbing materials. The subject application will facilitate and accelerate both methods. Note however that the insertion of sound absorbing material into the model in the second approach is not presently possible as the acoustic modeling is anechoic.

This paper describes the development of the ISS Environment Simulator (ISSES). The ISSES was developed for a CAVE-like immersive environment using OpenGL Performer for the graphics rendering the CAVELib/trackd for the interface to the CAVE hardware. A dedicated sound server was used for the acoustic rendering.

2. Radiation Analysis

Traditional radiation analysis uses Monte Carlo methods that rely on single particle wave functions to determine the interactions of each particle [11]. Basic radiation analyses using these methods can take hours or even weeks to complete. The more recent high charge/high energy transport (HZETRN) codes rely on solving equations of quantum mechanics [12]. The HZETRN code is algorithmically more complex than the traditional methods yet is more than 1000 times faster than the traditional codes and hence allows for rapid analysis. However, even with the HZETRN codes, comprehensive trade studies can still take weeks to complete because the analyses involve interpreting and comparing numerous graphs, charts, and two-dimensional figures. The present goal is to utilize the CAVE to enhance understanding and perception of the radiation environment so that these studies can be accomplished in days.

In our application, radiation analysis is performed using the ray tracing software RadICal [13] in conjunction with the HZETRN codes. RadICal calculates the locations of the intersections of a user-specified number of rays emanating from a target point with the shield geometry. These intersection points are then characterized by their location, direction of traversal, and the material type associated with the object. RadICal creates a file that contains the sequence and thickness of the materials that are encountered by radiation as it approaches the user-specified target point. This file provides inputs to the HZETRN codes. Using extensive databases that describe the external radiation environment, HZETRN calculates the radiation dose contributions along each ray and places those values in an output file. The current environment models for the HZETRN codes are an isotropic average of ionizing radiation over a typical low Earth (LEO) orbit and are therefore sufficient for longer-duration exposures (greater than one orbit, or 90 minutes). The environment models are in the process of being updated to include the inherent anisotropy so that they will accurately represent the surrounding radiation environment of the ISS at a particular place and time in the orbit.

Current design practice for spacecraft does not include radiation constraints, in part, due to the slow Monte Carlo analysis codes. Since these constraints are only taken into account in the later design stages, a less than optimum solution to radiation shielding problems such as the one that exists with the International Space Station often result. The faster HZETRN codes make it much easier to implement radiation constraints earlier in the design process and will help lead to optimum shielding design methods and lower design cost.

3. ISSES

The ISS Environment Simulator (ISSES) is an immersive application that allows the user to analyze, evaluate, and change the radiation and noise environments of the Habitation (HAB) module of the ISS. The application was developed to run in an immersive virtual environment such as the CAVE (Figure 1), but has also been successfully demonstrated on an ImmersaDesk. The application loads a radiation shield model of the entire ISS with interior detail only in the HAB module. Radiation and noise are of particular concern in the HAB module since the astronauts will sleep there. The interior details include the numbers and types of equipment racks, their radiation shielding, and localized noise properties. The application allows a user to navigate within the simulation, experience the noise in real time, alter the interior rack arrangement, run analyses of the radiation environment, and display the radiation environment in a variety of ways.

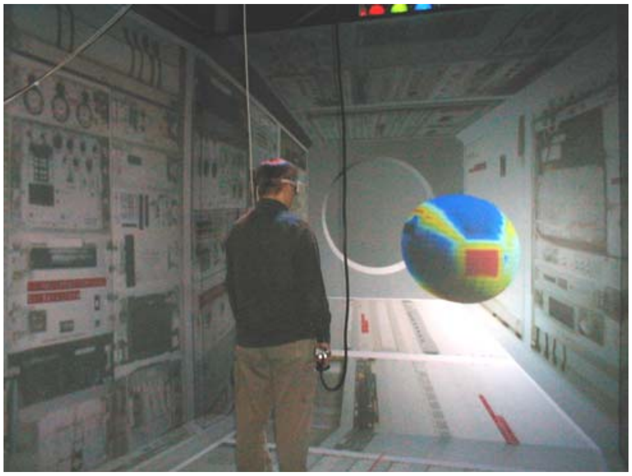

Figure 1. Interior of HAB module

The ISSES allows the user to modify the interior rack configuration using the navigation wand. At each rack location the user can cycle through a designated set of rack types by pressing a button on the wand while pointing at the desired rack. A ray cast from the tip of the wand is used as visual feedback to help the user point at a rack. The ray cast is also useful for pointing out features of the simulation to other viewers. While the user holds down the first button, the frame of a selected rack is highlighted using common intersection techniques. This highlighting enables the user to verify that the correct rack will be changed. Cycling through the various rack types is accomplished by releasing the first button. In the ISSES, the texture on the face of the rack is changed to reflect the new rack and if there is a noise associated with the rack, the noise is moved as well.

Once a desired arrangement of racks is set, the user can initiate the RadICal and HZETRN codes. These codes are used to calculate directional radiation dose contributions at any point in or around the ISS. The data from these calculations can then be displayed in two ways. The standard method is to calculate the directional dose for a single point and then display the results as a sphere centered at the desired location with a color map that represents the relative radiation intensities (Figure 2). The user starts the process by placing the end of the wand at the desired location and pressing the third button. Due to the relatively short amount of time it takes to run these codes for a single point, this process can be initiated within the application. This type of display is useful since the engineer can determine from which direction the higher levels of radiation are coming. Also, since the directional dose is viewed within the context of the ISS geometry, it is easy to determine the areas where additional shielding is required. For instance, the directional dose sphere in Figure 1 clearly shows gaps in the shielding between the racks on the left side of the module. By viewing this directional dose within the module, it is easy to see that these gaps correspond to the utility raceways between the racks. This tells the engineer that additional shielding may be required behind those raceways.

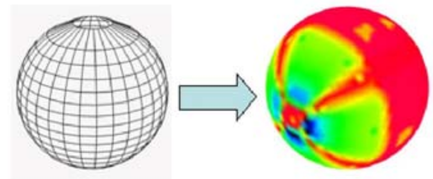

Figure 2. Directional Distribution Sphere

The other method of radiation display involves generating a scalar field of data points throughout the volume of the module that represents the total dose. The total dose is computed by summing the contributions from all the directions of the directional dose described previously. This field of scalar values must be generated ahead of time and is then visualized with a color-mapped cutting plane. This method is useful for showing the relative radiation levels and gradients throughout the module and is useful for determining general areas of the module to avoid for placement of radiation sensitive experiments, crew, or cargo.

ISSES was developed in C/C++ on an SGI Onyx2 (IR2 graphics, R1000 processors) using OpenGL Performer for graphics rendering and CAVELib/trackd [14] for interface with the CAVE. A custom, high-level API (Application Programming Interface) was developed to interface with the sound server and is described in section 5. The program structure is split into nine different modules. Each module contains functions that perform a specific task. For example, the scene module is responsible for loading in the initial geometry models and creating the Performer scenegraph while the sphere module is responsible for mapping the radiation directional dose data obtained from the radiation codes onto a sphere and loading it into the Performer scene. The behavior of the application is controlled by a set of configuration files that enable the user to customize the application within a certain degree. These configuration files, which will be described in the following sections, provide the application with some versatility.

4. Geometry

The ISS geometry provides the basis for both the visual environment and the radiation calculations in the ISS application. The ISSES loads geometry from both the

Alias/WaveFront "obj" and Inventor "iv" file formats. The "obj" file format was originally chosen because of the ability to translate to this format from virtually any 3D CAD package and because this format can be read by OpenGL Performer. Most of the ISS geometry is modeled with a relatively low level of detail (polygon count) in order to maintain short radiation computation times. A higher level of detail would significantly increase computation time while only minimally improving the radiation results [13]. The ISS geometry is then exported to the "obj" format. Some parts of the ISS geometry are translated into the Inventor file format so that certain visual properties of the geometry can be more easily altered.

A configuration file named *geometry.cfg* specifies the geometry files to be loaded into the initial Performer scenegraph. This file simply lists the geometry files to be loaded followed by a variable between zero and one that indicates the level of transparency to be applied to the geometry allowing the user to add semi-transparent geometry such as windows into the scene. The configuration file enables the user to run the application to analyze different ISS configurations and modules. Currently only the HAB module with the station in the 16A configuration (Figure 3) can be analyzed. However, this configuration file will allow for other configurations and modules to be used once these geometry models are obtained.

Figure 3. ISS Configuration 16A

To provide the user with a sense of direction, a model of the earth is inserted into the application. The model was created by mapping a texture of the earth onto a geodesic sphere in an Inventor file. A Rotor node is added to the file to give the earth a rotation. This model of the earth is not an accurate representation of the earth with respect to the ISS. The model was simply added to give the users a sense of direction with respect to the station.

The equipment racks are of particular interest due to their inherent radiation shielding and acoustic properties (Figure 4). The racks serve a wide variety of purposes on ISS. Some contain biology experiments or electronic equipment, while others serve as storage or refrigeration units. Since the racks are manufactured to a standard size, they are interchangeable within the module. Different rack arrangements lead to different acoustic and radiation environments within the module.

Fig. 4. ISS Equipment Rack

The characteristics of the equipment racks on the ISS are described using three configuration files. The first configuration file, named *rack_descriptions.cfg*, contains all the data associated with each of the rack locations. This file describes the locations and orientations of the racks at a specific location along with the geometry files to be loaded in that rack location along with the initial rack type. The second configuration file, named *rack_types.cfg*, defines the look and behavior of a specific type of rack. This file associates radiation material properties, a texture file, and possibly a sound with each rack type to an integer identifier. The radiation material properties are currently selected to illustrate the capabilities of the ISSES and are not based on actual values due to lack of data. Actual values may be substituted once they are obtained. A single texture in .rgb format is associated with a particular rack and mapped onto a rack face to provide a visual representation of the rack within the simulation. These textures are representative of what a typical rack may look like, but are not an exact representation of the complete set of racks onboard the ISS. Some of the textures used in ISSES came from high-resolution digital photographs of the actual ISS equipment racks while others came from digital photographs of equipment racks around NASA Langley Research Center. The third configuration file, named *cycletypes.cfg*, lists the total number and integer identifiers of the rack types the user can interactively change or cycle through in the application. This can be useful to limit the type and number of racks that can be moved within the ISSES application.

The crew cabins on the ISS are modeled in fixed locations in the HAB module and are of particular interest due to the significant amounts of time that astronauts spend in them. Because of this, there exists a high priority to minimize radiation and noise in these areas. The ability to rearrange the rack configuration allows the user to perform trade studies between radiation and noise levels within the crew quarters. For example, a user may instinctively place a heavy rack such as a refrigeration unit next to the crew quarters. This particular rack may provide the best radiation shielding, but may also generate enough noise to prevent an astronaut from sleeping. Representative human models are also included with some of the crew cabins. These models are used for both context and ray-traced radiation calculations, since the human body does absorb particles.

5. Acoustic Simulation

Most acoustic prediction methods and specifications are frequency-domain based. Acoustic pressure spectra are usually time-averaged quantities and are often summed into 1/3-octave bands or other single-valued metrics (e.g. overall sound pressure level). While several noise sources may meet a particular specification, one may be more disturbing than another. This is particularly true of transient sources such as pumps starting and stopping. The net effect is that it is not possible to use time-averaged frequency domain data to create the ISS sound environment. Instead, time domain data must be used to render the interior acoustic environment. The approach outlined below is suitable for use with either predicted or measured acoustic sources. The ISSES application at present utilizes measured quantities.

The interior acoustic environment is simulated using a specialized audio server, which obtains the location and orientation of the tracked user relative to the various noise sources to create the desired sound field. The location and orientation of the user (head tracking) and scene navigation data are obtained from the SGI client rendering the scene. Two different audio servers are presently supported – the AuSIM GoldServe [15] and the Lake Huron servers [16]. A configuration file named *audio.cfg* is used to allow the user to specify the desired audio rendering environment. The *audio.cfg* file contains all the necessary information for the particular server being used. As this file is loaded upon initialization of the application, the selection of audio server may be made without recompiling.

Binaural (perception of sound with both ears) simulation is considered the most accurate means of generating the three-dimensional sound field environment of the ISS. Either server platform may be utilized to generate a binaural audio stream for rendering over headphones. However, the BinScape simulation tool on the Huron server is limited to zero degree elevation, so its utility in the ISSES application is limited since acoustic sources are located arbitrarily in three-dimensional space within the HAB module. In order to get the most accurate binaural simulation, the GoldServe server is used in conjunction with wireless headphones. In situations where there may be a large number of participants, or when accurate rendering is less important, rendering over speakers may be desired. This mode is currently supported on the Huron server using the Space Array simulation tool. Of course, a sufficient number of speakers are required to generate the desired sound field.

Both audio servers perform real-time filtering to deliver glitch-free audio to the listener. In each case, the dynamic selection of filters is dependent upon the listener's location and orientation relative to the noise source(s). The update rate of the filters is dependent upon the tracker used by the SGI client, and upon how frequently the client passes this information to the audio server.

In order to make the selection of audio server hardware transparent to the client application, a high level 3D audio API was written to insulate the application from the details of the particular audio server in use. This API utilizes the CRE_TRON library for communication with the GoldServe server and the SNAP library for communication with the Huron server. Commands include main control functions for server initialization and termination, transport functions (play, stop, rewind), and positioning functions for the listener and sources.

Within the ISSES application, the acoustic simulation is presently limited to an anechoic environment. That is, the acoustic simulation does not account for the interior geometry of the HAB module, only the location of noise sources within it. Thus, consideration of acoustic treatments is presently not possible. An attempt was made, however, to create the sense of the reverberant interior space through several means. First, a recording of background noise from the MIR (Russian) space station was used to simulate the effect of a reverberant environment. The background noise was not spatialized. Thus, it sounded the same irrespective of the listener position. The direct versus indirect field was simulated by adjusting the level of the other sources relative to the background noise. In the case of the GoldServe server, sources were additionally given a frequency-independent directivity pattern, which reduced (but did not eliminate) the level inside and behind the instrumentation racks.

Note that the noise sources were assigned to locations at the front and center of each rack having acoustic attributes. In the absence of modeling of reflections, sources internal to the racks cannot presently be properly simulated. Lastly, all sources were programmed to cut off if the listener's location was outside the interior domain of the HAB module.

With the exception of the MIR background noise, all noises associated with the various racks were selected to be representative of sounds that one might encounter on the ISS, but the noises are not representative of any particular piece of equipment. Generic pump, fan, and compressor sounds were used because actual recordings of sources on the ISS were not available. When actual recordings and source radiation patterns become available in the future, they may be substituted for the generic sounds to lend better realism.

The result of the acoustic simulation modeling is that the user hears the various background and localized noises in the ISSES application in a manner similar to what might be heard in the actual HAB module. As the tracked user navigates the scene or moves within the CAVE, the audio is updated in real time so that localized noises emanating from specific sources sound as if they are coming from the correct direction. In the present hardware implementation, a single user is tracked. Thus, in the case of headphone rendering, there is a possible source of confusion for users who are not tracked, since the audio stream they are listening to is not based upon their position. This limitation is not inherent to the methodology, but is a reflection of the fact that there is a single tracked user in most CAVE-like environments. Tracking for additional listeners is straightforward and may be implemented in the future. Note that this limitation doesn't exist with the speaker rendering since the orientation of the tracked user's head doesn't affect the speaker outputs.

6. Comparison of Methods and Benefits

More traditional methods for designing efficient radiation and acceptable interior noise environments typically involve many uncertainties, take a long time to implement, and are understood by only a few. These traditional methods typically analyze a few points within a spacecraft for simplicity. For example, the results of the radiation calculations at these points are mapped onto directional distribution spheres similar to the ones used by the ISSES. The data mapped onto these spheres typically must be interpreted using a desktop computer screen, apart from the spacecraft geometry. It is difficult for anyone without a trained eye and familiarity with the ISS geometry to identify the geometrical features on these spheres without the context of the associated geometry. Even for someone with a trained eye it can take hours to interpret the results with any degree of certainty [17]. For example, the dose sphere in Figure 2 shows red areas between the green areas that relate to the utility raceways between the equipment racks. In the immersive environment, interpretation of the results is very easily accomplished by simply looking in the appropriate direction to determine the significant features. Without the proper context, uncertainties inevitably arise from such analyses. The ISSES provides a great opportunity for increased visualization and understanding of the radiation environment by allowing the user to experience changes as they are made in a life-size simulation and to interpret results in the context of the surrounding environment. Using the ISSES application, scientists and engineers can much more easily and accurately determine problems in the radiation shielding and interior noise.

Ionizing radiation shielding and interior noise design for spacecraft are inherently multi-disciplinary processes. Every component on a spacecraft, from food and water to electronic equipment racks, effects the radiation shielding. Radiation physicists must collaborate with every group involved with any part of the design process. In the past such collaboration has presented a tough challenge to this design process. Traditional methods require physicists and biologists to analyze tables of numbers to determine whether or not a specific design provides adequate shielding. In the case of an insufficient shielding design, the scientists would need to convince engineers to redesign the shielding in order to satisfy tougher radiation constraints. This process can be time consuming and inefficient. The need for a virtual design laboratory to facilitate collaboration between the many disciplines has been recognized by radiation physicists [11]. The ISSES provides the framework for this collaboration -- allowing scientists from all of the disciplines involved to interact and collaborate with each other to develop optimum shielding and noise environments. The ISSES application was recently demonstrated to physicists and biologists in the field of radiation protection at a workshop in Washington, DC. For most of the attendees, this was the first time they had been exposed to this type of analysis and design environment. Attendees in general found that it was easy to quickly evaluate and explore the ISS radiation and acoustic environments using the ISSES.

7. Discussion

The ISSES is still early in its development. More accurate data needs to be obtained before scientists and engineers can perform meaningful trade studies using the ISSES to reduce radiation and acoustic levels on the ISS.

A more complete set of textures for the equipment racks needs to be created to increase the accuracy of the visual environment. More importantly, accurate details about the shielding provided by the individual racks as well as the noise these racks generate needs to be determined. Without these details, the simulation only illustrates the potential for relevant results.

Several enhancements may be incorporated into the current application that would increase both its usability and versatility. One enhancement currently being integrated into the application is the interior modeling of other modules of the ISS such as the LAB module. Expanding interior modeling to other modules will allow for the use of the ISSES for the current ISS configuration instead of the final configuration. Another may include a more accurate simulation of the radiation environment of the ISS by incorporating time-dependence. Currently, the radiation environment used for the calculations is an isotropic average over a typical orbit. The radiation environment changes dramatically over the span of an orbit and that the radiation environment is not isotropic. One goal then is to include a time dependent model of the radiation that would also include directionality. By incorporating these enhancements, a more accurate simulation of the radiation environment surrounding the ISS can be modeled and used to increase the radiation and acoustic protection of astronauts. In terms of the user interface, volumetric visualization will be added in order to more easily assess the gradients of the radiation field, and voice control will be added to increase the flexibility for command and control of the application.

8. Concluding Remarks

In this paper, an immersive environment application that provides the framework for scientists and engineers to perform trade studies involving ionizing radiation shielding and interior noise is described. Using the ISSES application, several scientists and engineers can now step into a CAVE environment and collaborate with each other to develop a rack configuration that combines a maximum amount of radiation shielding while maintaining acceptable noise levels around targeted areas such as the crew quarters. The interactive environment, coupled with the radiation visualization techniques discussed in section 3 and the binaural sound rendering discussed in section 5, allows engineers to quickly and effectively determine areas that need improved radiation shielding and/or reduced noise levels.

Traditional methods of radiation shielding and acoustic design involve analysis of numbers and graphs as opposed to the 3D immersion technology employed by the ISS Environment Simulator application. By using the 3D immersion technology, even scientists and engineers with little or no background in radiation or acoustics, can analyze the data and perform rapid trade studies. By incorporating modern computer and immersion technology, the ISS Environment Simulator application allows scientists and engineers to analyze the ISS in a way that has never been possible before.

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