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INTERFACING WITH BUILDING DATA: TOWARD AN INTEGRATED MOBILE AUGMENTED ENVIRONMENT

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ABSTRACT

Communications between buildings and their occupants through multimodal Human Computer Interactions (HCI) can dramatically enhance the way buildings are experienced. Although building performance data is becoming more readily available, no research has been established to enable visualization of and interaction with this information in a robust way. This paper will present a method that will allow users to visualize and interact with building performance data in real space. It extends our research efforts to enable users to visualize such data for multiroom settings by developing methods to enable such environments to become mobile and being able to communicate with readily available building data.

INTRODUCTION

Mobile Augmented Reality (AR) visualization for multiroom settings is a challenge. Selection of appropriate motion tracker sensor technology is critical for multiroom settings as the user is in constant motion between rooms, permitting the emergence of registration errors at every entry to a new room. Maintaining immersiveness continuously is vital for a successful immersive visualization experience. Immersive building simulation can be utilized to visualize and manipulate indoor building performance data such as Computational Fluid Dynamics (CFD) datasets, in actual space and in real time (Malkawi, 2004). Many research efforts and technologies have already been established and have laid the groundwork for such a goal. These include research in the areas of sensors and controllers for sensing the built environments such as structural health monitoring (Johnson et al., 2003), sensor monitoring for thermal control (Riederer et al., 2002), building simulation to predict building behavior such as natural ventilation design (Carrilho-da-Graca et al., 2002), smoke and fire prediction in buildings (Lo et al., 2002), etc.. They have also been used for scientific data visualization of massive numerical representations using Virtual Environments (VE); examples include immersive visualization of CFD data (Teylingen et al., 1997; Shahnawaz et al., 1999) and use of HCI to design, evaluate, and implement interactive computing systems for immersive CFD data visualization (Wasfy and Noor, 2003; Malkawi and Srinivasan, 2005).

However, visualizing the CFD data in multiroom settings involves the coordination of a number of issues related to AR technology, such as registration errors, motion tracker technology, visualization technique, etc. An effective AR visualization for multiroom settings requires cautious removal of errors through selection of appropriate technologies and techniques to alleviate registration problems. In this regard, it is essential to recognize the research efforts to resolve these issues and to select appropriate technologies to alleviate issues surrounding augmented environments.

The human eye easily detects registration errors, and this poses a great challenge in creating seamless visualization. Registration errors range from 0.1 - 1.8mm for position and 0.05 - 0.5deg for orientation. Registration errors are due to tracker sensors, display technology utilized, and tracker mis-alignment. Tracker errors arise from inaccurate overlaying of virtual objects on the real pose of the tracker. Using calibration techniques, such errors can be reduced as in see through Head Mounted Device (HMD) (Azuma and Bishop, 1994; Genc et al., 2002) and video-based HMD (Bajura and Neumann, 1995). Display calibration errors arise from optical properties of the display such as field-of-view, optical distortion, etc. Since these are inherent properties of the display, it is sufficient to calibrate once. Tracker alignment errors are due to misalignment of the tracker base and / or the sensor attached to the HMD, and these can be effectively removed by tracker alignment calibration (Balliot et al., 2003).

Selection of a suitable six Degrees of Freedom (DoF) motion tracker is essential for effective immersive visualization. Some of the present technologies available include mechanical, electromagnetic, ultrasonic, inertial, and optical technologies, each having its own advantages and limitations (Azuma, 1997). For example, electromagnetic sensors are prone to distortion due to metals present in the environment; ultrasonic sensors suffer from noise and temperature; inertial sensors drift with time and cannot determine position; and optical sensors suffer from distortion due to object blockage. Table 1 provides a comparison of different sensor types and their associated static accuracies as position and orientation errors.

Table 1 Motion tracker technologies and their accuracies (position and orientation).

SENSOR TYPE	DESCRIPTION	STATIC ACCURACY POSITION (RMS)	STATIC ACCURACY ORIENTATION (RMS)	VERIFIED RANGE
Magnetic	Flock of Birds (Ascension, 2004)	1.8mm	0.5deg	20.3 to 76.2 cm
Ultrasonic	IS-600 Mark 2 PLUS (InterSense, 2004)	1.5mm	0.05deg	Not specified
Inertial	MT9 (Xsens, 2004)	-	< 1deg	Not specified
Optical	Laser Bird (Ascension, 2004)	0.1mm	0.05deg	Static accuracy at 1m

The immersiveness of the AR system largely depends on the removal of latency so that the virtual objects do not "swim around" in the real world. Latency is the time difference between the sensor tracking the position and the posting of the respective image on the HMD. Human eyes are enormously fast and process the new views immediately while the computer must generate images with new sets of transformation matrices from the sensors. Algorithms can be employed to predict future viewpoints to remove hardware-related latency issues. One such algorithm is "Kalman filter" (Kalman, 1960) that implements a predictor-corrector type estimator. The Kalman filter alrogithm has been utilized for immersive AR environments and integrated with various tracker technologies., for example in linear accelerometers and angular gyroscopes (Chai et al., 2003); optical HiBall trackers (Welch et al., 2001); and magnetic motion trackers (Malkawi and Srinivasan, 2005).

Although building performance data is becoming more readily available, no research has been established to enable the visualization of and interaction with this information in a robust way for multiroom settings. Presently, such enviroments are built for single-room settings that involve "hard-coded" spatial configurations and associated building-related data. Any change in the spatial configuration requires appropriate modifications to the code besides necessary calibrations pertaining to the new situation, thereby rendering these systems immobile. This paper discusses a method that will allow users to visualize building performance data for multiroom settings by developing integrated architecture to enable such environment to become mobile and being able to communicate with readily available building data. In addition, the paper presents a new application of the visualization technique, "isovolume," that enables effective visualization of volumetric building data while being immersed in the augmented environment.

INTEGRATED MOBILE AUGMENTED REALITY ARCHITECTURE

Augmented visualization for multiroom settings requires easy exchange of room geometry to the AR environment and rapid system calibration. The integrated mobile AR architecture presented here relates to the utilization of a magnetic tracker system for motion tracking and a wireless see-through HMD. The aim of this new architecture is to enable rapid setup of the AR system to new room settings. For this purpose, the integrated mobile augmented reality architecture consists of three components: data integration using Industry Foundation Classes (IFC), on-the-fly calibration, and a mobile AR environment.

Data Integration using IFCs

Mobile AR systems demand effective data sharing between the physical room and the augmented environment. Regardless of different Computer Aided Design (CAD) packages utilized to develop the room model, the spatial data needs to be channeled to the AR software environment without interruption. This calls for "interoperability" between various software programs through data protocol and attribute specifications that support efficient building information exchange. International Alliance of Interoperability's (IAI) Industry Foundation Classes provide a fundamental framework and specifications for such a common data model (Bazjanac and Crawley, 1999; IAI, 2004).

For this multiroom setup, the object-oriented IFCs enable the mapping of relevant data within each CAD program to a generic common data model that is easily accessible by the AR software. As the user navigates adjacent rooms, the AR software captures related room specifications and other essential data. While room specifications are utilized to generate wire-frame representation of the room for calibration and registration purposes, the room-related data (eg. temperature-velocity sensor locations) are plotted as colored virtual objects inside the 3D augmented environment for study purposes. In addition, relayed building data can be either "static" or "dynamic" as it relates to time. Static data refers to inert statistics that do not change with respect to time (room geometry, location of doors, windows, etc.). On the other hand, dynamic data refers to change in building information due to any operational building system changes (the opening of doors and windows, etc.). In this project, the transfer of the CAD model for multiroom settings utilizes static descriptions of the building data for mobile AR visualization.

On-the-fly Calibration

On-the-fly calibration is vital for accurate immersive visualization. Once the wire-frame CAD model of room geometry is imported into the AR environment, appropriate calibration needs to be performed. Existing calibration techniques are elaborate and time-consuming owing to multiple data sampling and related markers. These techniques require greater understanding of the HMD optics and tracker transformation properties, thereby permitting the utilization of these calibration techniques only to researchers rather than regular users such as architects, designers, and engineers. On-the-fly calibration methods provide a simple and effective way of calibrating the HMD such that the virtual objects accurately overlay in the real world.

Virtual objects overlaid in the real world are two-dimensional "rendered" objects, unlike objects in the real world. Due to reduction in dimensionality, the overlaying of these objects in the real world requires translation and scaling transformations in two dimensions only, i.e. *x* and *y* directions. Consider a virtual line (*ab*) displayed in the HMD visor that corresponds to the left-hand side vertical corner of the room settings (*a'b'*), figure 1.

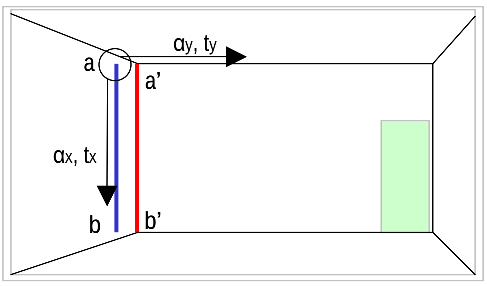

Figure 1 Virtual line and real world system – translation and scaling transformations.

Let the start point of the virtual line be P_{ab} (x_{ab}, y_{ab}) and the real world corner be $P_{a'b'}$ ($x_{a'b'}$, $y_{a',b'}$). If α_x and α_y are the scaling parameters; t_x and t_y, the translation parameters along *x* and *y* directions, then the translation and scaling transformations can be given as,

$$x_{ab} = \alpha_u x_{a'b'} + t_x$$
$$y_{ab} = \alpha_v y_{a'b'} + t_y$$

The corresponding matrix transformations are,

$$P_{ab} = \begin{pmatrix} x_{ab} \\ y_{ab} \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha_u & 0 & t_x \\ 0 & \alpha_v & t_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_{a'b'} \\ y_{a'b'} \\ 1 \end{pmatrix} = \kappa . P_{a'b'}$$

On-the-fly calibration Graphics User Interface (GUI) aids in modifying these transformations such that the virtual object superimposes precisely in the real world eliminating registration errors, figure 2. The user can access the calibration GUI while being immersed in the virtual environment. Although in certain situations a few calibration inaccuracies arise, this technique has major advantage due to significant time reduction in calibrating the AR system to new room settings.

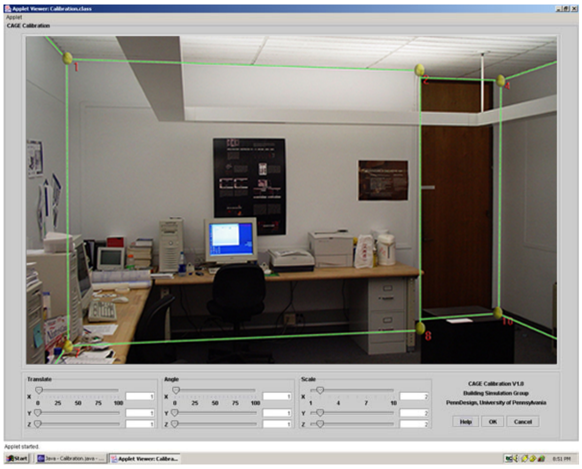

Figure 2 On-the-fly Calibration.

Mobile Augmented Reality Environment

The mobile AR environment enables interactive, immersive visualization of indoor thermal datasets for multiroom settings. Mobile AR visualization calls for careful AR hardware preparation to enable seamless immersive visualization. Consider a three-room experimental layout for mobile AR visualization, figure 3. Basic AR hardware preparation for this layout consists of appropriately affixing motion trackers to room ceiling based on tracker coverage and attaching wireless motion sensors to the HMD and hand-glove for tracking the movement of head and hand position-orientation, respectively. For multiroom settings, such optical overhead trackers along with wireless motion sensors are advantageous for three major reasons: optical trackers enable wide-area motion tracking; they acquire highly accurate 6DoF data; and lastly, since different room configurations are documented earlier, these trackers can be appropriately fastened to the ceiling board so as to avoid distortion due to object blockage to provide incessant motion tracking.

The intersection of areas of influence of trackers located in adjacent rooms allows the emergence of registration issues. Through on-the-fly calibration technique, such errors can be resolved rapidly.

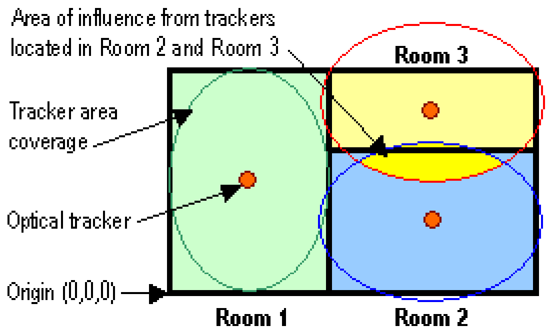

Figure 3 A sample three-room AR hardware preparation – plan view.

As the user steers across different rooms, the motion sensors track the 6DoF data of head and hand. While the head motion data is used for generating virtual objects for overlaying onto the real world, the hand motion data is employed for data interaction. With one global coordinate system, the entire setup can be considered as one large space. For example, the southwest corner of room 1 is the reference global origin (0,0,0). Through appropriate adjustments, trackers in rooms 2 and 3 can be fine tuned to relay with the same global origin. This enables continuous motion tracking for multiroom settings. As the motion sensors track the user in real time, the associated room data is transferred to the AR environment through data integration using IFCs. This allows generation of a suitable 3D wire-frame model of the room. With necessary calibration, the virtual wire-frame model is accurately superimposed onto the real world for immersive AR visualization. This efficient transfer and processing of data is made possible by a CFD analysis routine that generates thermal datasets based on new room boundary conditions and wireless AR visualization routine.

CFD analysis routine

CFD simulation tools facilitate prediction of thermal-ventilation performance data based on room geometry and boundary conditions. In this routine, the room geometry is discretized to uniform, finite mesh for analysis. With necessary boundary conditions assigned to this mesh, CFD analysis is executed. Gambit 2.0.6 (Fluent, 2004) is used for geometry modeling and mesh generation, followed by Fluent 6.02 (Fluent, 2004) to perform the simulation. Following convergence, the resultant post-processed simulation datasets are stored as "voxels" for discrete volumetric representation and visualization in 3D space. Preserving the datasets as voxels provides better accessibility to interact and manipulate 3D data in real time.

AR visualization routine

AR visualization routine assists in immersive visualization of post-processed CFD datasets with the aid of wireless see-through HMD and magnetic motion trackers. In this routine, 6DoF magnetic motion trackers known as "Flock of Birds" (Ascension, 2004) track the head movement in real time. Owing to distortion due to the presence of metal in the surroundings and to resolve latency, the raw tracker data is passed through Gaussian and Kalman filters. While the Gaussian filter smoothens the data to eliminate the jittering effect, Kalman filter predicts the future head position-orientation estimates. Necessary transformations to the virtual objects are performed using the filtered 6DoF data. These transformed objects are then superimposed in the real world by means of a wireless catadioptric HMD (Nvision, 2004). Due to the time-delay in CFD simulations, post-processed CFD data is employed in the visualization process. Real-time interaction with CFD datasets using speech / gesture modalities enable effective immersive visualization. In addition, the integration of Kalman filter removes the latency in head tracking (Malkawi and Srinivasan, 2005).

VOLUME VISUALIZATION

The distinct benefit of an AR system over a two - dimensional viewing surface is its ability to offer a fully immersive three-dimensional experience. Current CFD visualization techniques such as isosurfaces, isoplanes, and particle flow visualizations, are effectively realized using 2D planar displays. Although these methods effectively convey information on a screen, there is no advantage to their migration to a three-dimensional environment. Moreover, some of these techniques may not sufficiently represent the essential information in an immersive environment as they tend to "block" the flow of data or become "obstructed" by the users themselves. For example, consider two adjacent layers represented as blocks of cubes, rendered in blue and red colors, that represent temperature variations inside a room, figure 4. An user in an immersive environment will not be able to comprehend temperature data beyond the first layer as it obstructs further view. This is due to the opaqueness of virtual objects created. By dynamically varying the transparency attributes to the virtual objects, the view obstruction can be eliminated, figure 5.

Such shortcomings to existing visualization techniques for immersive environments have forced the development of new immersive visualization procedures. This is true for immersive CFD data visualization as the user experiences the volumetric data in an "immersive" manner, allowing data to be explored spatially rather than just observed on a computer screen.

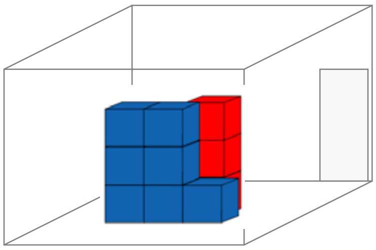

Figure 4 View obstruction during immersion.

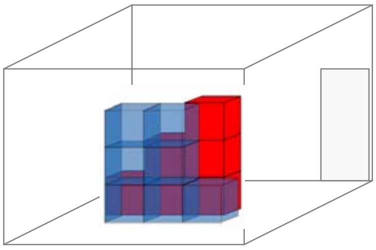

Figure 5 Dynamically varying transparency to eliminate of view obstruction.

Volume visualization of CFD datasets is characterized by multidimensional arrays of post-processed data. These datasets are defined on a uniformly sampled three-dimensional grid corresponding to the volume of the room. Nodes exist at the center of each grid unit and hold the simulated numerical values for environmental variables such as temperature, pressure, velocity, and humidity for that location within the room. Based on the data type, volume visualization can be either scalar or vector. While scalar visualization consists of single values for each point (eg. temperature), vector visualization comprises of both magnitude and direction for each point in space (eg. velocity magnitude and direction).

In this project, a visualization technique, the “isovolume,” was added as an integral part of volumetric visualization of CFD datasets for effective comprehension of volumetric data in an immersive environment. Isovolume refers to the collective volume generated by the user-defined upper and lower limits of any scalar volume data under investigation (Bailey, 1999). For example, a temperature isovolume displays the volume that ranges within the temperature limits defined by the user. The advantages of such visualization is the presentation of information at its actual location, offering an immediate understanding of thermodynamic spatial relationships in a room and the ability to explore this information through physical immersion. The following study represents the gradual increase in the upper limit of the temperature isovolume by 0.2deg from a lower limit 22deg. The room used for this study is a rectangular room with dimensions 23.5ft (length) x 15.75ft (width) x 12.00ft (height), figure 8. For simulation purposes, the room has been discretized into 1232 smaller grids.

The temperature isovolume connects all 3D grids that refer to the user-defined temperature value, creating a volume representing the temperature range specified. As the upper limit of the temperature isovolume is incrementally increased, the isovolume tends to grow from the inlet supply air duct, thereby occupying more space within the room, figures 6-9. When viewed in actual space with the aid of a see-through HMD, the isovolume provides more information for the designer / engineer to make elaborate and critical decisions. The user can gain a complete understanding of the data displayed by actually walking around, through, and “inside” the space under investigation. During this exploration, the three-dimensional quality of the isovolume is not lost, nor is any dimensionality reduction necessary to view the information.

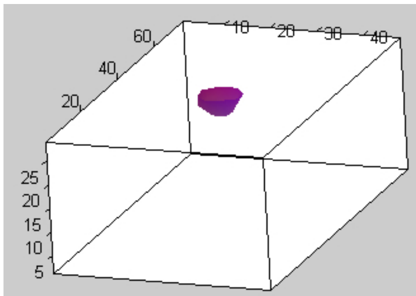

Figure 6 Isovolume – limits: 22.0deg to 22.2deg.

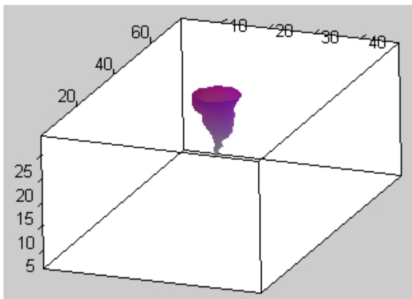

Figure 7 Isovolume – limits: 22.0deg to 22.4deg

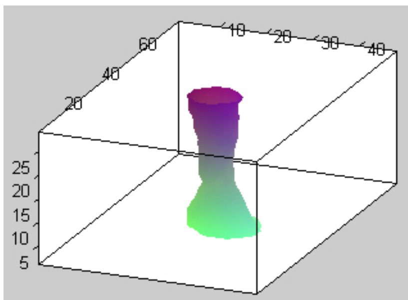

Figure 8 Isovolume – limits: 22.0deg to 22.6deg

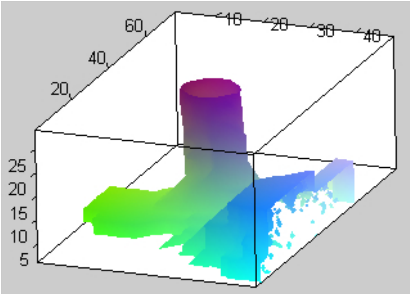

Figure 9 Isovolume – limits: 22.0deg to 22.8deg

CONCLUSION

This paper discussed a method that allowed users to visualize and interact with buiding performance data in real space for multiroom settings. As the integrated mobile AR system demonstrated an effective on-the-fly calibration technique for removing registration errors, it illustrated a new application of the visualization technique, "isovolume," as an integral part of volumetric visualization of CFD datasets.

Although the present study demonstrates the data communication through IFC model by utilizing static descriptions of the building-related data, operational system changes could not be transferred in real time within the present system. Future work will focus on extending the IFC model to offer some mechanisms to capture dynamic operational system changes for mobile AR environments in real time.

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