Using Immersive Computing Environments in Environments Research

He will require to grow accustomed to the sight of the upper world. And first he will see the shadows best, next the reflections of men and other objects in the water, and then the objects themselves; then he will gaze upon the light of the moon and the stars and the spangled heaven; and he will see the sky and the stars by night better than the sun or the light of the sun by day.

- Socrates to Glaucon, from Plato's *Allegory of the Cave*, Bk. VII, *The Republic*

SHU-CHING CHEN
Florida International University

SCOTT GRAHAM
Florida International University

WINIFRED NEWMAN
Florida International University

SHAHIN VASSIGH
Florida International University

KEQI ZHANG
Florida International University

INTRODUCTION

The growing toll of extreme events and disasters poses increasing challenges to the scientific and technological community. People residing in coastal areas bear significant economic loss and continue to endure the devastating effect of hurricanes on their lives. Eighty-six hurricanes from 1960 to 2008 impacted United States shoreline counties, affecting over 50 million people. The economic impact of hurricanes in South Florida alone totaled $450 billion in damages in the 20th century.[1]

Currently at FIU there are a number of research efforts in disaster related areas. This research is the result of work by faculty associated with the International Hurricane Research Center (IHRC), Lehman Center for Transportation Research, Southeast Environmental Research Center (SERC), and our group, the Sustainable Building System Informatics Research Initiative (SBSI). Over the past few yeas this research increased significantly becoming an FIU strategic strength in research in disaster mitigation and resilient construction.

To further this university-wide agenda the SBSI group proposed designing an immersive, interactive 3D computing environment that would accelerate the scientific work underway in this area. We believe that leveraging the advantages of large-scale virtual environments helps researchers gain new perspectives and advance collaboration while serving a critical role in a disaster vulnerable location. This paper describes the proposed instrument. Building on the technology of current computer assisted virtual environments, or CAVE™s, we designed a new system that improves existing configurations by using marker-less tracking and high screen resolution while maintaining a seamless field-of-vision.

A computer augmented virtual environment, or CAVE™ is a multi-person, often multi-sided, high-resolution 3D environment that facilitates viewing virtual content in an immersive, interactive setting. Our proposed Image-Cave or I-CAVE™ facility provides researchers with large-field-of-view in an immersive virtual reality (VR) environment to display GPS-tagged virtual models of buildings and building environments through 2D data and 3D virtual models. These models hold information on building system types, locations, specifications and pertinent architectural information including space allocation and circulation distribution using information fusion or integration merging information from heterogeneous sources with differing conceptual, contextual and typographical representations. By creating software that supports information fusion the instrument enables production of three-dimensional views of detailed accounts of storm effect, visualization of building behavior in extreme conditions as well as modeling capabilities of people movement during extreme events and disasters.

This scientific visualization instrument allows researchers to integrate their disciplinary findings through virtual simulation, access real-time feedback modeling, and enhance their existing models with powerful computing capability. We also developed a monitoring process to identify potential problems among the many interacting hardware and software components so that we could address problems before they delayed instrument users.

RESEARCH ACTIVITIES

FIU recently acquired a Riegl terrestrial laser scanner, a Nikon photogrammetric camera, and two Trimble R8 GPS units. This high-tech equipment revolutionizes the study of built environments by allowing prompt collection of geo-referenced, highly accurate 3D measurements for the interior, exterior and site of a building. The scanner derives 70,000 measurements per second with an accuracy of less than 1 cm and covers a circular area with a radius of 1,400 m. The point cloud measurements from the laser scanner provide the geometric data for developing virtual building models, while the digital images from the camera provide the texture data.

The integration of the real time GPS measurements with laser scanning measurements and digital images in 3D representations allows for an accurate understanding of buildings and surrounding objects (Figures 1 and 2). Further integration of data acquired with the existing equipment into a 3D VR environment allows expansion of researchers' work in data generation, calibration and validation of current and future spatial models developed by FIU computer scientists and engineers. The following is a brief description of research activities enabled by the instrument:

Research Area 1: Accurate high-resolution geometric and texture data for buildings are essential for developing virtual models for disaster mitigation and resilient construction. Using FIU as the test-bed we utilize the laser scanner to create geo-coded virtual models of buildings and their surroundings. The terrestrial laser scanning measurements provide us with unprecedented details of the geometric shape of a building. The voluminous 3D points raise challenges for analyzing and visualizing the data and extracting useful spatial features.

It is not uncommon that tens of millions of point measurements are collected using the laser scanner for a single building.[2] A typical personal computer workstation often cannot process and visualize the point cloud because of

limited memory and a bottleneck in I/O. Our I-CAVE™ software provides the computational and visualization power to analyze voluminous 3D point clouds, and extract the building geometric information from laser measurements.

Research Area 2: Disaster and extreme events change once familiar built environments into unfamiliar and foreign landscapes. Emergency response and strategic planning for short and long-term relief and tactical access of emergency responders depends on 1) how they perceive the changed environment or a disaster site, 2) how well they can adapt their reaction plan based on the existing site conditions, and 3) how quickly they can access critical building systems to gain control of buildings or facilities.

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Figure 1: Image of multi-dimensional scan-map made using the Riegel terrestrial laser scanner and Trimble GPS unit with multiple point clouds. The map encompasses approximately 81 square meter area on the FIU campus. *Map courtesy of the FIU GIS department made for a separate study with Dr. Newman.*

Multi-layered virtual maps that include detailed building information help responders to develop rapid reaction plans. Using these maps they can visualize building conditions prior to the event, obtain information with respect to systems location and specifications and run on site simulations for proper response. In addition, visualizing the architecture, layout and building system location can play a critical role in both rescuing effort as well as resuming control over the building operations.

To achieve this we will utilize FIU's main campus as the test-bed for surveying and mapping buildings. This effort includes incorporating dynamic information from LIDAR, the Riegl terrestrial laser scanner, the Trimble R8 GPS unit, miniature UAVs, and remote sensing. The increased computational capacity and visualization power of the I-CAVE™ enables the team to use large quantities of data for analyzing building geometric information for producing multi-dimensional maps.

Research Area 3: Television meteorologists use a color line buffer over a map or satellite image to issue and display hurricane warning and watch zones. This information, in combination with 2D evacuation maps, helps raise public awareness of evacuation orders, but does not provide coastal residents a detailed account

of the effects of storm surge. It often fails to persuade people to evacuate. Understanding factors that lead to under or over-evacuation as well as why people do not relate two-dimensional maps of evacuation zones to their personal experience is critical to improving the evacuation process.

The topographic elevation, buildings, and trees extracted from LiDAR (airborne light detection and ranging) data, Riegl terrestrial laser scanner, Trimble R8 GPS units, in combination with aerial and ground photographs and existing GIS data, allow us to build synthetic 3D visualization environments detailed to specific street addresses A real-time storm surge model offers us an "engine" to drive the 3D animation of storm surge flooding. Past work was supported by NOAA grants.

The I-CAVE™ will provide the computational and visualization power to enable research into rendering near-real-time 3D visualizations of storm surge data of exact locations of millions of coastal residents in the state of Florida, as a means to improve evacuation decisions (Figure 3).

Research Area 4: The study of structural behavior in hurricanes is an important component of disaster mitigation and ongoing research activities at FIU are contributing significantly to hurricane engineering. These activities focus on mitigating the massive losses due to hurricane-induced wind, wind-driven rain and creating resilient coastal communities. Arindam Chowdhury, Director of the Laboratory for Wind Engineering Research (LWER) at the International Hurricane Research Center (IHRC) at FIU pioneered the development of the "Wall of Wind" (WOW) facility. WOW is the only university research facility capable of simulating Category 5 hurricane winds. The WOW is capable of performing controlled and repeatable testing in flows that adequately and economically replicate hurricane winds accompanied by wind-driven rain.

The I-CAVE™ helps to advance this research by providing an intelligent synthetic virtual environment that can effectively communicate hurricane risk and efficacies of various mitigation strategies to a broad audience. It also further develops WOW research activities for enhancement of building codes and validating innovative mitigation technologies.

Figure 2: Detail of an image created using the Riegel terrestrial laser scanner and Trimble GPS with multiple cloud points.

(a) Ocean wave animation and (b) overland flooding animation.

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Figure 3: The animation component reproduces the storm-surge flooding processes in a synthetic 3D visualization environment. Data for storm-surge flooding came from numerical modeling based on hurricane track and intensity caused by hurricanes. High winds and heavy rain, often accompanying a hurricane, can also alter the environment significantly. To make the visualization of surge-flooding processing more closely representational of a natural situation we constructed six different animation engines to simulate water, wind, rain, and other phenomena caused by storms: (c) and (d) show flooding and traffic animation for the Rickenbacker Causeway during a hypothetical hurricane. The right panel shows a traffic blockage due to traffic blockage due to storm-surge flooding. From research conducted by Dr. Shu-Ching Chen at Florida International University using the GC3N software.

A number of research areas related to "Disaster Mitigation and Resilient Construction" facilitated by the proposed I-CAVE™ are described in the previous section. We propose that all programs in emergency management including research into the ways that the public and private sectors regulate, finance and build in system redundancy can be understood at a finer grain when modeled in a 3D environment that includes questions of context, human interaction, and physical perceptions.

DESCRIPTION OF THE I-CAVE™

The previous section outlines the robust research focus of our proposed CAVE used by researchers encompassing multiple disciplines. The following section presents the rationale for the proposed I-CAVE™, the design concept, and the technical development strategy.

In the past 20+ years, hundreds of CAVE™s have been built. The need for second- and now third- generation CAVE™s unmistakably demonstrates the value of augmented and immersive visualization of scientific data for research.[3] VR systems aim to deliver two key features: realism and real-time. In particular, the real time element is essential to provide an interactive experience to the user.[4] Current 3D interfaces use motion sensing, physical input, and spatial interaction techniques to control highly dynamic virtual content.[5] Low-cost solutions created by game developers (Nintendo Wii™, Sony Move™ and Microsoft Kinect™) are pushing researchers to meet high-end user expectations as immersive interaction becomes ubiquitous.[6] We anticipate using the I-CAVE™ for both Virtual Reality (VR) and Virtual Environment (VE) capability. Our goal is to be able to view scalable 3D data such as a virtual re-creation of a specific event while being able to actively manipulate the viewing environment using real-time dynamic geometric and physical modeling.

The need for an easy-to-use, accessible, and adaptable environment for interactive scientific visualization is demonstrated by our research examples. One of the key criteria for VR is the provision of an ''immersive'' display with significant tracked stereo visuals produced in real time at larger angle of view than forward-looking human eyes can see.[7] Head mounted displays are one way to provide immersion. The CAVE™, or room-sized projection-based surround virtual reality (VR) system is another. Variants of this kind of environment have been in development since at least 1991.[8]

We are designing several improvements. The key components of our I-CAVE™ are 1) spatial configurations that enhance the illusion of total immersion in real-time, 2) addressing the need for bright, high-contrast with fast image refresh rates of 30-60fps for reduced eye strain and enhanced 3D stereoscopic effects, and 3) a significant improvement in real-time motion tracking that minimizes or eliminates markers on the user to impact the ease of interaction with the 2D and 3D displays.
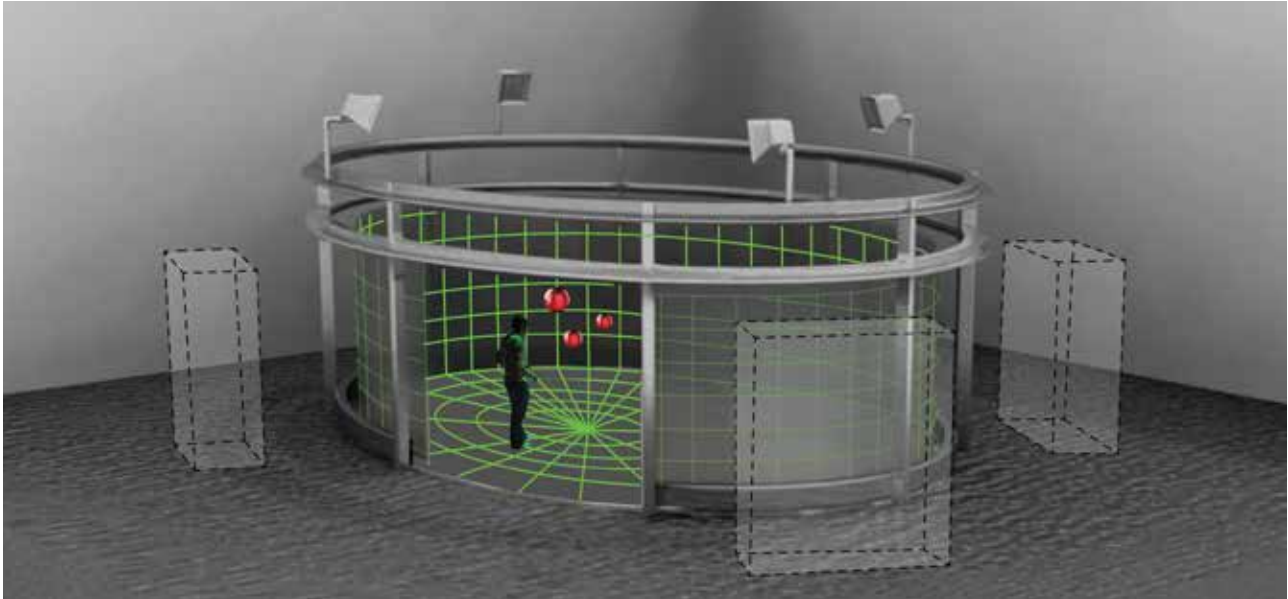
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The I-CAVE™ is a 16 feet by 10 feet ovoid with 10 feet high display screens. We designed a 5-sided room with 60 rear-projection DLP-chip 3D projectors. This gives us over 130M stereo pixels on a seam-less display topology. Motion tracking will be handled by marker-less motion capture (MoCap) using a four-camera set-up sourcing optical flow and surface contrast. Augmented with low-scale, off-the-shelf gesture recognition software, a tablet, and voice activated command capability. We use robust audio-surround sound to enhance sensory conditioning and sonic immersion. Device specifications and software development are given in the following sections.

The shape is ovoid with one half of the enclosure consisting of three curved panels and the other half comprised of one fixed panel and one sliding door-panel (Figures 4 and 5). A raised floor allows for rear-projection for the floor surface. Wall panel height is 10 feet of varying widths. This configuration was determined optimal because, 1) the curved display topology improves the VE immersive experience as it more closely mirrors our perceptual mode, 2) this configuration maximized the viewing environment for the size of the laboratory. High-speed tracking cameras are ceiling mounted with plans for future re-configuration if we are able to expand to a 6 sided environment. In order to reduce the throw-distance we are using mirrors to fold the focal length of the projectors. All projectors are rear- or under floor projection. Future additions include adding the ceiling plane, and re-configuring the tracking cameras.

The following section outlines the proposed display including projection, screen material, target brightness/contrast, resolution and tracking. Our goal is to provide at least the same 1080p resolution currently available in HDTV monitors. Projectors with DLP technology offer fast-image processing and high intra-image

Figure 4: Rendering of the I-CAVE™ showing the projector cabinets and mounted tracking cameras positioned above the space.

contrast ratio (this is the difference reference white level and reference black level found within the same image) needed to produce similar brightness levels. To get the full 3D effect projectors will be coupled with Volfoni crystal-shutter glasses synced to a 30-60fps output.

Projection: The display environment uses stereographic DLP projection technology using the new generation of projectors with full high-resolution WUXGA compatibility. With dual-head stereographic projection. These projectors combine signals from DVI1 and DVI2 (or HDMI1 and HDMI2), place them beside each other and interpret them as a single source. Active shutter glasses synchronized by an embedded light pulse in the projected image work with the DLP linked projector to create two images on the screen at one time to form the 3D image viewed through the active glasses. The refresh rate is 120 Hz (or 60 fps) per eye so that the image appears in 3D to the human eye. DLP linked projectors communicate with the glasses by sending additional data in-between each frame of video making data emitters obsolete and eliminating position emitters. The advanced synchronization reduces significantly the 'ghosting' effect of trace images commonly experienced in 3D vision.

Our display builds on and extends Calit2 StarCAVEs primary pentagonal cross-section and dual-polarized projectors. The LCoS LCD projectors used at Calit2 require a dual-polarized set-up where both the projector and the viewing glasses are polarized to enable stereoscopic viewing. This absorbs ≈90% of projector lumens, as you have to polarize both the projector and the user's glasses. DLP synced projectors eliminate the need for the additional polarization and improve image brightness levels. We also use over twice the number of projectors (60) to increase resolution and brightness/contrast ratios.

Screen: Our seam-less screen display topology is composed of 1.3mm thick large-scale acrylic composite sheets on a support structure (Figure 4). Based on our choice of projector the screen material selected is an optical grade cell-cast acrylic sheet with a flat, glossy surface. It is matte on both sides. It is a composite single element screen with a proprietary mix of particles suspended in an acrylic with grey die. Large sheets cut to shape can be bent for curved viewing surfaces with a native 16:10 aspect ratio allowing for great flexibility in environment configurations. Older CAVE™s tend to be cuboid and to some extent create an added hindrance to the 3D registration of the projected image. The low retardation makes this screen excellent for 3D polarization and the higher-than-glass 93% light transmission with no bi-refringence (or double refraction) is one of the best available for optical sensor applications. This material provides excellent acutance and black levels and allows us to get a smoothly curved display surface that eliminates the bezel problems of LCD arrays of LCD monitors. The continuous surface minimizes any visible seams and when combined with a readily available public software (Warpatizer and similar) render image distortion negligible.

Brightness and Contrast/Color Perception and Resolution: The target display resolution replicates high-resolution monitor rates of 1080p. The selected projectors provide up to 20,000:1 contrast ratios, with 16-microsecond pixel response time. Previous CAVE research indicates that sharper, brighter, high-contrast imagery allows for users to use significantly more of their perceptual abilities in addition to displaying larger scientific data sets. Bright, high-resolution, high-contrast visuals at ≈20/40 vision are excellent. Significant improvement (3:2) in visual performance was observed where there were small differences (2:3) in brightness/luminance contrast.[9] High-resolution display
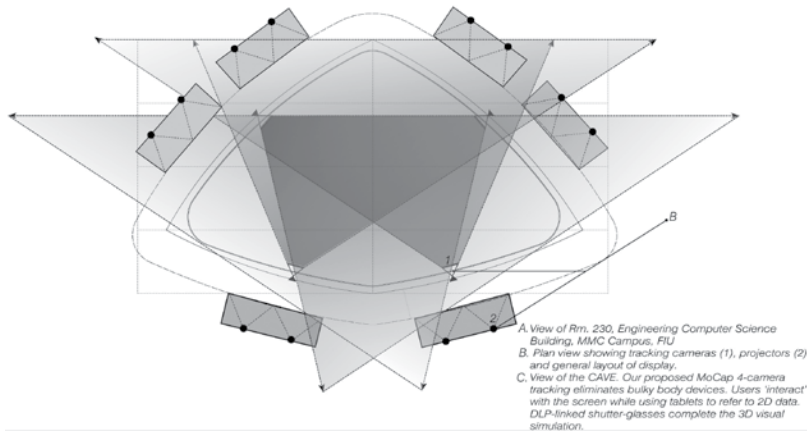
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benefits both 2D and 3D visualization tasks since more pixels are viewable at once making it possible to make distinctions between small-scale attributes and elements.[10] Researchers at Brown University's Center for Computation and Visualization (CCV) showed that in a text-intensive 3D system where pixel density was more critical than field of view or display size, the system with higher pixel density did not require zooming for text reading tasks.[11] They found that a high-resolution (40dpi) display that can display objects at a short viewing distance without blurring texture features gave the best performance. Our proposed CAVE™ tiles the display panels with up to 8 1080p tiles to replicate the density of viewing capacity of display monitors.

Tracking: In large-scale immersive virtual reality (VR) environments one of the most common problems is tracking the position of the user's head while he or she is immersed in this environment to reflect perspective changes in the synthetic stereoscopic images. Tracking technologies target the position and orientation in space either for the user's head, hand or body so that it can be used and re-produced in a virtual environment.

Motion tracking is a critical aspect of many virtual and augmented reality applications and there are a wide variety of different tracking technologies and approaches.[12] Tracking methods include infrared-optical, Radio-Frequency (RF) and haptic tracking systems. Alternate tracking methods with multi-person users include Ultra-Wideband radar (UWB). One approach that has gained in popularity in recent years is vision-based tracking. Traditional vision-based tracking requires markers as reference points or a pre-loaded model of the physical environment, but markers clutter the physical environment and pre-loaded models can be time-consuming to create. Our goal is to build on current 2 camera configurations by using 4 shutter-synchronized cameras attached with band-pass infrared filters and illuminated by infrared array-emitters. Cameras are inexpensive, have large range, and provide raw images that are rich in information. These systems show results of latency of 40 ms when simultaneously tracking the pose of two artifacts with 4 infrared markers, achieving a frame-rate of 24.80 fps.[13] Our target frame rate is between 30-60fps. Our tracking scheme is low cost, requires very little setup, obtains high accuracy and has large range span.

SOFTWARE

We are building on existing software and modifying it to fit the specific needs of our researchers and scientists. There are two types of software applications to consider: 1) a flexible 3D modeling engine that provides a scripting interface to

Figure 5: Plan of I-CAVE showing position of tracking cameras, projectors and general layout of display.

control the simulation behavior of the model and 2) an animation engine geo-referenced for precision modeling of scientific data in synthetic visualization environments. In addition, we need an easily available graphic library and a VR peripheral network to integrate interaction devices.

The two main components of our high-level software architecture are based on readily available engines. Users that cannot use commercial solutions like Avizo for 3D rendering will move to this next level of access that are our two high-level software: Virtual Reality Engine (VRE) and GC3N, both built by our team.

First, we develop our 3D VRE using readily available gaming software like Unity or similar as a framework We test different engines to balance various capabilities including platform independence and a well-documented library with reliable and easy-to-use development. One option is Unity 4 that supports the Windows DirectX 11 graphics API to bring higher visual fidelity and faster rendering times. The surface and object shading also add richer simulation capability. An alternative is VRG3D developed and used by the CCV at Brown University. Compared to VRG3D, most VR software has large libraries that require programmers to adapt to additional coding styles such as "context-specific variables." FreeVR, for instance, does not work with the standard Windows development tools so is not an adequate cross-platform solution and is not nimble enough for a demanding academic environment.

Our second proposed animation engine will offer users a higher degree of model accuracy using near-real-time animation of data. For this we will build on the work of Dr. Chen. His animation engine, GC3N integrates geo-coded data from various sources with rationalized 3D virtual models using a VTP to generate a 3D synthetic environment using C++ libraries and OpenGL APIs.[14] This gives scientists and researchers greater analytical flexibility with their data depending on the level of accuracy needed in a given application. GC3N has a user-friendly interface that lets users fly or walk around the 3D environment, zoom- in or -out of a scene, as well as select designated locations within the environment. This provides users with a nimble interface to navigate through a 3D synthetic environment.

The last two components of our software include a graphic library and a virtual reality peripheral network. We propose to use VPRN, a device-independent and network-transparent system for accessing virtual reality peripherals in VR applications. VRPN provides a unified interface to input devices, like motion trackers and controllers. The VRPN system consists of programming interfaces for both the client application and the hardware drives and a server application that communicates with the hardware devices. Second, G3D is a widely available and free graphic library for desktop graphic application development. G3D is a commercial-grade C++ 3D engine available as Open Source (BSD License). It makes low-level libraries like OpenGL and sockets easier to use without limiting functionality or performance. G3D is a rock-solid, highly optimized base on which to build a 3D application with multiple rendering modes, data import and export that works across platforms.

CONCLUSIONS: IMPACT ON COLLABORATIVE RESEARCH AND INSTITUTIONAL DEVELOPMENT

Computer augmented visualization instruments pose significant challenges to develop, maintain, monitor, and improve over the lifetime of their use by researchers from varied disciplines. In order to assure that the effort is a stable

ENDNOTES

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shared-use instrument we plan to place our instrument in the CS department centrally located on the Florida International University campus. The instrument we propose requires not only the services of multiple disciplines (Engineering, Architecture, and Computer Science, Earth and Environment Sciences) to develop and maintain, but our team works with individual researchers to develop software support and hardware as needed for particular experiments.

By providing scientific visualization of integrated, cutting-edge cybernetic information network arrays and massive amounts of key data otherwise difficult to access, our proposed I-CAVE™ will impact computer science and geo-spatial research in disaster management and mitigation nationwide. The research and technology developments made possible by this instrument will potentially transform the decision-making process in operations related to pre- and post-disaster management in building design technology, thus greatly benefiting broader society. The enabled research benefits applications in environmental monitoring, post-disaster cognitive-mapping and way finding, pre-disaster building and building site design, education, and public health and safety.

This project initiates a new way to support building design for disaster management, retrofitting, maintenance and planning. Most important, the project provides a research platform for architecture, engineering, and construction education. Students and faculty in computer science, architecture, and several engineering disciplines will use the I-CAVE™ to model, simulate and analyze the relationship between constraints, scenarios and performance. The work augments collaborations with students and researchers in related social sciences, especially economics, government and public policy, and students in health-related disciplines like occupational therapy, nursing and medicine.

The I-CAVE™ accelerates scientific work underway in the area of disaster rescue, recovery, and resilience by leveraging the fundamental advantages of an immersive, large-scale virtual environment to help researchers gain new perspectives and further their collaboration while serving a critical importance in a significantly disaster vulnerable region. The new mode of representation grounds our understanding of the built environment in disaster and post-disaster conditions leading to improved design and more navigable post-disaster built environments.

In order to address ongoing and increasingly massive disaster events in urban coastal areas, our SBSI group proposed the I-CAVE™ to support disaster and extreme event response research, but the potential uses for this flexible, interactive and dynamic environment are vast.[15] Our advances in marker-less tracking of movement and seamless display will contribute to the ongoing research in CAVE™ design, but more importantly, create a new environment for environmental research at our university.

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