A New Collaborative Infrastructure: SCAPE

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Abstract

This paper presents a multi-user collaborative infrastructure, SCAPE (an acronym for Stereoscopic Collaboration in Augmented and Projective Environments), which is based on recent advancement in head-mounted projective display (HMPD) technology. The SCAPE mainly consists of a 3'x5' interactive workbench and a 12'x12'x9' room-sized walk-through display environment, multiple head-tracked HMPDs, multi-modality interface devices, and a generic application-programming interface (API) designed to coordinate the components. The infrastructure provides a shared space in which multiple users can simultaneously interact with a 3D synthetic environment from their individual viewpoints. We detail the SCAPE implementation and include an application example that demonstrates major interface and cooperation features.

1. Introduction

There is great interest in tools and infrastructures that allow multiple users at a local site or remote sites to effectively perform collaborative tasks in intuitive manners. These exists a large body of research efforts in the area of computer-supported collaborative work (CSCW) as well as work in tele-collaboration infrastructures and applications to facilitate collaborative interfaces [4, 15, 17, 18, 24]. Hollan and Stornetta [11] suggest that successful collaborative interfaces should enable users to go "beyond being there" and enhance the collaborative experience, instead of imitating face-to-face collaboration. Recent efforts have been made to develop tools and infrastructures to support collaboration in 3D virtual or augmented environments [21, 23].

The subject of this paper is to present a new collaborative infrastructure, SCAPE (an acronym for Stereoscopic Collaboration in an Augmented and Projective Environment) (Fig. 1). SCAPE, which is based on the recent development in head-mounted projective display (HMPD) technology, mainly consists of a 3'x5' interactive workbench and a 12'x12'x9' room-sized walk-through display environments, multiple head-tracked HMPDs, multi-modality interface devices, and a generic application-programming interface (API) designed to coordinate the components. This infrastructure is capable of: (a) providing a shared space in which multiple users can concurrently observe and equally interact with a 3D synthetic environment from their individual viewpoints; (b) simultaneously creating an outside-in and inside-out views of a 3D dataset, through the workbench representation and through the immersive room, respectively; and (c) merging the paradigm of virtual reality with that of augmented reality in a single system.

In the rest of this paper, we will first briefly review recent advances in 3D collaborative interfaces and recent development in the HMPD technology in section 2, describe the conceptual design of the SCAPE and major design considerations and limitations in section 3, present a SCAPE implementation in section 4, and include an application example in section 5 to demonstrate the functionality and the framework of the SCAPE and user interface features.


(a) (b)

Fig.1 SCAPE: stereoscopic collaboration in an augmented projective environment: (a) Concept illustration; and (b) Simulation of outside-in bench view and inside-out walk-through view.

2. Related work

2.1. 3D collaborative infrastructures

There are several different approaches to facilitating three-dimensional collaborative work. This section will briefly review a few representative methods.

An attractive and yet expensive solution is to use projection-based spatially immersive displays such as CAVE-like systems [5, 6, 7, 23] or the responsive workbench [22], which allow a number of users to view stereoscopic images by wearing LCD-shutter glasses. In these projection-based displays, users can see each other and therefore communicate face-to-face. Unfortunately, the images can be rendered from only a single user's viewpoint, and therefore the stereo images are perspective-correct only for the tracked user. The other non-tracked users will notice both point-of-view distortion and motion distortion. This makes it impossible to provide users a single visually consistent environment.

Several efforts have been made to overcome this limitation. Agrawala [1] proposed the two-user responsive workbench that allows two people to simultaneously view individual stereoscopic image pairs from their own viewpoints by using four different frame buffers. Two pairs of stereoscopic images are rendered sequentially at ¼ the display frame rate. The system cuts the display frame rate in half for each user compared to the single viewer approach, which leads to noticeable flicker (e.g. 30Hz for each eye with ordinary display hardware having 120Hz maximum frame rate) and cross talk. Therefore, using this technique, the number of users is limited to 2 for acceptable quality. Kitamura [21] proposed an alternative solution, namely IllusionHole, which allows three or more people to simultaneously observe individual image pairs from independent viewpoints without the sacrifice of frame rate. The IllusionHole display consists of a normal bench display and a display mask, which makes each user's drawing areas invisible to others. However, the maximum number of users is limited, each user has a limited movement space, and the viewing area for each user is small.

A recent creative effort toward telecollaborative infrastructure is the work on "The office of the future" [26], led by Henry Fuchs and his colleagues at UNC-Chapel Hill. Their idea is to turn a common office environment into a spatially immersive display environment, or to make a virtual adjoining office of multiple remote offices. The basic idea is to use real-time computer vision techniques to dynamically extract per-pixel depth and reflectance information for the visible surfaces in the office including walls, furniture, objects, and people, and then to either project images on the surfaces, render images of the surfaces, or interpret changes in the surfaces.

Augmented or mixed reality interfaces can superimpose graphics and audio onto the real world, combining the advantages of both virtual environments and physical environments. Thus they facilitate the development of collaborative interfaces that go "beyond being there," while they also support seamless interaction with the real world, reducing the functional and cognitive seams [2]. Some effort has been made to pursue the collaborative AR metaphor. For example, Rekimoto [27] used tracked hand-held LCD displays in a multi-user environment and miniature cameras attached to the LCD panels to allow virtual objects to be composited on video images of the real world. While these displays are small, lightweight, and high resolution, they don't support stereoscopic views. Billinghurst [2] and Szalavari [29] proposed using see-through HMDs with head and body tracking in a collaborative interface, which allows multiple local or remote users to work in both real and virtual worlds simultaneously. Bimber and his colleagues proposed the concept of Virtual Showcase, which allows two or four tracked users interact with the virtual content of the showcase while maintaining the augmentation of the virtual contents with real artifacts [3].

AR is an ideal metaphor for collaborative interfaces because it addresses two major issues: seamless collaboration and enhancing reality. As the fundamental components, however, the conventional stereoscopic head-mounted displays suffer typical ergonomic problems such as field-of-view, size, weight, and mobility [28]. The head-mounted projective display (HMPD) [8, 20] is an emerging technology that can be thought to lie on the boundary of conventional HMDs and projective displays such as the CAVE systems [5]. It has been recently demonstrated to yield 3D visualization capabilities with a large-FOV, lightweight and low distortion optics, and correct occlusion of virtual objects by real objects [12, 13, 17, 19]. Thus, it can be alternative for collaborative AR interfaces.

2.2. Overview of the HMPD technology

An HMPD consists of a pair of miniature projection lenses, beam splitters, and displays mounted on the head and a supple and non-distorting retro-reflective sheeting material placed strategically in the environment. An image on the miniature display, which is located beyond the focal point of the lens, rather than between the lens and the focal point as in a conventional HMD, is projected through the lens and retro-reflected back to the exit pupil, where the eye can observe the projected image.

Fig. 2 HMPD prototype

Two major aspects, the projective optics rather than an eyepiece as used in conventional HMDs and a retro-reflective screen rather than a diffusing screen as used in other projection-based displays, distinguish the HMPD technology from conventional HMDs and stereoscopic projection systems, making it appropriate for a wide range of applications [14, 17]. For example, Kawakami [19] and Inami [17] developed a configuration named

X'tal Vision and proposed the concepts of object-oriented displays and visual-haptic displays. Parsons and Rolland [25] proposed the HPMD technology as a tool for medical visualization. Hua and Rolland furthered the efforts with an ultra-light, high quality projection lens, and implemented a compact prototype using the custom-designed lens [13]. Their prototype achieves 52 degrees FOV and weighs about 750 grams. Figure 2 shows the front view of the prototype. Our recent work on the SCAPE collaborative infrastructure is based on this prototype.

3. Concept of SCAPE

The HMPD technology is well suited for 3D local or remote collaborative applications because it allows enhancement of the real world with 3D computer-generated information, intrinsically provides the capability for creating an arbitrary number of individual viewpoints with non-distorted perspectives and without crosstalk among users, and retains the natural face-to-face communication among local participants, owing to the essence of retro-reflection. The single-user HMPD technology can be extended to multiple-user mode by deliberately applying retro-reflective surfaces in the workspace and integrating multiple head-tracked HMPDs and interaction devices. This section will briefly describe the conceptual design of the SCAPE and discuss practical design considerations and limitations in its implementation.

3.1. Shared workspace to support collaboration in 3D augmented environments

One example of shared workspaces is a multi-user interactive workbench environment using multiple head-tracked HMPDs equipped with multi-modality interaction devices (Fig. 3). We refer to this configuration as the interactive workbench, through which multiple participants, wearing head-tracked HMPDs, are able to view and manipulate a 3D dataset superimposed on its physical counterpart, which is deliberately coated with retro-reflective material. If two users point to the same part of the dataset, their fingers will touch, which does not happen in the CAVE systems. Additionally, the ability to display multiple independent views offers the intriguing possibility of presenting different aspects or levels-of-detail of a shared environment in each view. This configuration is closely similar to the two-user responsive workbench [1] except that the number of users is unlimited and without the sacrifice of the display frame rate.

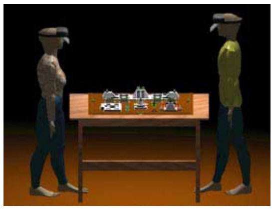


Fig.3 Illustration of an interactive workbench for collaboration

A variation of the interactive workbench is a cylindrical display (Fig. 4) in which a retro-reflective cylinder is installed on a revolvable platform, whose rotation is detected by an angular sensor [14]. Together with multiple head-tracked HMPDs and hand-held devices, it provides a shared medium for users to equally interact with a visualized subject in an intuitive way (i.e. walking around or rotating the cylinder to view it from different perspectives, or retrieving information for the selected part). The shape and the location of the cylindrical screen do not distort the perceived shape or location of visualized objects. Indeed, the shape of the screen can be many other possibilities, for example, clothing or other non-regular shaped surfaces.

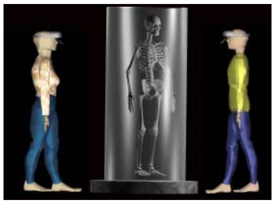


Fig.4 Illustration of cylindrical display for collaboration

Both the workbench and the cylindrical display configurations provide the same outside-in perspectives of a 3D dataset as the responsive workbench [1] or IllusionHole [21] do, in which the users can only explore the dataset from an external point of view. Using the HMPD technology, it is also possible to create a CAVE-like room-sized space when inside-out perspectives, such as walk-through, are preferred. The conceptual design of the SCAPE combines an interactive workbench with a room-sized display environment to create outside-in and inside-out perspectives simultaneously (Fig. 1-a). Such a design provides a shared space in which multiple users can simultaneously observe and interact with a personalized 3D synthetic environment from their individual viewpoints: an outside-in view of a miniature visualization through the workbench, or an inside-out view of a large-scale walk-through visualization in the room (Fig. 1-b). Switching between miniature and walk-through views can occur seamlessly by maintaining a unique world coordinate system for all users and a continuous viewing system for each user between the two different scales of visualization. Moreover, the miniature visualization on the workbench can also represent different levels of detail from that of the walk-through.

3.2. Design considerations and limitations

The SCAPE implementation is mainly affected by the characteristics of available retro-reflective samples. The difference between retro-reflective surfaces and diffusing or specular surfaces lies in the fact that a ray hitting the surface at an angle is reflected back on itself in the opposite direction (Fig. 5-a). In HMPDs, this indicates that the perception of image shape and location is independent of the shape and location of a retro-reflective screen. Practically, however, a retro-reflective material can only work well for limited angles. Three angles are most commonly used in describing the performance of retro-reflective materials: entrance angle, ω_e, observation angle, ω_o, and cone angle, $\Delta\omega_o$ (Fig. 5-b). The entrance angle specifies the angular range in which a material remains highly retro-reflective. The observation angle gives the angle difference between an incident ray and the reflected ray. The cone angle specifies the angular width of a reflected beam. Wide entrance angle, zero observation angle, and zero cone angle are preferred in an HMPD. Imperfect reflective properties have direct or indirect impact on imaging characteristics and quality, and thus affect the following aspects of the SCAPE design:

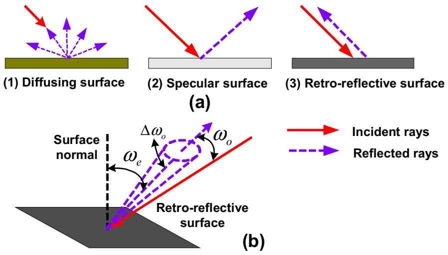


Fig. 5 Retro-reflection and retro-reflective material: (a) Difference in retro-reflection from diffusing and specular reflections; (b) Performance of retro-reflective material

Screen shape: A truly retro-reflective screen can be tailored into arbitrary shapes without causing image blurring and introducing distortions to virtual images, while a diffusing screen does. Practically, retro-reflection is only dominant with ±40° entrance angles for available samples, which sets up the constraint of screen shape. As incident angles increase, the drop of reflectivity results in a gradual vignetting effects on image brightness. Therefore, for a given visual field, we predict that a concave shape can improve image brightness of marginal fields, but a convex shape will worsen the brightness of marginal fields. When design a multi-wall room display, round corners, rather than squared corners as in CAVE systems, are preferred to minimize the gradual drop in image luminance because of the decrease of reflectivity when the incident angle increases.

Screen position: A truly retro-reflective screen can be applied to any possible location in the physical space without causing image blurring or degrading image quality. It further indicates that no precise calibration is necessary to position a retro-reflective screen in an augmented environment. A retro-reflective screen with non-zero observation angle leads to different image magnification if positioned at a different distance from the image plane, which sets up constraints on room size. A zero-observation angle is required. Some samples have up to 3 degrees of observation angle. Users are expected to perceive slightly blurred images if the screen is far away from the focused image plane.

Cross-talk and number of users: For a truly retro-reflective screen, the stereo pair of images projected for the left and right eyes, or different channels of images projected for individual users, are naturally separated. Practically, a non-zero cone angle can cause crosstalk if a screen is too far away from a user. The cone angle of the reflected beam is as narrow as 0.4 degrees for the measured sample, thus crosstalk between left/right eyes can possibly occur when the user is over 9 meters away from a screen, and for such a distance no crosstalk is present if two users stand side-by-side. Therefore, with this sample, 9 meters is the upper bound of a walk-through display to avoid interference between left/right images. In this case, it is possible to generate as many unique perspectives as needed for each user in a collaborative environment, without introducing crosstalk from any other participants. The performance of different material technologies varies and should be verified to support the above statement.

Functional augmentation: The optical see-through capability allows augmenting the real world with computer-generated information, while preserving the direct awareness of the user's surrounding environment without any tradeoff of visual quality, compared with video-based see-through HMDs. Furthermore, users can only perceive virtual objects when they look toward surfaces coated with the retro-reflective materials. Thus, it could be said users can naturally switch their focus of interest between the real and virtual workspaces, which will not happen in conventional optical see-through HMDs. Moreover, the combination of projection and retro-reflection makes an HMPD capable of intrinsically providing correct occlusion cues of computer-generated virtual objects by real objects. However, if the retro-reflective material is not deliberately applied, virtual objects will erroneously disappear when a virtual object is intentionally floating between a real object and the user. This imposes limitations on the scope of applications.

Field-of-view (FOV): Wide FOV is desirable for wearable displays. The feasible FOV of an HMPD is not only constrained by that of the projective optics, but also limited by the maximum entrance angle of retro-reflective materials. In fact, to avoid significant degradation of luminance in peripheral visual fields, the maximum entrance angle of the screen used in a system sets up the upper-bound FOV of an HMPD. For example, for the tested samples, the FOV of an HMPD should be equal or less than 80 degrees, if a flat retro-reflective screen is assumed.

Environmental lighting: The lack of brightness is a common problem in LCD-based optical see-through HMDs, but it is aggravated in HMPDs due to the fact that light passes through the beamsplitter multiple times, which leads to the loss of at least 75 percent of the light. Thus, the lighting in the environment has to be dimmed to a minimal level which may be difficult for reading. The lighting also limits viewing distance, and therefore the size of the room.

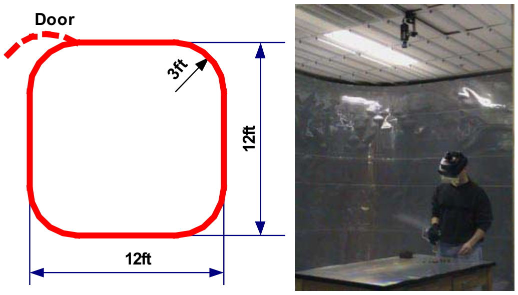
4. SCAPE implementation

With the above design considerations in mind, we describe a preliminary implementation of the SCAPE hardware and software in this section.

4.1. Hardware implementation

The SCAPE display environment currently consists of a 3'x5' workbench and a 12'x12'x9' four-wall arched cage made from retro-reflective film, multiple head-tracked HMPDs, multi-modality interface devices, computing facilities, and networking. Visual-cue acquisition facilities we have been developing will be integrated in the near future. In our current experimental setup, the design of the 3'x5' workbench is simply a tabletop coated with the reflective film and placed in the middle of the room, about 3' above the floor.

The shape of the cage is specified in Fig. 6-a, composed of four 6-foot flat walls and four arch corners with 3-foot radii. The height of the walls is 9 feet. The round corners, rather than squared corners as in CAVE systems, are designed purposely to minimize the gradual drop in image luminance, which was explained in the previous section. The walls and corners are assembled together before coating with reflective film, and one of the corners is designed as a revolvable door. The enclosure allows a full control of lighting. Naturally, a 6-wall cage is possible if both the floor and the ceiling are coated with the film. A Hiball3000 sensor by 3rdTech (www.3rdtech.com) is used for head tracking purposes, so our ceiling is installed with the 12'x12' array of LED strips. Because of the minimal requirements on wall alignment and the low cost of the film, the expense in building the reflective cage is much less than that of building a CAVE. Figure 6-b shows the physical setup of SCAPE.



(a) (b)

Fig.6 SCAPE implementation: (a) Shape and size specification of the room; (b) Experimental setup.

Two HMPDs are driven by a SGI Octane workstation with one R12000 processor and one four-channel VGA output option. Each set of two channels outputs a pair of stereoscopic images to an HMPD. The head position and orientation of each user is detected by the Hiball3000 optical tracker or an Ascension Flock-of-Bird magnetic tracker. The stereoscopic image pairs are generated without distortion for each user according to their individual viewpoints. More users can be supported if more HMPDs, tracking, and computing resources are available.

In terms of interface devices, a tracked 5DT Dataglove is currently used for data manipulation on the bench and in walk-through visualization (see application example). To support augmentation of virtual objects with physical objects, we have developed a vision-based 2D object tracking method to detect position or orientation of the physical objects placed on the workbench. An infrared camera with infrared lamps mounted on the ceiling continuously captures the image of the workbench and objects placed on it. In a dimmed room-lighting condition, the low-level co-axial infrared illumination makes the image of the retro-reflective background extremely bright and that of the diffusing objects dark. Thus simple segmentation algorithms are applied to the image to recognize the objects and determine their two-dimensional position and orientation. Under different application contexts, this tracking method with minor modification can be used to track multiple physical objects in augmented environments, recognize simple hand gestures to interact with virtual environments without special attachments or hand markers, and develop widgets to facilitate cooperation among multiple users. Multiple cameras will be integrated to support 3D tracking and more complicated recognition. We have been also developing several hardware and software widgets to assist interfacing and cooperation (see application example). Other interface modalities will be considered in the near future as well.

4.2. SCAPE software architecture

The SCAPE application-programming interface (API) provides a cross-platform, modular, and extensible framework for augmented collaboration (Fig. 7). The software architecture, which employs a C++ class hierarchy, allows for medium and high level programming control for rapid deployment and testing of prototype applications. Among medium-level constructs are those typical to virtual environments, such as scenegraph generator, multimodal stereo rendering contexts, interface device drivers, and video acquisition. We concentrate this discussion on the description of three higher-level controls that facilitate interaction.

Complex interactive, collaborative environments require a cohesive structure for maintaining devices and information specific to each user. The SCAPE library employs a high-level construct, called an Actor, to perform the task. Each Actor maintains a corresponding viewpoint, object trackers, such as head and limb trackers, and interaction devices, such as gloves and widgets, specific to a particular user. Since specific users may need access to privileged or personal information, Actors allow for user specific update methods and provide hooks into private scenegraph data for maintaining personal information, such as a history list of places visited in the virtual world.

Networking support relies on client-server architecture and builds from the type-safe communication methods of the CAVERN G2 API, a networking library for virtual environments [www.openchanelsoftware.org]. We employ a generic Collaborative Server class capable of routing or multicasting arbitrary data over a TCP/IP network, and Collaborative Client modules which are extended for task-specific communication.

The Auto-Configurator class allows stock program configuration options, including an extensive set of calibration and registration parameters obtained through the calibration process, to be input via text initialization (ini) files; this design decreases the frequency of program recompilations. Callback functions extend the Configurator for the parsing of application-specific data. Providing the highest level of control, an Auto-Collaborator class encapsulates all client-side objects -- including Scenegraph, Render Window, Actors, and Collaborative Clients -- necessary for building simple networked, augmented applications with relatively few lines of code. The Collaborator is designed to provide support for three modes of augmented collaboration:

- Interactive local collaboration – Multiple users at the same physical site have equal access to the augmented simulation. They perceive the simulation from independent perspectives, may have access to user-specific virtual data, and alter the state of the simulation dynamically.

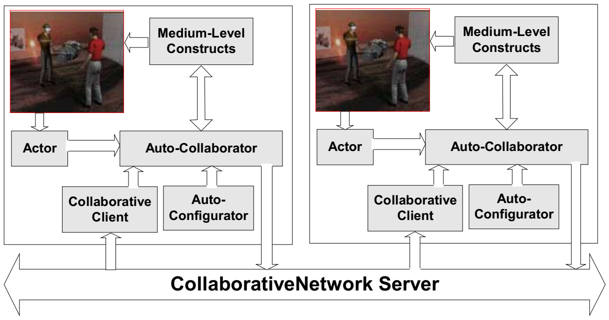


Fig. 7 Diagram of the SCAPE software architecture

- Passive remote collaboration – Local users alter the state of the augmented simulation dynamically, while remote users perceive only the public contents of the simulation and cannot influence its state.
- Interactive remote collaboration – Both local and remote users identically alter the state of the augmented simulation, have access to user-specific private data, and can communicate both visually and audibly.

Thus far, only the first two modes are implemented and the third mode will be developed in future work. An efficient video streaming capability is also one of our goals.

4.3. Calibration

In SCAPE, each user is provided an individual view into a shared environment. In order to maintain a shared synthetic environment with which to interact, proper calibration of the hardware is required so that the synthetic representation is consistent and continuous for all users from arbitrary perspectives. This requires the coordinate systems of the various devices to be properly aligned: a physical world coordinate system (PCS) in which all physical objects, including walls and workbench, are positioned; trackers' coordinate systems (TCS) in which head and hand motions are measured; and a virtual world coordinate system (VCS) in which all virtual objects are defined. In the AR interface, the PCS has to be chosen as the reference system and all others have to be aligned with the reference, which is referred to as the registration process.

The registration process takes three major steps: (1) Determining tracker-world transformations for all the tracking devices involved to align their TCSs with the PCS; (2) Determining intrinsic and extrinsic parameters of each HMPD's viewing optics; and (3) Obtaining the viewing orientation and projection transformations for each user, based on viewing optics parameters, to generate view-dependent stereoscopic image pairs and align the VCS with the PCS. The first step can be accomplished by measuring three known points on the PCS using the corresponding tracking system. Because we have been using different types of trackers in our experiments, each tracker has to be aligned individually. For the less accurate magnetic tracker, look-up-table calibration methods [10] have to be taken to compensate the large magnetic distortion. The second step involves individual calibration of each HMPD and head tracker pair. In the case of HMPDs, a special calibration procedure is needed, and we have developed a calibration method to determine the intrinsic/extrinsic optical parameters, which is similar to camera calibration methodology [30], and a computational model on how to apply these parameters to viewing and projection transformations. The third step involves a process to determine the viewing orientation and projection parameters such as field-of-view, view frustum, frustum asymmetry, and computational baseline for the left/right eyes based on the intrinsic and extrinsic parameters [9]. Due to length limitations, we will omit the details of the method. In our API, we implement the associated functions for establishing an accurate computational model from the intrinsic/extrinsic parameters and for customerizing the viewing and projection transformations for each user to generate their corresponding image pairs.

5. Application examples

In this section, we present an application example to demonstrate some of the SCAPE characteristics, the API framework, and some aspects of the interface and cooperation features we have implemented: Aztec architecture explorer.

The 3D scenegraph, an Aztec City obtained from www.3DCAFE.com, mainly consists of a micro-scale scene with a low levels-of-detail (LOD) representation and shaded rendering, which users can examine via the workbench, and a macro-scale scene with a high LOD representation and textured rendering, which users can walk-through in the room. Two individual perspectives (capable of unlimited users if resources are available) are currently rendered for two head-tracked users. Users can either discuss the Aztec City planning with other participants through the workbench view, or explore its architectural style via the walk-through.

In the mode of workbench-only collaboration, the users share exactly the same micro-dataset but from individual perspectives, and therefore collaboration takes place in the intuitive face-to-face manner. They can simply point to the spot of interest with hand to direct the focus of attention of the group. We are implementing a "Magnifier" widget, which allows a user to closely examine the magnified view of a spot of interest. The head trackers provide absolute measurements of the users' physical positions relative to the workbench such that correct perspectives are maintained when they walk around the bench.

A virtual avatar (e.g. simply a color-coded arrow) is created for each user in the micro-scene, and is visible for all participants. Each avatar represents the current location of its associated user in the macro-scene, which provides the user and other participants an awareness of his/her locations.

Each user is also assigned a unique physical ID, such as an encoded checker piece in our experiments, which is recognized and located by the vision-tracking interface described in Sec. 4. For each user, his/her ID location on the bench represents a unique location in the macro scene, and is used to initialize his/her viewpoint, together with the orientation measurement of his/her head tracker, when switching to the macro-view. Therefore, by manipulating his/her physical ID on the workbench, a user can rapidly move to the site of interest in a sufficiently large walk-through scene.

In the mode of walk-through, head-tracker measurement is relativized to its corresponding ID position to walk around in the macro scene. A user can

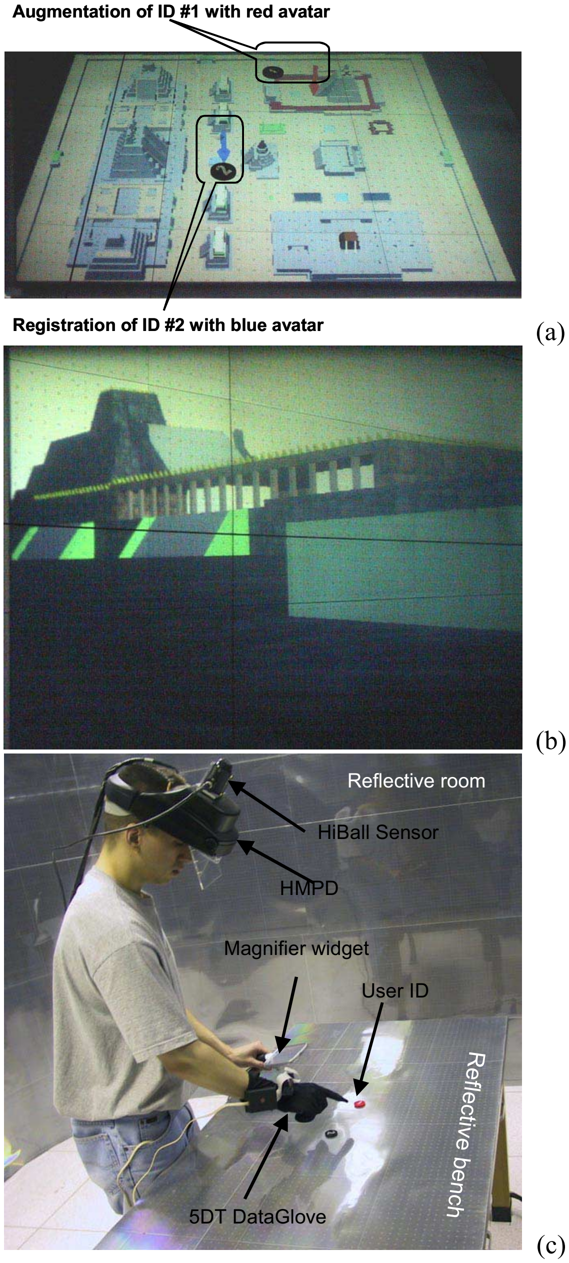


Fig. 8 Aztec architecture explorer: (a) Outside-in miniature workbench view; (b) Inside-out large-scale walk-through view; (c) Experimental setup.

also move his/her viewpoint by making "forward" or "backward" gestures with his/her glove, rather than physically walk "forward" or "backward", which overcomes the physical constraints on mobility. The virtual bench avatar is always updated accordingly when the head-tracker or glove is updated. This navigation mechanism allows a user to rapidly shift focus of interest by moving his physical ID on the bench, or slowly walk through the site by head-tracker and glove. The bench view can be thought of as a shared map to explore the large city. When a user refers to the map view, both the avatars and physical IDs help to quickly identify the locations of other users or his/her previous locations.

Switching between bench and walk-through views is done by determining if the user's physical ID is available. Laying down the ID switches him/her to the macro-scene, and removing the ID resumes the micro-view. Figures 8-a through 8-c show a workbench view with the augmentation of an avatar and physical ID, the walk-through view corresponding to the avatar representation, and the physical setup, respectively.

In the explorer application, we actually implement two paradigms simultaneously: virtual reality and augmented reality. The micro-scene has to be registered properly with the physical bench, physical stones, and virtual avatars. Absolute measurements of head-trackers are taken to maintain the registration. The macro scene is a fully immersive walk-through environment, which is supposed to be significantly larger than the physical room. Relative measurements of the head-tracker are taken to navigate the environment.

6. Conclusions and future work

We have developed a multiple-user collaborative infrastructure, SCAPE, based on the head-mounted projective display (HMPD) technology. The proposed SCAPE infrastructure is capable of providing multiple local participants: (1) functional integration of virtual and physical space; (2) seamless integration of shared workspace and interpersonal face-to-face communication space; (3) personalized perspective-correct augmented views of the visualization subject; and (4) equal and natural accessibility to the synthetic environment. In the future, emphasis will be put on the remote collaboration component, integrating the visual and audio acquisition facilities and evaluating the system as a tool for stereoscopic collaborative applications with our collaborative laboratories over high-speed networks. Meanwhile, more efforts will be made on the interface design to make local or remote collaboration experiences more comfortable and intuitive.

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