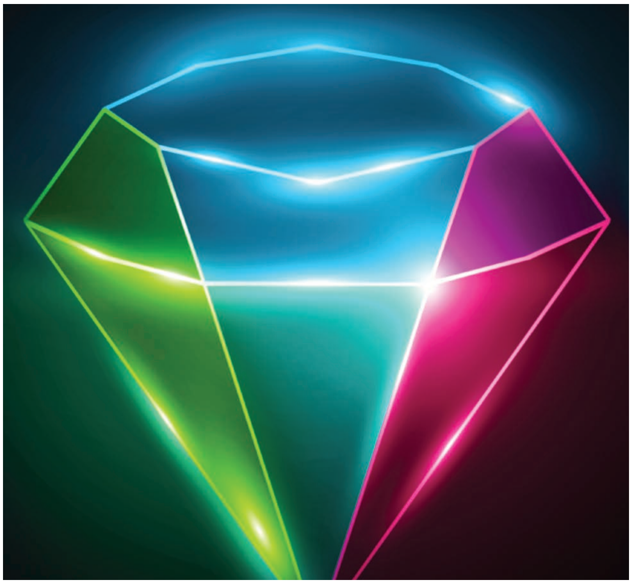

Large Area Displays: The Changing Face of Visualization

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Although very large immersive displays that can accommodate current data's scale, resolution, and complexity have progressed rapidly in the past decade and are now accessible to lay consumers, installation and maintenance challenges remain.

Visualization is a large domain that encompasses the science that deals with massive data processing, display, and interaction. The term usually refers to a cyclic process in which interaction with the displayed visualization should trigger further processing and analyses. Thus, the quality of displays, particularly the large area displays so useful in collaborative projects, is critical to visualization's successful practical application. In that sense, visualization is the body, and the display is the face for expression, communication, and interaction. Without a high-quality display, visualization has no more utility than a body without a face.

We underline this synergistic relationship to make an important point: the tremendous advances in data processing techniques for large-scale visualization would have been futile without the past decade's commensurate progress in large area display technology and its breathtaking promise for the future.

A survey of work from the early 1990s to the present reveals that the display community is at a golden moment in large area display development in which it is enjoying the fruit of recent phenomenal progress and identifying open problems and ambitious visions for the next generation to explore.

A WIDER VIEW

In the early 1990s, single desktop monitors were the norm—the high end being a 19-inch diagonal with about a 250,000-pixel resolution. Data, in contrast, was entering the realm of petabytes and terabytes to meet the simulation and visualization demands of national projects in various scientific domains. Visualization, in particular, became an essential tool for most projects, which also depended on colocated multiuser collaboration. The data scale and resolution that these projects required along with their reliance on collaboration were way beyond what narrow field-of-view desktop displays could handle.

To meet the growing demand for visualization tools, in 1993 researchers at the Electronic Visualization Laboratory at the University of Illinois at Chicago introduced the first cave automatic virtual environment (CAVE), a display of three to five walls that resembled a room. As Figure 1a shows, each wall has one or more mono or stereoscopic projectors, enabling an unforeseen degree of immersion. Virtual reality systems incorporate versions of these CAVEs with interactive joysticks and head-tracking devices to facilitate view-dependent navigation and simulation tasks.

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Figure 1. Early large area displays. (a) University of Illinois at Chicago's CAVE and (b) Princeton University's 18-megapixel display wall, which uses a 6 × 4 array of 24 projectors. (c) UCI's 7-megapixel wall, which uses a 3 × 3 array of nine rear projectors, showing (d) a completely seamless image that looks like a single projector display, although it comes from nine projectors. The UCI projectors had severe color variations, which researchers alleviated by developing camera-based automatic registration software.

Table 1. Very large planar display walls in the late 1990s.

Laboratory	Projector array	Display size (ft.)	Resolution (megapixels)
Princeton	6 × 4 array of 24 rear projectors	18 × 18	~18 (6,000 × 3,000)
Argonne National Lab	5 × 3 array of 15 rear projectors	16 × 8	~10 (5,000 × 2,000)
Argonne National Lab	3 × 2 array of six rear projectors (mobile)	4 × 3	~3 (2,000 × 1,500)

By the late 1990s, engineers were synchronously shuttering CAVE projectors with active stereo glasses to provide a 3D stereoscopic experience. However, resolution was still limited to less than 1 megapixel per wall, thus not even coming close to the scale and resolution demands of scientific and information visualization applications. Moreover, CAVEs were focused on single-head tracking, which precluded multiuser applications.

During this same time, very large planar display walls such as those shown in Figures 1b-1d were emerging. In these displays, multiple projectors overlapped their respective boundaries on a planar projection surface to create a large display wall. Table 1 lists the details of some of these displays.

Figures 2a-2c show one of the projectors and some problems on the display walls. Setup was a major drawback to such displays. Overlapping high-gained rear projection screens alleviated the hot spot issue—brighter in the center than on the fringes—but overlapping imagery required sophisticated mounts with six degrees of freedom that engineers had to manually adjust to align each projector with its neighbors or to align image content across projectors (geometric registration). Such tinkering took many work-hours, even for setups with only two to four projectors, and still did not correct the hot spot issue.

To alleviate this problem, engineers placed metal masks on the optical path between the projector and screen in an attempt to blend the two projectors' contributions to the overlap in a complementary manner. However, as Figures 2c and 2d show, this remedy did not allow fine per-pixel control, which resulted in a screen door effect—an image viewed as if through a screen door. The large color variations across projectors exacerbated the effect, even when projectors were the same brand.

Traditional semiautomatic color management techniques, such as gamut transformation and matching, did not help because multiprojector displays produced unprecedented degrees of spatial brightness and color

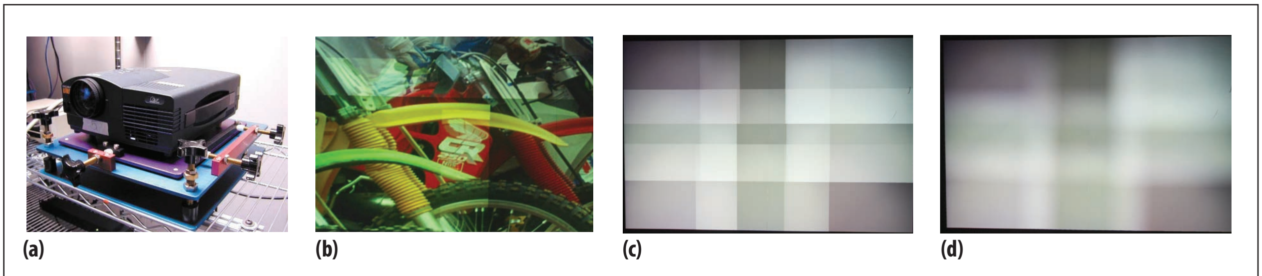
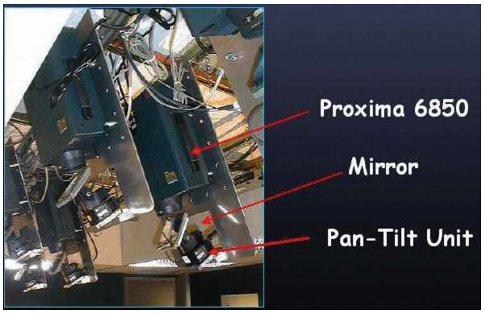


Figure 2. Obstacles in image and projection tuning. (a) A projector mount with six degrees of freedom, which required time-consuming manual tinkering to adjust the projector's position to align image content. (b) Error in geometric registration at the overlap of four projectors. (c) Images suffered from color variation and brightness hot spots at overlaps. (d) Correcting hot spots using metal attenuation masks often produced an image that resembled what the viewer might see through a screen door.



(a)

(b)

Figure 3. Evolution of automatic registration techniques. (a) Automatic panning and tilting in UNC's Pixel Flex project and (b) a mirror mounted on a pan-tilt unit that directed each projector's light to different areas of the flat wall, enabling the display to operate in a different scale, form factor, and aspect ratio. Although these systems are no longer operating, their design inspired a new generation of systems that use automatic registration.

variations. Thus, installing and maintaining such a system was labor intensive and expensive, requiring an in-house maintenance crew.[1]

AUTOMATIC REGISTRATION

The obvious approach to a more sustainable solution was to use a camera to capture the display properties at a very high resolution and then correct the results automatically. By the late 1990s, computer vision research in panoramic image generation was making significant progress, producing techniques similar to the process for registering images from multiple projectors. As a result, the next decade saw a phenomenal amount of work in camera-based automatic geometric registration and color seamlessness—removing perceived spatial variations in color.

In these automated solutions,[2] one or more cameras provided feedback to a server that controlled the multiple projectors and applied the appropriate warps and attenuations at a per-pixel resolution to achieve a seamless display. The color seamlessness problem remained open until 2009, when researchers at the University of California, Irvine (UCI) developed a constrained gamut morphing approach[3] that enabled the completely automatic deployment and maintenance of large planar display walls.

Researchers at the University of North Carolina, Chapel Hill (UNC) subsequently used automatic deployment to create reconfigurable display walls by coupling front projection systems with mirrors mounted on pan-tilt units to direct the light on a planar wall.[2] Figure 3 shows such a projector setup. These flexible units made it possible to change the display's form factor, size, and resolution on demand, enabling the same six projectors to be in a 6×1 array for a wide-format display and then in a 3×2 array for a display with 4:3 aspect ratio. Automatic registration after each reconfiguration made it possible to create a seamless display in minutes. At the same time, new distributed rendering paradigms were efficiently rendering large amounts of 3D data in real time, which made these reconfigurable displays highly suitable for any large data visualization application.[4,5]

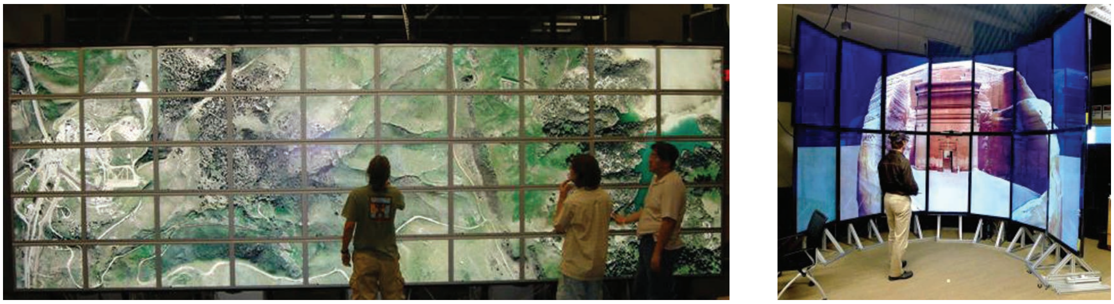
Around the same time, the advent of thin LCD panels enabled researchers to build display walls of multiple LCD panels. Figure 4a shows UCI's HiperWall, the first 55-panel setup. Similarly, a 70-panel HiperSpace was built in the Immersive Visualization Lab at the University of California, San Diego (UCSD).

Because removing the seams in such LCD wall displays and economically mounting them are formidable engineering obstacles, vendors offered these displays, shown in Figure 4, only as expensive turnkey solutions that lacked the flexibility of reconfiguration. Even so, because distributed rendering architectures like the Scalable, Adaptable Graphics Environment make it easy to port visualization applications on these walls, they are still a popular option for some visualization environments.

IMMERSIVE DISPLAYS

By 2007, display walls literally changed the face of visualization systems by becoming the most popular option for large-scale visualization. However, it soon became evident that complex multidimensional data demanded immersive environments as well as scale and resolution. For many applications, the user needed a sense of presence and immersion to effectively navigate, modify, and visualize data.

This dream of a completely immersive display was not new. Henry Fuchs of UNC first envisioned such immersion in his 1990s Office of the Future (OOTF),[6] an environment with a sea of cameras for capture and multiple projectors for display. As Figure 5 shows, the idea was to provide a display for visualization within the user's own office environment, as opposed to having the user walk into a special display area.



(a) (b)

Figure 4. Multilayer LCD panel display walls: (a) UCI's 110-megapixel HiperWall and (b) UCSD's TourCAVE.

Meeting such an ambitious goal required both the 3D reconstruction of large scenes and 3D real-time gesture recognition, which were still open problems at the time. By the early 2000s, however, projects like blue-c[7] had made huge strides in this direction. The resulting novel projection-screen technology used layered LCD glass panels that could turn opaque for projection and transparent for scene acquisition through cameras behind the screen. With this technology, blue-c researchers built the first end-to-end system with multistream videocapture, 3D scene reconstruction, and the projection of the reconstructed scene in an immersive CAVE system with three walls and active stereo.

Nonplanar geometry

Even this novel technology was not ripe enough to realize OOTF's vision of breaking away from specific display geometry toward an unrestricted environment, but a varied set of nonplanar display geometry seemed the perfect middle ground. Designers could choose surface geometries for immersive displays to suit the users' needs, space, applications, and interaction modalities. Cylindrical, hemispherical, or other uncommon immersive shapes, such as a bowl or an eggshell, became popular for immersive visualization, training, simulation, and edutainment applications. In the mid-2000s, companies such as Elumens, Global Immersion, Fakespace, Christie, and Eon Reality began delivering such systems but only as expensive and rigid turnkey solutions.

Although some immersive displays also used the LCD panels shown in Figure 4, their piecewise-planar rigidity limited their use to a small range of curvature and a compromised sense of presence, as in the TourCAVE display at UCSD, shown in Figure 4b. Projectors offered a much better solution, since they can direct light over any kind of curved surface to achieve a display of any shape and size. However, immersive multiprojector displays had the same issues as the early display walls: registration on nonplanar shapes was much more challenging, and once again researchers had to resort to manual or semiautomatic registration techniques, which hindered the displays' mass deployment.

Figure 5. UNC's Office of the Future vision in 1998. Nearly a decade before the technology became available, the OOTF imagined displays unfettered by a particular geometry such as a CAVE or other separate walk-in spaces for visualization.

Automatic registration revisited

Unlike automatic registration in previous years, the main challenge this time around was how to accommodate nonplanar surfaces. Reconstructing very large nonplanar surfaces requires recovering large 3D scenes from multiple stereo rigs, which is still unreliable and problematic.[6] Unlike 3D modeling applications in computer vision, any small error in reconstruction can produce severe errors in the display's geometric registration.

The need for higher accuracy was only one obstacle. Another was the registration problem's highly underconstrained nature: because it was not possible to know device parameters or surface geometry ahead of time, automatic registration techniques were largely impractical. Consequently, most early camera-based

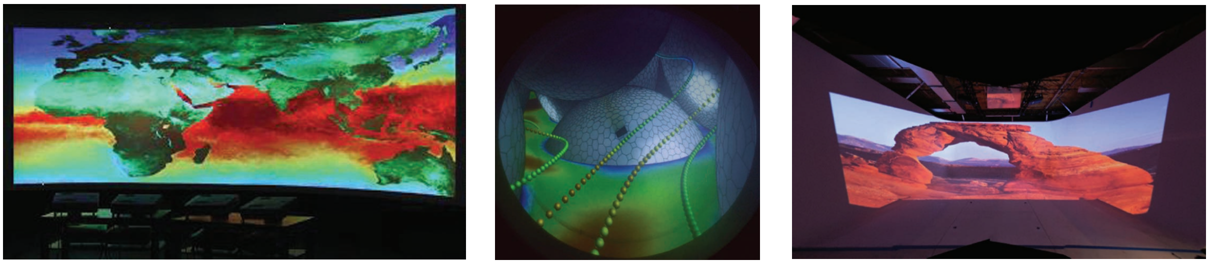


Figure 6. Nonplanar displays that use UCI's automatic registration technique: (a) a 4 × 2 array of eight projectors on a cylindrical display with a 14-ft. radius and angular span of 90 degrees, (b) four projectors on a dome with a 5-ft. radius, and (c) a 30 × 22 × 13-ft. swept-surface display at Disney Imagineering.

registration techniques for nonplanar displays assumed that users would know the surface geometry or device parameters, such as pose, orientation, and focal length. However, most users do not have enough technical savvy to provide such information, and, not surprisingly, the mass deployment of such displays never occurred.

In 2009, UCI researchers began to make significant progress in surmounting these obstacles,[8-10] observing that most immersive displays are not arbitrarily nonplanar, but constrained nonplanar—their boundary curves follow some well-defined constraints, such as a cylinder falling in the general category of an object with a vertically extruded surface. This new perspective led to three broad categories of immersive display surfaces:

- vertically extruded surfaces formed by extruding a planar curve along a vertical line, such as a cylinder;
- swept surfaces formed by sweeping a planar profile curve along a planar path, such as a truncated dome; and
- partial or full spheres.

Figure 6 shows displays that use automatic optimization techniques developed by UCI researchers for constrained nonplanar surfaces. At the heart of these techniques is a novel paradigm of nonlinear optimizations that uses a single uncalibrated camera without any markers instead of calibrated stereo cameras. The paradigm identifies enough prior knowledge about the general properties of boundary curves to sufficiently constrain the problem and recover the unknown camera properties, surface geometry, and projector pose and orientation. For very-large-scale displays, a single uncalibrated camera on a nodal pan-tilt unit can easily achieve the registration with a higher accuracy than multiple stereo cameras, which tend to be a nonrobust setup. Complete automation and the simplicity of a single camera combine to make deployment easy for lay users.

These techniques brought a new engineering flexibility, even to CAVEs, which for so long had been treated as segregated planes. With traditional registration methods, engineers not only had to register each plane separately, they also had to manually or semiautomatically register the projectors in each wall with ones in the adjacent wall. This wall-by-wall registration prohibited overlapping projectors across the corners, which in turn made color registration much more difficult.

Designers can use automatic registration for nonplanar walls to treat a three- or five-wall CAVE as a vertically extruded or swept surface, respectively. Treating the display as a 3D shape rather than as a collection of walls allows more casual projector placement and permits overlaps across corners, both of which make deployment much easier.

With this implementation flexibility and resulting increased sense of presence, automatic registration technology is ripe for use in a variety of constrained nonplanar displays and could greatly impact edutainment, simulation, and training.

NEW PATHS

As visualization moves from display walls to large immersive displays that provide a stronger sense of presence, researchers are looking ahead to important missing elements, such as the ability to interact naturally using very large displays in collaborative projects. Much work has focused on interaction through touch-sensitive sensors and embedded cameras, but we have yet to see people interacting with one another in a natural way by using face-to-face body language through very large immersive displays. This capability is essential to visionary academic projects like OOTF and the future envisioned in movies.

The major roadblock to realizing this dream is the tightly controlled centralized architecture, in which a single server must somehow coordinate a group of disparate devices, such as cameras and projectors. This loosely coupled arrangement of devices limits scalability and easy deployment.

UCI researchers working on the ubiquitous displays project[11,12] are looking at an entirely new architecture. As Figure 7 shows, a distributed network of active display units—each with a projector and embedded sensors, including a camera—and computation and communication units populate a workspace. The active displays run identical single-program, multiple-data algorithms that collectively and automatically achieve all the characteristics of a ubiquitous display: scalability, reconfigurability, flexibility, and interactivity. Users can move the displays; define display collections, or *frescos*, to work as a single display; achieve seamlessness on a surface that might not be entirely white or planar; and interact with the data on the display in a natural way.

UCI researchers have begun to explore this distributed paradigm, and our team has already built a planar display wall using active display units, each of which sees its own projection and a small part of its neighbors' projections. Figure 8a shows the projection setup. The research team has also developed distributed registration techniques that use quick response (QR) codes to automatically reconfigure projectors whenever they are moved. Figure 8b shows a front view of self-registration, which such a move triggers. In minutes, the distributed registration process produces a seamless display, such as the one in Figure 8c.[11]

The cameras embedded in the projectors also capture gestures so that users can interact with the display. However, managing gestures and reacting to them is not trivial, since each camera sees only a part of the display, and a user's gesture can cross multiple cameras. A distributed paradigm must ensure that the algorithm running on each active display hands gesture management control from one device to another when appropriate, reacts to gestures that a device has not seen, and maintains data consistency.

Although UCI researchers have taken steps toward realizing these goals by developing the first distributed interaction paradigm for 2D applications on planar display walls,[12] such work is nascent. Capturing the myriad 2D and 3D interactions on surfaces that are not flat and white is still a challenge. Realizing that dream requires not only research intensely focused on distributed interaction paradigms but also significant improvement in robust vision techniques to reliably detect 2D and 3D gestures. The fruit of such efforts will drastically alter visualization, empowering users at all levels of expertise with a new efficiency in data exploration, visualization, and modification.

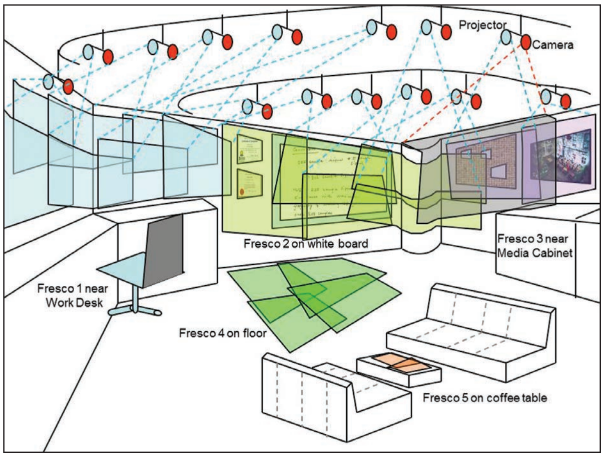
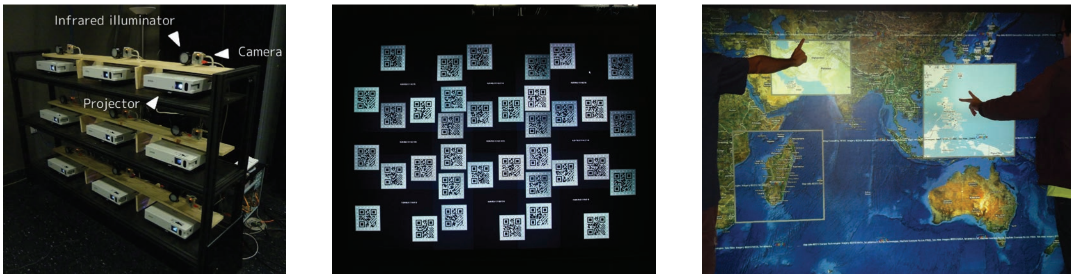


Figure 7. How ubiquitous displays might work. Active displays created by augmenting a projector with sensors (including a camera) and a computation and communication unit form a distributed network, or fresco, that users can move and reconfigure as needed.

MERGING REAL AND VIRTUAL

Large, dynamic, complex datasets demand visualization overlaid on the artifact itself rather than through a separate display. In Figure 9, for example, projecting light onto a chipped and faded cultural artifact lets archeologists see its original shape and color. Such in situ visualization has endless possibilities. For example, lighting reliefs of the Colorado River at a very high resolution using projectors reveals river activity in different ages. Placing a physical artifact of a dam in this relief would automatically change the visualization, as projectors adapt and light the entire relief differently to show its effect on the physical phenomenon.

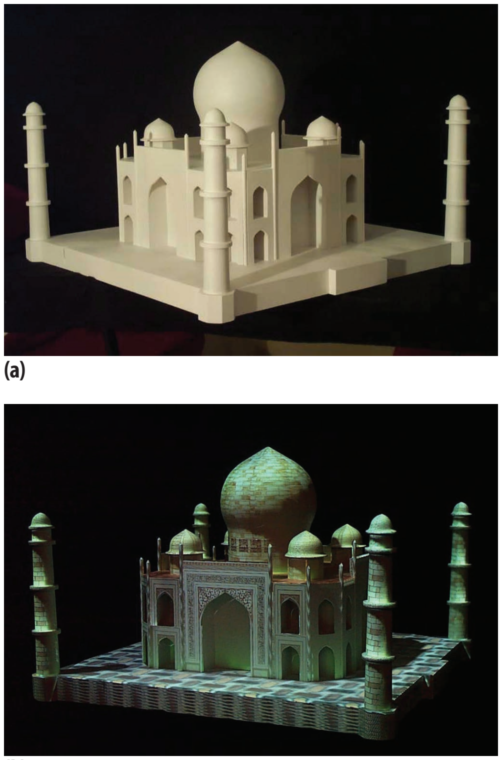


(a) (b) (c)

Figure 8. UCI's planar display wall, which uses (a) a distributed network of nine active displays in a 3 x 3 x 3 array. (b) Using QR codes, the display undergoes distributed registration. (c) Minutes later, the display is ready for map visualization and navigation involving several users.

(a) (b) (c)

Figure 9. Appearance editing for in situ visualization using three superimposed projectors lighting a cultural heritage artifact. (a) The original artifact, (b) visualization of the restored artifact with light projection, and (c) in situ visualization of aging and annotations. Projectors automatically direct light to achieve the desired visualization.



(a) (b)

Figure 10. Using in situ visualization to add depth to architectural lighting. (a) Applying semiautomatic registration techniques to an image of the Taj Majal (b) simulates its appearance on a moonlit night.

Historians could annotate the same relief model with facts and figures, or urban planners and emergency management strategists could use it for their scenarios. In the entertainment industry, in situ visualization could add depth to architectural or theatrical lighting.

Ramesh Raskar first demonstrated the power of this visualization in 1999 using four projectors to light a small white table-top model of the Taj Mahal as part of UNC's Shader Lamps project.[13] Raskar applied semiautomatic registration techniques to the projected content in Figure 10a to simulate the appearance of the Taj Mahal on a moonlit night (Figure 10b). Since then, UCI researchers have collaborated with Dan Aliaga and his team at Purdue University to explore the use of superimposed projectors to completely automate the in situ visualization of such objects at a much higher resolution.[14]

Despite progress, in situ visualizations remain limited to small artifacts and setups in which projectors are mounted outside looking in. Achieving in situ visualizations on large reliefs and objects requires a distributed network of active displays lighting relatively arbitrary nonplanar surfaces. The registration challenges are many, since unknown devices and surface geometry result in an underconstrained system. Fortunately, multiple overlaps between devices allow them to see parts of the same surface geometry, which provides opportunities for validation across devices and thus offers enough constraints to solve the problem robustly. However, much work remains to be done to make in situ visualizations a commodity system accessible to users at all levels of expertise.

BEYOND TWO DIMENSIONS

Researchers have recently directed much work toward moving 2D displays to multiview technology, producing autostereoscopic displays that are essentially 2.5D.

About a decade ago, such displays were primarily stereoscopic, either active through synchronous switching of shuttered glasses with the projection-based display, or passive through the selective filtering of differently polarized light from the projectors through glasses. The relatively recent rejuvenation of parallax barrier technology has led to glasses-free autostereoscopic displays and their extensions to large-scale applications with multiple users.[15] Such advances have come at the cost of resolution, but work on tensor displays is addressing that problem.[16] We have also begun to see small-scale 3D holographic displays from companies like Holografica and QinetiQ.

The ultimate dream of work on very large area displays is to achieve an immersive, truly 3D experience on a massive scale with the highest resolution. Such displays have the potential not only to redefine visualization but also to shape different kinds of education and exploration modalities. When combined with breakthroughs like light field displays,[16,17] the potential of visualization displays is limited only by imagination.

Open problems remain—from developing scalable distributed display architectures to deploying novel display technology and creating unified and scalable interaction to developing a data management and rendering paradigm. However, dedicated effort and resources have already resolved problems that once seemed insurmountable. Continued effort could bring similar results and ensure that the day of very large, truly interactive, immersive, and accessible displays is not far off.

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