

The Reality Deck—an Immersive Gigapixel Display

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A vast number of data sources, such as supercomputers and sensors, have become “fire hoses,” generating information far more quickly than it can be digested. For example, the AWARE-2 camera system can capture a 1.47-Gpixel photograph.¹ (AWARE stands for Advanced Wide Field of View Architectures for Image Reconstruction and Exploitation.) In cosmology, the Large Synoptic Survey Telescope (www.lsst.org) will feature a 3.2-Gpixel sensor and capture approximately 200,000 images annually.

One approach to visualization is to fit vast quantities of data on a single display. Various summarization, abstraction, and focus-plus-context techniques aim to accomplish that while providing users with the data’s overall patterns and structure.

Maximizing the available screen real estate demonstrably affects visualization.² Tiled display arrays (powerwalls) embody this concept, offering a large, high-resolution, collaborative workspace. For applications that benefit from physical immersion (for example, surrounding the user with visuals), CAVEs (Cave Automatic Visual Environments) are suitable, potentially offering a fully immersive field of view (FOV) and stereoscopic 3D.³

Immersive virtual environments (IVEs), however, present a fundamental dichotomy. For visualizing large-scale datasets, the total screen real estate and resolution must be maximized, making powerwalls more appropriate. However, powerwalls lack immersion, and physical constraints can limit their resolution (for example, a 100 ft. planar powerwall is unwieldy to construct and use). Conversely, CAVEs offer immersion, but their maximum resolution is roughly 100 Mpixels per eye for state-of-the-art systems. Furthermore, their

total workspace can be somewhat constrained (approximately 9 × 9 ft. for typical setups).

Motivated by this situation, we designed and built the Reality Deck, the world’s first gigapixel-resolution display in a fully enclosed setting. Figure 1 depicts a synthetic, to-scale rendering of the facility; Figures 2 and 3 (and other figures in this article) show applications. The Reality Deck offers more than 1.5 Gpixel of resolution, a 360-degree horizontal FOV, and a workspace of approximately 33 × 19 × 11 ft. This configuration lets multiple users naturally explore data at different scales by approaching or distancing themselves from the displays while maintaining the panoramic context. This display real estate can be abstracted in planar or immersive configurations.

Immersive Virtual Environments

IVE design is driven largely by two factors: the visual acuity (VA) and degree of immersion. VA is a metric that quantifies the quality of the visuals a display can deliver. Maximizing VA lets users approach the display surfaces and naturally perform multiscale exploration (rather than perceive the display technology’s resolution limits). For details on VA, see the sidebar.

The degree of immersion is the level of suspension of disbelief that a visualization system provides. Carolina Cruz-Neira and her colleagues defined five key factors for maximizing immersion:³

The Reality Deck is a visualization facility offering state-of-the-art aggregate resolution and immersion. It’s a 1.5-Gpixel immersive tiled display with a full 360-degree horizontal field of view. Comprising 416 high-density LED-backlit LCD displays, it visualizes gigapixel-resolution data while providing 20/20 visual acuity for most of the visualization space.

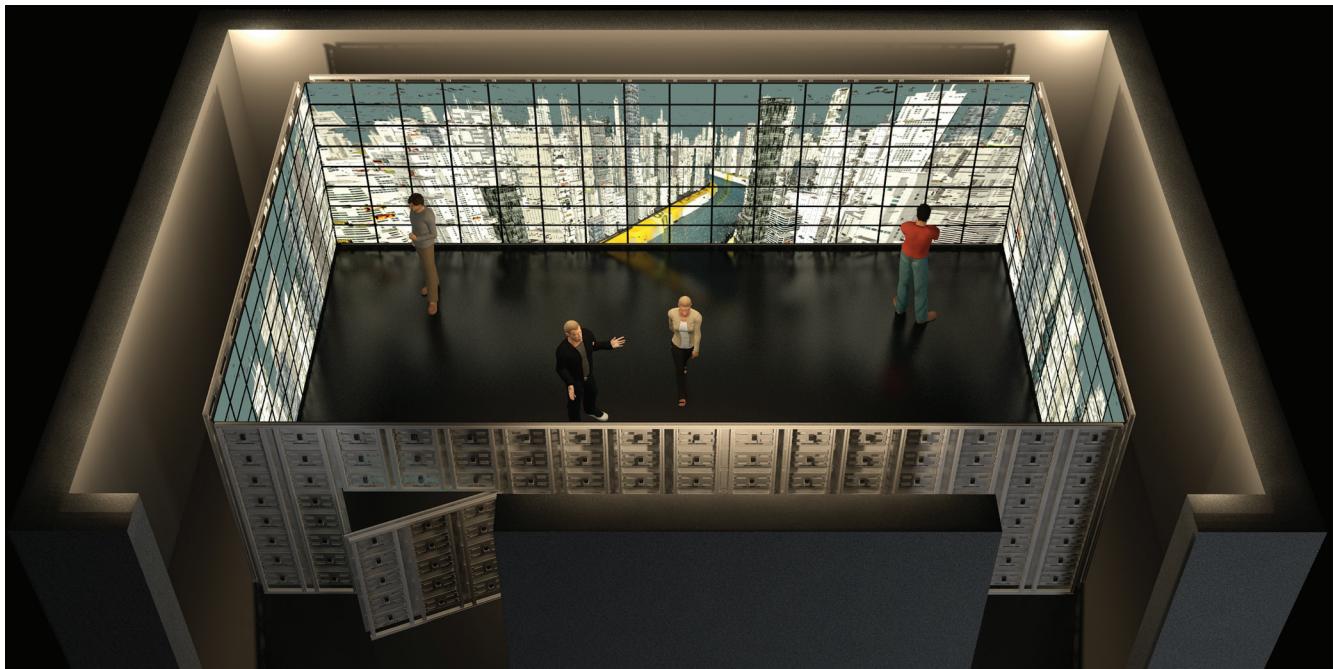


Figure 1. A synthetic, to-scale view of the immersive gigapixel Reality Deck facility displaying a geometric model of future New York City (approximately 40 million triangles with hundreds of materials).



Figure 2. An interior view of the Reality Deck, showing the front wall and partial side walls. A user is exploring a fused geographic-information-system dataset of downstate New York, which incorporates elevation information, road networks, and detailed 3D geometry for select areas. Insets illustrate the detail that can be resolved by approaching the facility walls, with building facades and architectural details easily distinguishable.

- *a view-centered perspective* (head tracking),
- *panorama* (surrounding the viewer with visuals),
- *body and physical representation* (users' awareness of the interactive workspace's physical constraints),
- *intrusion* (restricting the user's senses) and
- *the FOV* (the display portion users can observe without rotating their head).

The CAVE's popularity is a testament to its ability to optimally combine these factors. Whereas maximizing VA allows for natural zooming through the data, maximizing immersion enables a wider range of panning by looking around.

CAVEs are routinely used for data visualization in a number of scenarios, but the concept arguably isn't keeping up with growing datasets. For example, the CORNEA (kvl.kaust.edu.sa/Pages/CORNEA.aspx), a high-end CAVE installation, offers approximately 100 Mpixels per eye. But modest examples of panoramic images from www.gigapan.com can exceed 1 Gpixel.

Another consideration for current immersive facilities is their ability to deliver quality visuals as a factor of the observer's position in the visualization space. As Figure 4a shows, the CORNEA provides VA of approximately 20/34 but only at a sweet spot in its center. For a single user, moving

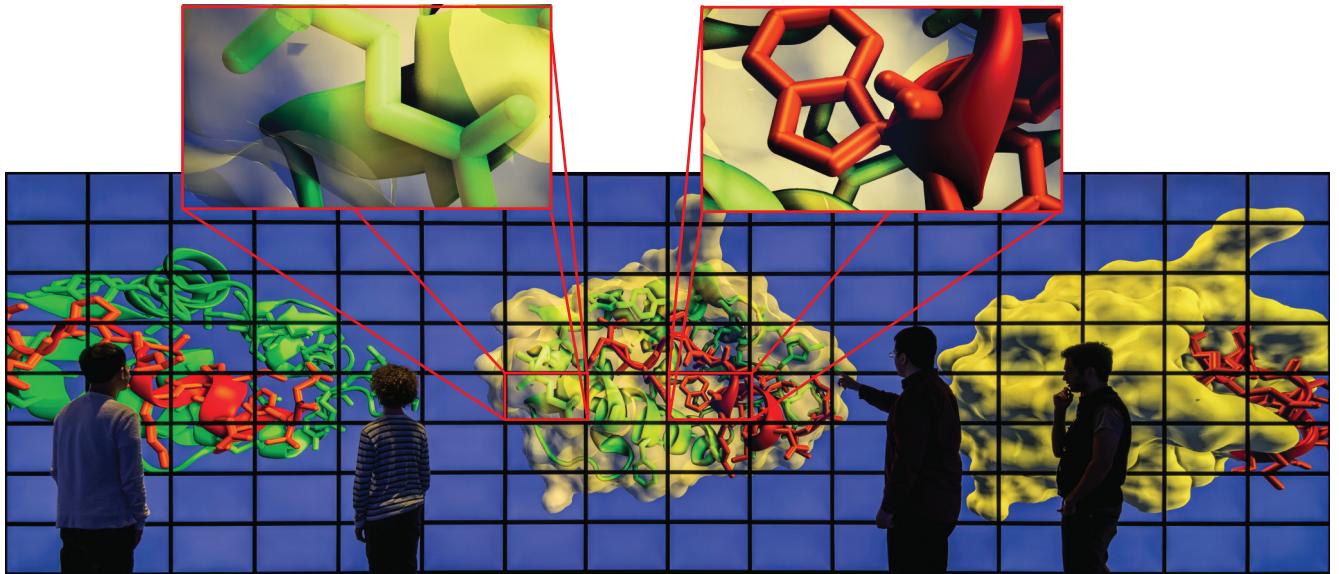


Figure 3. Visualization of the MDM2 oncprotein binding to the p53 tumor suppressor. Users are simultaneously exploring different visualization modalities that bring out various features of the dataset. The insets show zoomed-in crops of the visualization, highlighting the effects of ambient occlusion, which in combination with alpha blending, provides additional depth queues to the viewers.

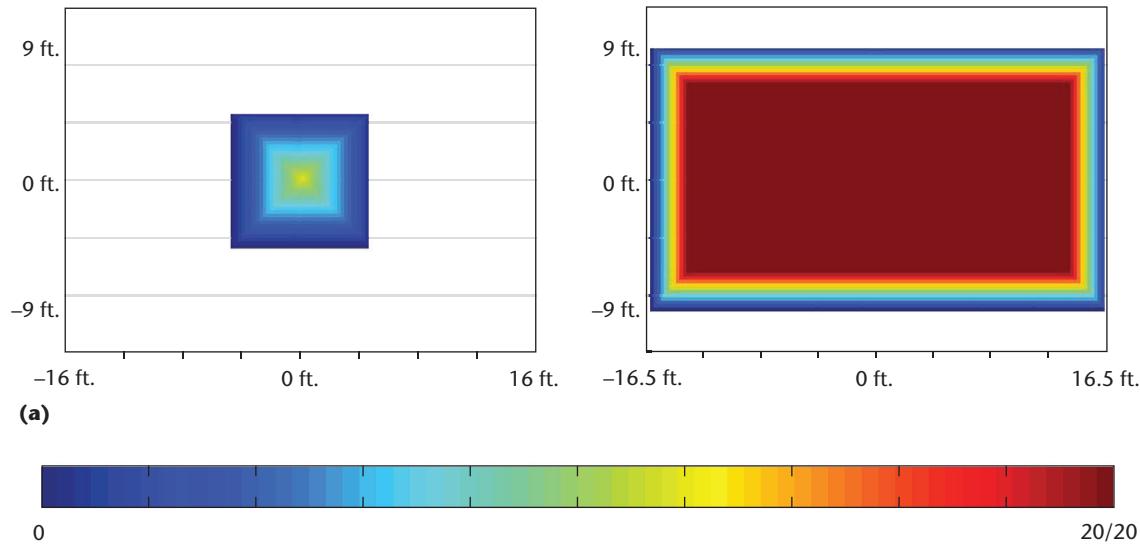


Figure 4. Visual acuity (VA) heatmaps (floor plan views) for the CORNEA CAVE (Cave Automatic Visual Environment) and Reality Deck. (a) The CORNEA offers 20/34 VA in a 10×10 ft. workspace. However, the maximum visual quality is achievable only at the facility's center. (b) In contrast, the Reality Deck offers a large workspace of 33×19 ft. Given its monitor configuration, 20/20 VA can be achieved approximately 31 in. from the displays. This translates to a total workspace area with 20/20 VA of approximately 384 sq. ft.

away from this sweet spot can occur naturally in a head-tracked 3D application. This movement results in the user approaching display surfaces that don't saturate his or her visual system, creating a suboptimal visual experience. Even worse, in multiuser scenarios, only one user can occupy the location with maximal VA, forcing lower-quality visuals on the other collaborators.

Conversely, powerwalls are targeted at visualiz-

ing high-resolution data. High-end systems, such as the Stallion powerwall (www.tacc.utexas.edu/resources/visualization), can reach 300 Mpixels of aggregate resolution. However, these facilities materialize as a single planar surface, resulting in two issues. First, they offer only a small degree of physical immersion to users (whose FOV is saturated by the large display, but without any panorama). Second, planar designs can be unwieldy

Visual Acuity

As you approach a fixed-resolution display's surface, the individual pixels become increasingly discernible. Visual acuity (VA) is often used to "quantify" a visualization's quality. In a hypothetical 2D world, for a display of width W (in inches) and horizontal resolution H (in pixels), the dot pitch (distance between two pixels) is $P = W/H$. If you're looking at a single pixel at the center of the display from D inches away, that pixel covers an angle of approximately $\tan^{-1}(P/D)$ on your horizontal field of view (FOV). The VA for this setup is equal to the portion of the pixel that covers 1/60th of a degree of your FOV, or $1/\tan^{-1}(P/D)$.

This VA metric correlates directly to the more commonly used Snellen fraction, which quantifies vision. The fraction $20/X$ corresponds to "this person can see at 20 feet what a person of average vision can see at X feet." You determine a person's Snellen fraction by asking him or her to distinguish characters (or optotypes) that have been precisely spaced to project to certain visual angles at fixed distances. You divide the Snellen fraction to get the VA metric.

Frequently, the Snellen fraction (rather than the less intuitive scalar metric) is used to quantify a display's VA. For example, for an iPhone 5 display, $W = 2.17$ and $H = 640$. Looking at the display from $D \approx 10$, you get a VA of approximately 0.856 pixels per minute or a Snellen fraction of $20/23.4$. The same calculation along the diagonal yields a VA of $20/21$. This led to the name "Retina display" because if the user approached the display more, he or she wouldn't be able to perceive additional visual information.

Recently, it was argued that VA shouldn't be the primary driver in tiled-display design.¹ Although doubling the VA metric doesn't necessarily correspond to doubling the perceived visual information, there are positive effects (for example, reduced perceived aliasing). The proliferation of high-DPI screens indicates that sharp visuals matter in displays. More important, increased resolution allows the visualization of minute details that would otherwise require zooming to resolve. Increasing the display's VA affords additional levels of detail that users can reach simply by moving closer to the screen, expanding the potential for physical navigation (which is beneficial to exploration²). Christopher Andrews and his colleagues offered great insight into how resolution affects different types of data visualizations.³ So, optimizing the VA metric was a primary concern when we designed the Reality Deck (see the main article).

References

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to scale owing to spatial constraints and potential ergonomic issues of traversing large distances during visual exploration.

Hybrid designs contemporary with the Reality Deck, such as the CAVE2,⁴ bridge the gap between CAVEs and powerwalls. These designs place more emphasis on CAVE-like characteristics such as stereoscopic 3D.

"Immersifying" a Tiled Display Wall

As a higher-level goal, we felt that the Reality Deck should provide the high pixel density of tiled displays but also the full FOV of CAVEs. As a next-generation facility, it should offer a significant leap in aggregate resolution (with the gigapixel milestone being an obvious choice). Also, 20/20 VA should be available for most of a large visualization space, to promote physical navigation. Additionally, the facility had to fit in the available 40×30 ft. lab space and cost no more than US\$1,000,000.

The Reality Deck defines an enclosed space surrounded by high-pixel-density displays. The

displays' arrangement presented an open design problem. After considering different placements of display surfaces, we opted for a rectangular arrangement with four walls. This layout enables interesting usage scenarios, depending on the nature of the data and collaborative situation. It's different from most CAVE systems, which use a cube-like arrangement of displays. Our rectangular layout allows for more operational flexibility and maximizes the use of the available lab space.

The straightforward mapping lets the Reality Deck's four walls serve as configurable viewports into the virtual world, akin to a CAVE. Or, we can interpret the display as a single continuous planar viewport. This configuration is useful for large-scale 2D data (for example, geographical-information-system parallel coordinates). A visual discontinuity exists where the two extremes of the logical frustum meet on the physical display surface (typically in the middle of the rear wall). To naturally ameliorate this shortcoming, we employ our Infinite Canvas technology.⁵ This continuous-viewport display mapping addresses traditional

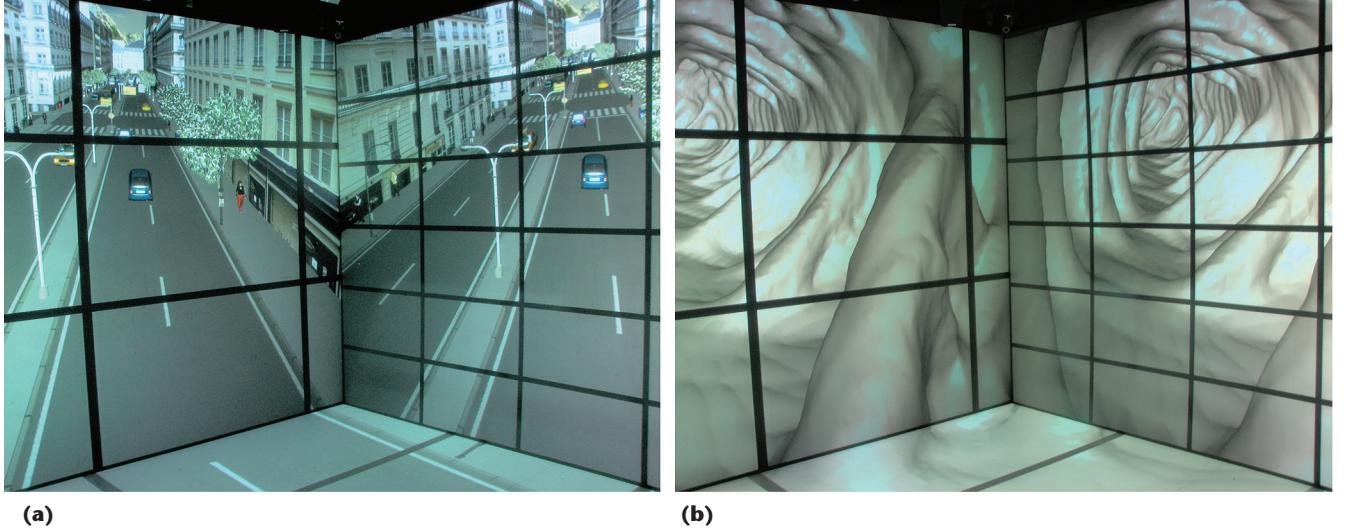


Figure 5. We evaluated the perceptual effects of the screen and bezel size for different LCD monitors in the Immersive Cabin. In both images, the left wall simulates a large-format planar monitor (60 in. diagonal) and the right wall is the Samsung S27A850D monitor with modified bezels (27 in. diagonal).

planar powerwalls' scalability problems. (We describe the Infinite Canvas in more detail later.)

In multiuser scenarios, we can subdivide the display space in various ways. For example, we can split it into four planar tiled displays, one per wall. Here, each of the two long walls offers approximately 471 Mpixels of resolution; each narrow side wall has 295 Mpixels. For additional immersion, we can create two CAVE-like systems, with three walls each, operating independently. Each of these CAVEs offers roughly 0.76 Gpixel resolution, depending on the border space that separates the CAVEs' viewports. This pixel count is several times larger than that offered by state-of-the-art CAVE systems, at the expense of bezels and anaglyph-only stereo (owing to the selected panel technology).

Building an Immersive Gigapixel Display

Hardware component selection is a critical aspect of constructing a large-scale visualization system. From the display system to the visualization cluster, every component affects the resulting system's overall capabilities. Here, we discuss several engineering choices we made when constructing the Reality Deck.

Display Selection and Customization

Arguably the most critical component of a visualization environment is the display subsystem. CAVEs are usually based on projectors, whereas tiled display arrays use both projectors and LCD monitors.

Projectors can create a nearly seamless image but require regular maintenance. For our five-sided, 10-projector CAVE-like Immersive Cabin,⁶ we always manually recalibrate the system after

maintenance. This can be time-consuming for the Immersive Cabin and would be unmanageable for a system employing hundreds of projectors. Additionally, projectors produce significant heat and noise, and the need to accommodate the throw distance (as much as 1.5 ft. for short-throw lenses) affects the space requirements. Finally, projectors are generally much more expensive than LCDs to acquire and maintain. Because of these drawbacks, we eliminated projectors early during design.

We then considered different types of LCD monitors on the basis of these criteria:

- **Resolution target.** On the basis of the available space and supergigapixel-resolution target, the monitors should provide approximately 100 pixels per inch (PPI).
- **Bezel size.** Ideally, the bezel should be smaller than 5 mm; it shouldn't exceed 8 mm for a 23 in. display and 15 mm for a 30 in. display. We based these metrics on the bezel dimensions of commercially available monitors with potential structural modifications.
- **Display size.** Larger monitors are preferable as long as they can deliver the required pixel density.
- **Image quality.** The monitors should use high-quality panels with good contrast, backlight uniformity, and viewing angles.
- **Stereo support.** Stereo is very desirable, but not at the cost of image quality or significantly reduced pixel density.

We evaluated a number of displays with panel sizes from 23 to 60 in.; IPS (in-plane switching), PVA (patterned vertical alignment), and PLS (plane-to-line switching) panel technologies; and

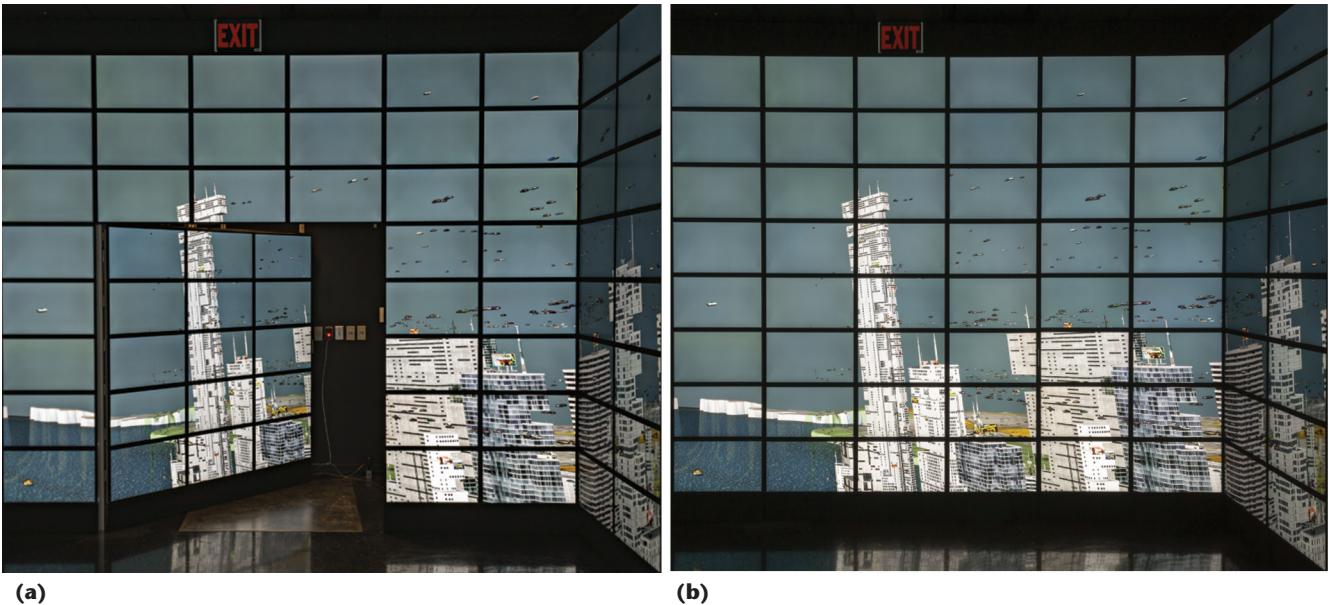


Figure 6. The Reality Deck's door. (a) A 3×5 grid of displays is mounted on an aluminum subframe and rotates around a spring-loaded hinge. The mechanized door can be operated from within the Reality Deck. (b) When closed, the door blends into the rest of the structure, in this case showing a futuristic view of New York City.

various bezel sizes. We also considered secondary factors, such as power consumption and weight, which affect the requirements for the mounting, power, and cooling infrastructure. We simulated the different tiled-display designs in our Immersive Cabin (see Figure 5) to analyze the bezels' perceptual effects on different visualization tasks, (for example, medical and architectural visualization) in an informal user study. We took this study's results into account when selecting the displays.

We considered several offerings from various vendors, including ultranarrow-bezel LCDs and monitors with stereoscopic 3D support. We rejected these offerings, for reasons we explain later. At the time of construction, no commercially available display satisfied all five criteria; however, the Samsung S27A850D provided a good balance. It's a professional 27 in. PLS panel with $2,560 \times 1,440$ resolution and excellent contrast, color saturation, and viewing angles. Unlike CCFL (cold-cathode fluorescent lamp) monitors, the S27A850D uses LED backlighting, which significantly reduces the weight and power requirements (46 W for the S27A850D versus 134 W for a Dell U2711). Finally, although the original bezel is relatively large, we easily modified the monitors with a custom mount that reduced the bezel to 14 mm.

Given the available physical space, we arranged the monitors in four orthogonal surfaces. The front and back walls are 16 displays wide; the left and right span 10 displays. All four walls are eight displays tall, for a total of 416 tiled monitors.

The mass-produced nature of commercial monitors entails certain variation in image quality,

even for products from the same batch. We evaluated every monitor before modification, looking primarily at image uniformity when the monitor displayed a full white and a full black signal. We also identified color reproduction issues. We took three photographs of each monitor from a fixed camera position, with a standardized set of camera and display settings. On the basis of the stacks of images, we replaced 98 of the first batch of 441 monitors. After testing the second batch, we selected the best 416 displays, and a set of spares, for modification and use.

Using lightweight monitors let us design custom mounting brackets and a simple aluminum frame so that individual monitors can be aligned with submillimeter accuracy (confirmed via laser leveling) and can be replaced by a single person. The plastic cover of the S27A850D houses the circuit board, user controls, and power supply. We moved these components to the rear bracket, creating a uniform black frame around the display with no visual distractions. The door to the facility is a section of the frame that's mounted on a hinge and holds a 3×5 grid of monitors. It is power operated but can be opened manually in an emergency. When closed, the door is completely flush with the rest of the wall and visually indistinguishable from the other displays (see Figure 6). The displays are offset from the floor by approximately 7 in. to allow for the installation of tracking cameras and sound speakers.

Figure 4b shows a heatmap of the VA in our facility, illustrating the 384 sq. ft. space in which the system achieves 20/20 or better VA.

Visualization Cluster and Peripherals

The large number of displays presented a challenge for designing a cost-efficient high-performance visualization cluster. We evaluated several configurations, at various GPU- and display-per-node densities.

Our final setup consists of 18 Exxact nodes, with dual hexcore Intel Xeon E5645 CPUs. Each node contains four AMD FirePro V9800 GPUs. The head node is a similarly configured machine with a single GPU. Most cluster nodes drive 24 displays, six per GPU, in a 3×2 monitor grid. The displays of two render nodes in the facility's front-right and back-left corners operate in 1×4 groups. This ensures that no display group straddles the facility's corners, which would necessitate two rendering passes when the facility operates in immersive mode.

Each display group is abstracted as a single framebuffer using AMD Eyefinity functionality, simplifying software development and improving performance. The cluster is in a machine room next to the facility and connects to the displays using Gefen DisplayPort fiber-optic extenders. All nodes are interconnected via Ethernet and 40 Gbps InfiniBand networks. The facility uses approximately seven miles of cables.

The Reality Deck also uses a 24-camera Opti-Track tracking system based on the S250e infrared camera. Several research techniques, which we describe later, use this tracking system for both user interaction and performance optimization. Additionally, we deployed a 24.4 surround-sound system with Genelec 6010A speakers and JBL LSR4312SP subwoofers. The facility hardware, including spare monitors and a hot-swappable spare visualization node, cost approximately \$950,000.

Visualization Software and Performance Benchmarks

We created two visualization frameworks for driving the Reality Deck, using a number of third-party libraries (for example, Nvidia SceniX and Equalizer⁷) and custom extensions for interaction, tracking, and out-of-core rendering. Because each node in our cluster drives four Eyefinity display groups, 72 instances of the rendering application run at the same time. So, we distribute input and per-frame variable data (such as physics-enabled scene graph object state) to each node. Also, the visualization is handled locally, unlike systems based on OpenGL command-stream distribution (for example, Chromium).

The most critical aspect for GPU performance is having sufficient GPU memory for the large frame buffers required when driving a six-display Eyefin-

ity group with $7,680 \times 2,880$ resolution from a single GPU. In such situations, the OpenGL buffers and two multisampled full-screen render targets can require 2 Gbytes or more of memory. So, the minimum we considered suitable was 4 Gbytes per GPU.

We evaluated the low-level rendering performance with the SPECviewperf 11 benchmark. When we moved from a single WQXGA display to the full six-display Eyefinity group, performance dropped between 3 and 20 percent, depending on the application. Moving to 8x multisampling decreased performance by an additional 24 to 40 percent, but the visualization remained interactive even with the increased image quality and resolution. For shader-bound workloads, performance scaled linearly as we moved from one to six displays per GPU.

The Reality Deck is the only display to offer more than a billion pixels in a horizontally immersive setting and a large workspace that encourages physical navigation.

Given the high resolution per GPU, some traditional rendering algorithms (for example, volume rendering and GPU ray tracing) must be redesigned for interactive performance in the Reality Deck. Others, such as virtual or gigapixel texturing, can still run at 60 Hz provided that sufficient memory exists, memory transfers are managed asynchronously, and no full-screen render targets or compositing at the OS level is used. We expect that newer generations of GPUs will lift some of these performance restrictions.

With high-resolution data, a major bottleneck during rendering is that all the data doesn't fit in GPU memory. Our visualization pipelines support real-time out-of-core texturing, similarly to sparse virtual texturing,⁸ by decomposing data into fixed-size tiles loaded from external memory (or a network share) on the basis of the results of a visibility determination pass. For a virtual texture comprising approximately 60,384 tiles, precompressed to the DXT1 format at 520×520 resolution, we can achieve approximately 730 Mpixels/s of total CPU-GPU streaming bandwidth to each GPU in the system. This effectively provides 33 fps for bandwidth-bound applications.

Or, we can limit the number of tiles uploaded per frame to achieve higher frame rates. We can

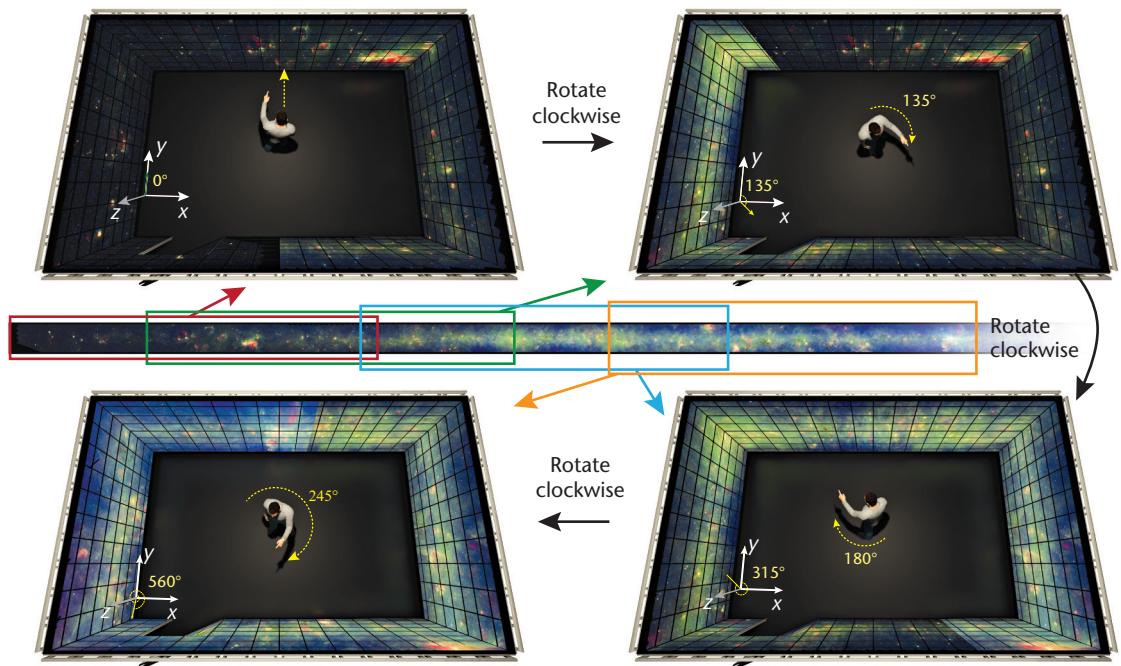


Figure 7. A synthetic view of the Reality Deck illustrating the use of the Infinite Canvas to explore the GLIMPSE/MIPSGAL Milky Way survey. The user first looks at the front wall then rotates clockwise, while the system uses the aggregate rotation σ to calculate the new data mapping. After an aggregate rotation greater than 360 degrees (see the bottom-left image), the user sees a new view of the data. All wall images are captured directly from the Reality Deck and show that the remapping discontinuity is always behind the user.

also use our research on acuity-driven gigapixel visualization (which we describe later) to further optimize data transfers, on the basis of the user's location in the Reality Deck.

Supporting Techniques

The Reality Deck is the only display to offer more than a billion pixels in a horizontally immersive setting and a large workspace that encourages physical navigation. The continuous display surface enables unique data exploration techniques, such as the Infinite Canvas. Meanwhile, the gigapixel resolution presents unique challenges in rendering different data types. Our acuity-driven gigapixel-visualization framework accounts for the distance between the user and the display when making streaming choices. We've also developed a novel frameless visualization to enable high-resolution volume rendering at interactive frame rates.

The Infinite Canvas

The Infinite Canvas is a navigation technique for physically exploring high-resolution data that extends arbitrarily along a single dimension. We first place the virtual camera in a closed, curvilinear surface with dimensions that approximate the aspect ratio of the facility's floor. We then map imagery onto this geometric surface. The

Infinite Canvas interactively manipulates the mapping on the basis of the user's position and orientation in the Reality Deck. Through this manipulation, users see the illusion of a surface that extends arbitrarily along one dimension because the wraparound discontinuity is kept outside their FOV.

More formally, using the tracking system, we obtain the user's position \mathbf{p} and 2D orientation \mathbf{d} , as well as the aggregate rotation σ with respect to a fixed reference vector. Additionally, we intersect the vector $\mathbf{p} - \mathbf{d}$ with the canvas's geometry to obtain \mathbf{p}_{back} , the point directly behind the user on the canvas surface. We then calculate an angular offset σ_{start} :

$$\sigma_{\text{start}} = 2\pi \left| \frac{\sigma}{2\pi} \right| - \text{atan2}(\mathbf{p}_{\text{back}_x} - \mathbf{p}_x, \mathbf{p}_{\text{back}_y} - \mathbf{p}_y).$$

If the data to be visualized spans a $[0, 1]$ range on the horizontal axis, we can extract a region $\alpha \cdot [\sigma_{\text{start}}/2\pi, \sigma_{\text{start}}/2\pi + 1]$, where α is a scale factor equal to the ratio between the mapped geometry's circumference and the canvas's total width. (For example, if the data is three times larger than the immersive display, $\alpha = 1/3$.) We then map this section onto the geometry, starting and ending at \mathbf{p}_{back} , placing the mapping discontinuity behind the user (see Figure 7). This mapping is computed

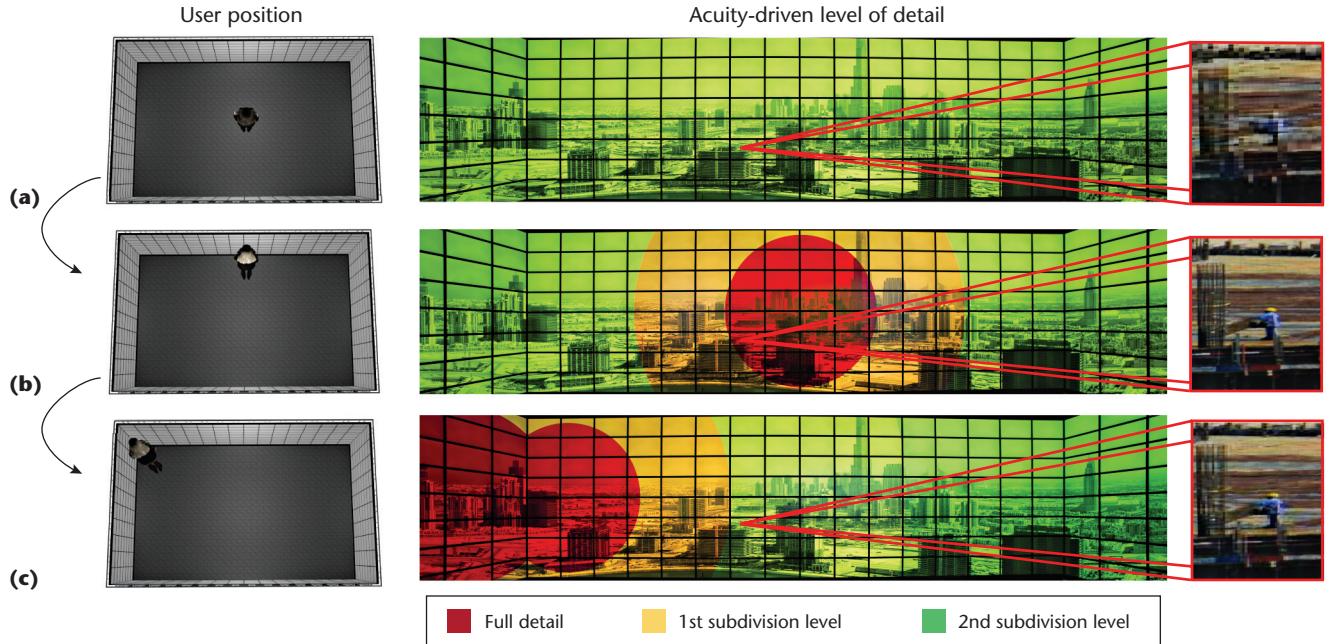


Figure 8. Using our acuity-driven gigapixel-visualization technique to explore a panorama of Dubai from Gigapan. (a) The user starts in the middle of the Reality Deck (the renderings on the left show her position). On the basis of her distance from the displays, our system selects the appropriate level of detail (LOD) for each pixel. The current LOD is color mapped and visible in the wide-angle photographs from the Reality Deck’s interior. (b) As the user approaches the front wall, the system adapts the LOD, delivering the full detail of the data to the displays closest to the user. (c) The LOD updates as the user moves to the facility’s front-left corner. The insets on the right show zoomed-in views of a small section of the front wall, illustrating the change in resolution as the user changes position.

inside a GLSL shader at runtime and is used to sample an out-of-core texture. For additional implementation information, see “Visual Exploration of the Infinite Canvas.”⁵

We found that the Infinite Canvas complements well the traditional approach to data exploration in the Reality Deck (walking along the displays and looking for points of interest). Indeed, without the Infinite Canvas, users eventually encounter the 2D frustum discontinuity at the facility’s rear wall and then use a controller to further scroll the data along its major dimension. The Infinite Canvas does let users skip through sections of the data with an external input device. However, it allows them a greater degree of mental immersion by obviating the need for a context switch between manipulating the visualization virtually and navigating physically by walking.

Acuity-Driven Gigapixel Visualization

During the exploration of gigapixel imagery, data transfer overhead to the visualization nodes can be substantial. To texture a 1.5-Gpixel display at full detail using 256^2 tiles, more than 13 Gbytes per second of bandwidth are required for a 30 fps refresh rate. In the previous example, all the Reality Deck’s displays were textured at full detail

(assuming a one-to-one mapping between display resolution and texels). However, users can perceive this detail only when standing at an optimal distance from the displays (in our case, roughly 31 in.). At larger distances, adjacent pixels become increasingly indistinguishable as their projections in the user’s visual system begin overlapping. So, it makes sense to select the image level of detail (LOD) dynamically, on the basis of the user’s distance from each display.

Most commodity rendering pipelines determine the image LOD on the basis of the projection of a particular pixel into texture space. In our visualization framework,⁹ we scale this projection on the basis of the user’s distance D' from a particular display. Specifically, if we assume an original texture space projection A , we calculate

$$A' = \frac{D'}{D_{\text{opt}}} A$$

(the farther away the user, the larger the texture space projection, resulting in a higher selected level in the LOD pyramid). On the basis of this notion, we calculate an acuity-based LOD offset m_{acu} :

$$\frac{1}{2^{m_{\text{acu}}}} = \frac{D_{\text{opt}}}{D'} \Rightarrow 2^{m_{\text{acu}}} = \frac{D'}{D_{\text{opt}}} \Rightarrow m_{\text{acu}} = \log_2 \left(\frac{D'}{D_{\text{opt}}} \right).$$

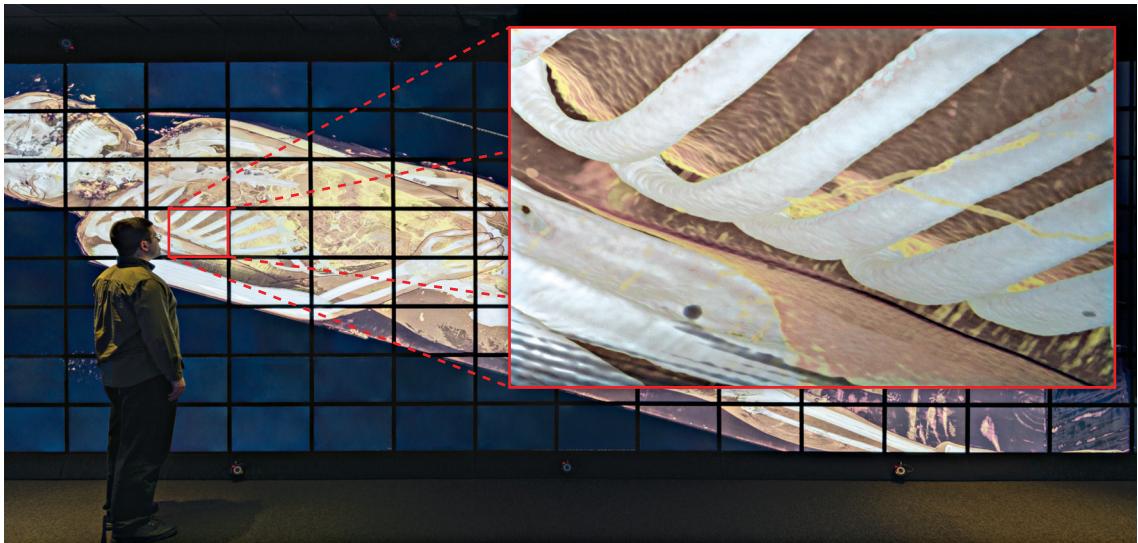


Figure 9. Exploring the Visible Human dataset using our frameless-visualization technique on a 471-Mpixel section of the Reality Deck. Despite the massive rendering resolution, the system remains interactive, achieving a stable 5 fps. Traditional volume rendering requires approximately 10 s to generate one frame, resulting in a noninteractive experience. The inset shows the image quality (including high-quality filtering, ambient occlusion, and global illumination) that can be achieved when the frameless visualization algorithm converges.

We bias this offset for quality, for the resulting LOD level

$$m' = m_{\text{MIP}} + \left\lceil \max \left(0, \log_2 \left(\frac{D'}{D_{\text{opt}}} \right) \right) \right\rceil,$$

where m_{MIP} is the normal LOD selected by the rendering system.

Figure 8 illustrates the operation of our technique (which happens per pixel on the GPU, with minimal performance overhead). Because this acuity-driven texturing delivers less than maximum detail to the displays, we evaluated the potential impact on user performance. A user study had subjects search for different-sized targets in a gigapixel-resolution image. With our technique, users didn't have to make special accommodations in their distance from the displays when searching for targets.⁹ Finally, we benchmarked our technique on synthetic usage sessions stemming from real tracking data and observed a substantial 70 percent reduction in data transfer overhead.

Frameless Visualization

Most applications use the GPU to produce a set of pixels over a regular 2D grid, which is then displayed using double buffering. As the resolution increases, so does the latency associated with generating a single frame. As an alternative, researchers have proposed frameless rendering that decouples pixel computation from the display system by approximating full-resolution images from

sparse sample sets.¹⁰ This comes at the expense of temporal coherency.

We developed a system for reconstructing high-resolution, high-frame-rate images from a multilayered collection of samples that are rendered framelessly. Unlike traditional frameless-rendering techniques, we generate the lowest-latency samples locally. These initial points also guide the sampling of more complex and computationally expensive effects (for example, global illumination).

Our system is based on a distributed single-pass ray-casting volume renderer. At the level of a single GPU and its attached displays, our system uses ray casting to generate samples at subnative resolution. It asynchronously reconstructs these samples into a low-resolution temporally upsampled preview image. This image is also used during the creation of the priority map that guides the remote rendering of higher-quality unstructured samples. The system can modify this map on the basis of the user's position in the Reality Deck.

An external source can provide a stream of rendered samples, which the system combines with the ones stored locally to progressively refine the final image. For Figure 9, a GPU cluster was the sample source. However, depending on the display configuration, the source can be an auxiliary GPU in the same system or even a cloud-based service. The resulting sample stream is broadcast across the network, and each visualization node stores samples belonging to the local viewport in a buffer that matches the display's full resolution.

During compositing, the system uses various

sample attributes (for example, age) to determine which samples to use during interaction. Depending on the rendering source's proximity to the local GPU, the latency can vary widely. Local, low-latency samples can be reliably used during scene changes. In contrast, remotely generated samples can have very high latencies, depending on the network configuration and the rendering parameters. Such samples can be used only to improve static scenes' resolution and image quality.

We demonstrated our frameless visualization in the Reality Deck using the Visible Human volumetric dataset ($512 \times 512 \times 2,048$ resolution). All render nodes used the same rendering modality but had different reconstruction filter and step sizes. Figure 9 shows the results on a 471-Mpixel section of the Reality Deck, when backed by a 30-GPU cluster. Double-buffered volume rendering at full resolution requires approximately 10 seconds per frame, during which the display freezes. In contrast, our system maintains interactive response (at a steady 5 fps), while image convergence takes between 1 and 2 minutes, depending on the view. Network bandwidth is a major limiting factor in further scaling of the system; we plan to investigate the performance impact of low-latency InfiniBand networking.

Discussion and Lessons Learned

Building a facility such as the Reality Deck is an act of balancing costs, features, and feasibility. For example, early during design, we planned to incorporate stereoscopic 3D. However, after examining the hardware landscape, we determined we'd have to employ either high-frame-rate active-stereo panels or a passively polarized solution.

Active-stereo monitors generally offer high pixel densities (for example, 1,080 resolution at 23 in. diagonal) but are implemented using twisted pneumatics or similar panel technologies that compromise on color consistency and viewing angles. Those two features are of utmost importance for a scientific-visualization display that promotes physical navigation, potentially placing users at grazing angles in relation to some monitors.

On the other hand, passive solutions offer half the display resolution when stereo is enabled and can suffer from "polarizer ghosting" when not viewed head-on.⁴ You can solve the ghosting issue by adjusting the display's polarizer layer, but this eliminates the option of using commodity products and increases the cost.

More advanced solutions can provide individual stereoscopic image pairs for multiple users by combining time multiplexing, polarization altering,

and color channel decomposition from multiple projectors.¹¹ Such an approach has substantial collaborative potential. However, it has limited practicality for large visualization systems because it requires six DLP (Digital Light Processing) projectors to provide a multiuser stereo frame buffer to six viewers.

Because a primary driver in the construction of our facility was to push the boundaries of aggregate resolution, we forewent stereoscopic 3D and relied on depth cues provided through motion parallax (which have been demonstrated to be stronger than stereo alone for some tasks). Given the collaborative nature of the Reality Deck, handling head tracking in multiuser scenarios is important. The solution depends on the application at hand. Approaches such as view-vector clustering followed by image blending¹² are possible if the computational cost of multiple rendering passes is affordable.

Building a facility such as the Reality Deck is an act of balancing costs, features, and feasibility.

Similarly, during design, we balanced bezel size with total resolution, landing on the side of visual fidelity. Several companies provide "bezelless" or ultranarrow-bezel displays (based on LCD or DLP technologies). However, such products are generally targeted at the digital-signage industry and aren't optimized for pixel density. (For example, such offerings often provide $1,920 \times 1,080$ resolution at 55 in. diagonal, resulting in 40.05 PPI versus 108.79 PPI with the Reality Deck. This substantially reduces the space in which users receive 20/20 VA.)

Design of the Reality Deck started in 2011, but future system builders will face similar dilemmas (with higher pixel density quantifiers). For example, 4K monitors are becoming increasingly affordable, offering approximately 160 PPI at 28 in. diagonal. A system comprising such displays could conceivably be constructed today (with performance and connectivity being potential caveats). The question becomes whether large displays' benefits scale to such extreme resolutions and display footprints (research has been conducted on significantly smaller systems). We feel the Reality Deck is the first platform that can answer such questions and are quantifying the scalability of

various visualization tasks when the display spans upward of 1 Gpixel in aggregate.

The Reality Deck (and other facilities such as the CAVE2) differs fundamentally from prior visualization systems in that it defines not only a display surface but also a clearly outlined space large enough to promote user movement. The techniques we've described arose organically from patterns in this movement. The acuity-driven LOD scheme leverages a fundamental property of large displays (users might be looking at portions of the visualization beyond their VA threshold), which is amplified by the Reality Deck's sheer size.

The Infinite Canvas was inspired by users' tendency to scan visualizations by physically navigating from one end of the display to the other. Our techniques are motivated by relatively basic observations, but they can still enable seamless interaction and substantially improve system performance. Although physical navigation has been an active research area for several years, we feel that its evaluation in the context of specific applications in extremely large immersive systems presents fertile ground for innovation. ■■■

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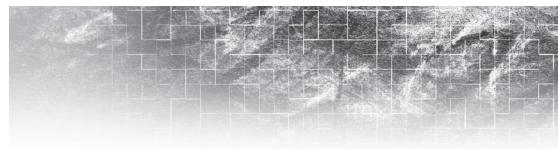
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