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A Virtual Frame Buffer Abstraction for Parallel Rendering of Large Tiled Display Walls

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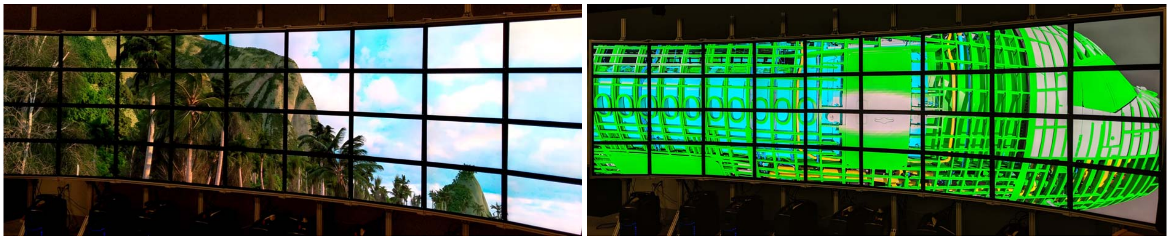

Figure 1: Left: The Disney Moana Island [18] rendered remotely with OSPRay's path tracer at full detail using 128 Skylake Xeon (SKX) nodes on Stampede2 and streamed to the 132Mpixel *POWERwall* display wall, averages 0.2-1.2 FPS. Right: The Boeing 777 model, consisting of 349M triangles, rendered remotely with OSPRay's scivis renderer using 64 Intel Xeon Phi Knight's Landing nodes on Stampede2 and streamed to the POWERwall, averages 6-7 FPS.

Abstract

We present *dw2*, a flexible and easy-to-use software infrastructure for interactive rendering of large tiled display walls. Our library represents the tiled display wall as a single virtual screen through a display "service", which renderers connect to and send image tiles to be displayed, either from an on-site or remote cluster. The display service can be easily configured to support a range of typical network and display hardware configurations; the client library provides a straightforward interface for easy integration into existing renderers. We evaluate the performance of our display wall service in different configurations using a CPU and GPU ray tracer, in both on-site and remote rendering scenarios using multiple display walls.

Index Terms: Tiled Display Walls; Distributed Display Frameworks

1 Introduction

Tiled displays are important communication tools in modern visualization facilities. They are beneficial to visualization in many ways: displaying the features of data at a large scale increases the user's sense of immersion, better conveys a sense of scale (e.g., when viewing an entire car or airplane), and the high resolution provided is valuable when visualizing highly detailed datasets (Figure 1). Perhaps most importantly, tiled displays are powerful communication tools and can engage a large group of collaborators simultaneously.

A number of high-end visualization facilities feature tiled displays, using either multiprojector systems, CAVEs [4, 17], or multiple high-resolution LED panels—such as TACC's 189 MPixel *Rattler* display wall and 328 MPixel *Stallion*, NASA's 245 MPixel HyperWall 2, or SUNY StonyBrook's RealityDeck. Unfortunately, the exact requirements, configurations, and software stacks for such tiled display walls vary greatly across systems, and thus there is no easy or standardized way to use them [3]. Visualization centers often build their own proprietary software for driving such walls, requiring system-specific modifications to each software package to use the wall. Typical software set-ups often assume that each display node will render the pixels for its attached display [6, 9, 16]. Rendering on the display nodes is sufficient for moderately sized datasets but not for large-scale ones. To support large data, systems typically render on an HPC cluster and stream the image back to the display wall.

DisplayCluster [10] and SAGE2 [12] are two general and widely used streaming frameworks for tiled display walls that can support local and remote collaborations with multiple devices, such as kinect, touch overlays, or smart phones/tablets. One disadvantage is that communication with the display wall must be performed through a master node. The master node, therefore, must be powerful enough to process and stream all the pixels for the entire display wall to avoid becoming a bottleneck. DisplayCluster is used for scientific visualization as it supports distributed visualization applications using IceT [13]. However, IceT, a sort-last compositing framework, is less well suited for large tile-based ray tracing applications [19].

In this paper, we describe a lightweight open-source framework for driving tiled display walls from a single node or distributed renderer. In our framework, the display wall is treated as a single virtual frame buffer managed through a display service. Our framework supports both dispatcher and direct communication modes between the rendering clients and display service to support typical network configurations. The direct mode can relieve network congestion and the bottleneck on the master node, which makes it possible to use low-cost hardware for display walls, e.g., the Intel NUC mini PCs [1]. Moreover, our framework can easily be used by both CPU and GPU renderers for portability. We demonstrate integration of our library into OSPRay [20] and a prototype GPU raycaster [21] for interactive rendering on typical tiled display walls and low-cost display walls. Our contribution are:

- We present a lightweight open-source framework for driving tiled display walls that can be integrated into CPU and GPU renderers;
- The framework can transparently operate in the dispatcher or direct mode to support typical network configurations;
- We demonstrate this framework for use in deploying low-cost alternatives for display walls.

2 Related Work

2.1 Cluster-Based Tiled Display Walls

A large number of supercomputing centers now use a tiled display wall for some of their high-end visualizations. These systems come in a mix of configurations, in terms of the display layout, hardware used to drive the displays, and network connectivity to local and

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remote HPC resources. For example, TACC's Stallion and Rattler systems and NASA's Hyperwall 2 use a single node per display; however, the POWERwall at the Scientific Computing and Imaging (SCI) Institute uses one node per column of four displays. Each node on the POWERwall is directly accessible over the network, and on Hyperwall 2, each node is connected directly to Pleiades. However, on Stallion and Rattler, the display nodes are not externally visible and must be accessed through a head node. We refer to the survey by Chung et al. [3] for a more in-depth discussion of tiled display wall frameworks.

2.2 GPU Rendering on Tiled Displays

Parallel rendering on a cluster based on OpenGL is a common solution for driving tiled displays. Eilemann et al. [5] presented an experimental analysis of the important factors for performance of parallel rendering on multi-GPU clusters. The basic approach for OpenGL-based applications is to run an instance of the application on each node, with a master node used to broadcast user interactions to the display nodes. The Chromium project [9], an automatic method for such approaches, intercepts the application's OpenGL command stream and broadcasts it to the worker nodes. The Chromium Renderserver [16] also supports the distributed-memory parallel rendering using Chromium. However, it is inherently limited by the available processing power on the display nodes, requiring powerful on-site hardware.

An alternative to having each node render the pixels for its display is to use a compositing or pixel routing framework that can route pixels from the render nodes to the corresponding display node. One of the first methods using such an approach was described by Moreland et al. [14], who used a sort-last compositing scheme for rendering to tiled display walls. The same general approach is now available in IceT [13], where users can specify a number of output windows and provide a callback to render specific frusta for the displays. Equalizer [6], introduced by Eilemann et al., supports scalable parallel rendering and can distributed rendering works directly to worker nodes. However, Chromium and Equalizer are all specific to OpenGL, and IceT is less applicable to tile-based ray tracers. Moreover, these frameworks impose the rendering work distribution on the application, and are not suited to applications that perform more complex load balancing.

2.3 Distributed Display Frameworks

A work similar to our own for driving tiled display walls was proposed by Johnson et al. in the "DisplayCluster" framework [10]. Similar to our proposed framework, DisplayCluster makes a clear distinction between a display wall "service", which receives pixels and presents them on the appropriate displays, and client applications, which produce these pixels and send them to the service. DisplayCluster assumes that the display nodes are connected over a high-bandwidth network, but that they are not visible to the external network and must be accessed through a head node. The head node communicates with clients over TCP and broadcasts the received pixel data to the display nodes over the Message Passing Interface (MPI) [8]. The display nodes then decompress the pixel data and discard portions of the received image that are outside their display region. DisplayCluster has found wider use in the communities (e.g., by the Blue Brain Project), and has been used for displaying interactive rendering from Stampede on Stallion [11].

SAGE2 [12] is another popular windowing environment for tiled displays, designed for collaborative workspaces on tiled display walls. OmegaLib [7] is designed for similar use cases, with a focus on stereo tiled display environments. DisplayCluster, SAGE2, and OmegaLib support displaying multiple applications on the wall simultaneously, each streaming to its own virtual window, which can be repositioned using the library. These libraries are more similar to full-featured window managers, whereas, in contrast, we aim to

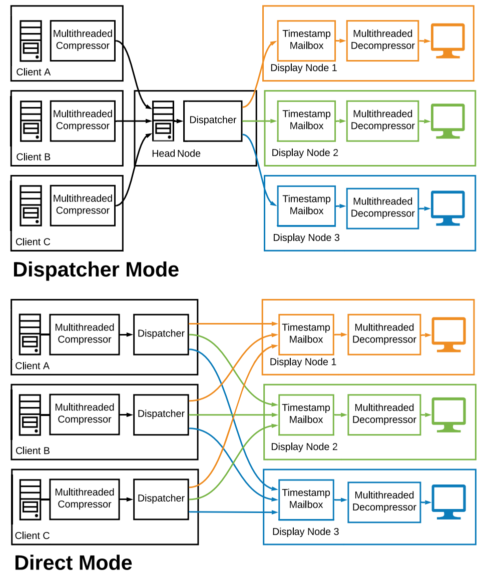


Figure 2: An overview of *dw2* in the dispatcher and direct communication modes. The best mode for the system's network architecture can be used as needed, without modifying the rendering client code.

provide a simple lightweight framebuffer abstraction that can be rendered to by a single application.

Biedert et al. [2] recently demonstrated a parallel compositing framework for streaming from multiple asynchronously running image sources, leveraging GPU video compression and decompression hardware. They achieve consistently real-time rates compositing hundreds of sources into a single 4K or tiled video stream. However, their system requires GPU-accelerated video encoding and does not consider a synchronized full-resolution frame rate across the displays.

3 Framework Overview

Our framework, *dw2*, is split into an MPI parallel display service that manages the mapping from the single virtual framebuffer to the physical tiled display wall (Section 3.1) and a client library used to connect renderers to the display service (Section 3.2). The client can be a single program, an MPI-parallel program, or a distributed application with some custom parallel communication setup. To allow for different configurations of the clients and displays, e.g., rendering on the display nodes, on a different on-site cluster, or on a remote cluster, we use TCP sockets to communicate between the clients and displays through a socket group abstraction. We provide pseudo-code of how the display service cooperates with the rendering clients in the supplementary material. Source code and detailed instructions can be found in the project repository: `https://github.com/MengjiaoH/display_wall`.

3.1 Display Service

The display service supports two modes: a *dispatcher mode*, where a central dispatch node manages routing of tiles to the display nodes, and a *direct mode*, where clients send tiles directly to the display nodes (see Figure 2). The latter mode can achieve better network utilization and performance, but on some systems the display nodes are not visible to the outside network for security reasons and must be accessed via a single externally visible node.

The display service is run using MPI, with one process launched per display on each node. In the dispatcher mode, an additional process is needed, and rank 0 is used as the dispatcher on the head node. At start-up the service is passed information about the windows to open on each node, their location on the wall, and the bezel size, to provide a single continuous image across the displays.

In both the dispatcher and direct modes, rank 0 acts as the information server for the wall. Clients connect to the service through this rank and receive information about the display wall's size and configuration. In the dispatcher mode, all clients connect to the dispatcher through a socket group. In the direct mode, clients are sent back host name and port information for each display that they then connect to directly. Each display process returns its size and location in the display wall to allow each client to perform tile routing locally. Each tile consists of an uncompressed header specifying its size and location, along with the JPEG compressed image data.

On both the dispatcher and the display processes, multiple threads are used for receiving and sending data, and for decompressing tiles on the displays. Communication between threads is managed by *timestamped mailboxes*, which are locking producer-consumer queues that can be optionally filtered to return only messages for the current frame. Each socket group is managed by a pair of threads, one that takes outgoing messages from the mailbox and sends them, and another that places received messages into an incoming mailbox. In the dispatcher mode, the dispatcher receives tiles, reads their header, and routes them to the display processes they cover via MPI. In the direct mode, each client tracks the individual display information received above and runs its own dispatcher to route tiles directly to the displays via the socket group. Each display places incoming messages into a timestamped mailbox. A set of decompression threads take tiles for the current frame from the mailbox, decompress them, and writes them to the framebuffer. Once all pixels in the virtual framebuffer have been written, the frame is complete.

After the frame is complete, process 0 sends a token back to the clients to begin rendering the next frame. This synchronization prevents the renderer from running faster than the displays, and thus a buildup of buffered tiles, causing them to run out of memory. However, it causes a delay on how soon the renderer can start on the next frame. To alleviate this delay, users can configure the number of frames that can be in flight at once, allowing the renderer to begin the next frame immediately to buffer some number of frames. If the renderer and displays run at similar speeds, this approach will significantly reduce the effect of latency.

3.2 Rendering with the Client Library

The client library provides a small C API to allow for easy integration into a range of rendering applications (also see supplemental materials). Clients first query the size of the virtual framebuffer from the display service using `dw2_query_info`, after which they connect to the service to set up a socket group. Depending on the mode used by the display service, the library will either connect to the dispatcher or to each individual display. Connections are established using socket groups, where each client sends a token returned with the initial information query and its number of peers, allowing the display process to track when all clients have been connected. All clients then call `dw2_begin_frame`, which returns when the display service is ready to receive the next frame. The client can divide the image into tiles as it sees fit to distribute the rendering workload. After a tile is rendered, the client calls `dw2_send_rgba` to send it to the display service. The tile is then compressed and sent to the dispatcher or the overlapped displays by the library. The client library also leverages multiple threads for compression and networking, in the same manner as the display processes.

4 OSPRay Integration

We integrate our client library into OSPRay (version 1.8) through a pixel operation that reroutes tiles to the display wall. Pixel operations in OSPRay are per-tile postprocessing operations that can be used in local and MPI-parallel rendering through OSPRay's Distributed FrameBuffer [19]. After querying the display wall's dimensions, we create a single large framebuffer with the display wall's size and attach our pixel operation it. The framebuffer is created with the `OSP_FB_NONE` color format, indicating that no final pixels should be stored. By sending the tiles in the pixel operation and creating a `NONE` format framebuffer, we can send tiles directly from the node that rendered them and skip aggregating final pixels to the master process entirely.

(a) Landing Gear, on the NUCwall (b) The Moana Island, on Rattler.

Figure 3: The test images and use cases of (a) the landing gear remote rendering to the low-cost NUCwall and (b) the Moana Island Scene on-site rendering to Rattler.

5 GPU Raycaster Integration

The prototype GPU raycaster [21] uses OptiX [15] (version 6.5) for rendering on a single node equipped with one GTX 1070 GPU. To allow rendering to large-scale display walls, we extend the renderer with an image-parallel MPI mode that divides the image into tiles and assigns them round-robin to the processes. On each rank, we create a tiled framebuffer containing the tiles it owns and render them using the prototype's existing renderer code. After the tiles are rendered, each rank passes its tiles to *dw2* to be sent to the displays. To achieve interactive performance at high resolution, we also extend the rendered with a screen-space subsampling strategy.

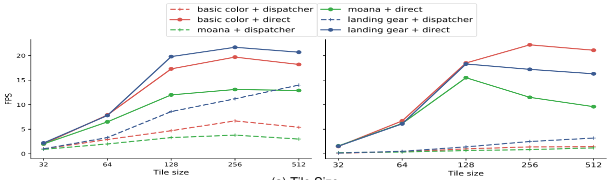
6 Experiments and Results

We evaluate the performance of *dw2* in on-site and remote streaming rendering scenarios to study the performance of the dispatcher and direct modes, the impact of compression and the client's chosen tile size on performance, and scalability with the number of clients and displays in Section 6.1. We demonstrate interactive rendering use cases of *dw2* on a range of datasets in Section 6.2 using OSPRay and the GPU renderer.

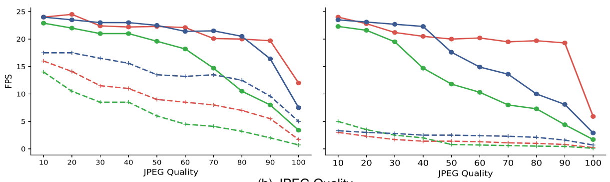
We conduct our evaluation on three tiled display wall systems: the POWERwall and NUCwall at SCI and Rattler at TACC. The POWERwall has a 9×4 grid of 2560×1440 monitors (132Mpixel), with each column of four monitors driven by one node, along with an optional head node; each node has an i7-4770K CPU. The NUCwall has a 3×4 grid of 2560×1440 monitors (44Mpixel), with each column of four monitors driven by an Intel NUC (i7-8809G CPU). We run on a subset of TACC's Rattler, a 3×3 grid of 4K monitors (74Mpixel), with each display driven by a node with an Intel Xeon E5-2630 v3 CPU. The POWERwall and NUCwall use the same network configuration, where each node has a 1Gbps ethernet connection and is accessible externally. Rattler's display nodes are not accessible externally and are connected to a head node using a 1Gbps network, with a 1Gbps connection from the head node to Stampede2.

6.1 dw2 Performance Evaluation

To isolate the performance impacts of the different configurations of *dw2* from the renderer's performance, our benchmarks are run using pre-rendered images created using OSPRay. These images are representative of typical visualization and rendering use cases on display walls, and they vary in how easily they can be compressed. The Landing Gear contains a complex isosurface with a large amount of background and compresses well, and the Moana Island Scene

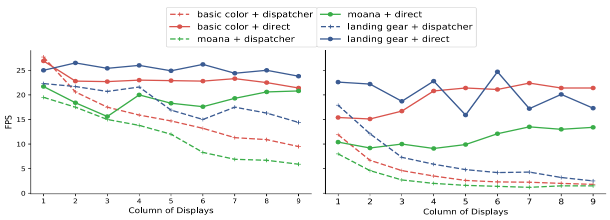


(a) Tile Size.

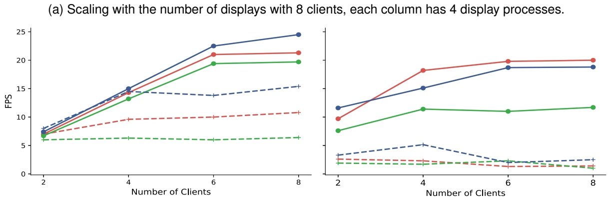


(b) JPEG Quality.

Figure 4: The performance impact of different tile sizes and JPEG quality settings in both modes on the POWERwall. Left: Clients run on-site on an eight-node KNL cluster. Right: Clients run remotely on eight KNL nodes on Stampede2.



(a) Scaling with the number of displays with 8 clients, each column has 4 display processes.



(b) Scaling with the number of clients sending to all 9 display columns.

Figure 5: Scalability studies on the POWERwall. Left: Clients run on-site on an eight-node KNL cluster. Right: Clients run remotely on eight KNL nodes on Stampede2.

contains high-detail geometry and textures and is challenging to compress (see Figure 3). Additionally, we benchmark on a generated image with varying colors within each tile to provide a synthetic benchmark case that is difficult to compress. For on-site client benchmarks, we use a local cluster with eight Intel Xeon Phi KNL 7250 processors; remote rendering benchmarks use eight KNL 7250 nodes on Stampede2.

In Figure 4a, we evaluate the display performance when using different tile sizes on the client. We find that small tile sizes, which in turn require many small messages to be sent over the network, underutilize the network and achieve poor performance. Larger tile sizes correspond to larger messages, reducing communication overhead and achieving better performance as a result. This effect is more pronounced in the dispatcher mode, as the overhead of the small tiles must be paid twice: once when sending to the dispatcher, and again when sending from the dispatcher to the display.

In Figure 4b, we evaluate the performance impact of the JPEG quality threshold set by the client. As display walls are typically on the order of hundreds of mega-pixels, compression is crucial to reducing the bandwidth needs of the system to achieve interactive rendering performance.

In Figure 5, we evaluate the scalability of *dw2* when increasing the number of displays or clients. We find the direct mode scales well with the number of displays and clients, since each client and display pair can communicate independently, whereas the dispatcher mode introduces a bottleneck at the head node.

Based on the results of our parameter study, we recommend using

Figure 6: Unstructured volume raycasting in our prototype GPU renderer run locally on six nodes, each with two GTX 1070s.

Figure 7: Data-parallel rendering of the 500GB DNS volume ($10240 \times 7680 \times 1536$ grid) with OSPRay on 64 SKX nodes on Stampede2, streamed to the POWERwall in direct mode, averaging 6-10 FPS.

dw2 with a 128^2 or 256^2 tile size with JPEG quality of 50-75, and we prefer the direct mode if the underlying network architecture supports an all-to-all connection between the clients and displays.

6.2 Example Use Cases

We demonstrate *dw2* on interactive rendering of several medium- to large-scale datasets across the three display walls using a range of client hardware. Figures 1 and 7 show medium- to large-scale datasets rendered remotely on 64 or 128 Stampede2 Skylake Xeon nodes with OSPRay and streamed back to the POWERwall using the direct connection mode. In Figure 6, we use our GPU prototype raycaster to render across six nodes, each with two NVIDIA GTX 1070 GPUs, and displayed locally on the POWERwall using the direct mode. In Figure 3b, we show the Moana Island Scene rendered on Stampede2 with OSPRay and displayed locally on Rattler, using the dispatcher mode. In Figure 3a we render the Landing Gear AMR isosurface on-site using the eight node KNL cluster and displayed on the NUCwall in direct mode. For both on-site and remote rendering on CPU and GPU clusters, *dw2* allows renderers to achieve interactive performance (also see the supplemental video).

7 Discussion and Conclusion

We have presented an open-source lightweight framework for rendering to large tiled display walls from a single source, based on a virtual frame buffer abstraction concept. Our framework is easy to integrate into rendering applications and provides the flexibility required to be deployed across the display wall configurations typically found in visualization centers. Moreover, we have demonstrated that combining low-cost display nodes with remote rendering on an HPC resource can be a compelling option for interactively driving tiled displays.

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REFERENCES

[1] Intel® NUC – Small Form Factor Mini PC. https://www.intel.com/content/www/us/en/products/boards-kits/nuc.html.

[2] T. Biedert, P. Messmer, T. Fogal, and C. Garth. Hardware-Accelerated Multi-Tile Streaming for Realtime Remote Visualization. In *EGPGV*, 2018.

[3] H. Chung, C. Andrews, and C. North. A Survey of Software Frameworks for Cluster-Based Large High-Resolution Displays. *IEEE transactions on visualization and computer graphics*, 2013.

[4] C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart. The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*, 1992.

[5] S. Eilemann, A. Bilgili, M. Abdellah, J. Hernando, M. Makhinya, R. Pajarola, and F. Schürmann. Parallel Rendering on Hybrid Multi-GPU Clusters. In *Eurographics Symposium on Parallel Graphics and Visualization*. The Eurographics Association, 2012.

[6] S. Eilemann, M. Makhinya, and R. Pajarola. Equalizer: A Scalable Parallel Rendering Framework. *IEEE transactions on visualization and computer graphics*, 2009.

[7] A. Febretti, A. Nishimoto, V. Mateevitsi, L. Renambot, A. Johnson, and J. Leigh. Omegalib: A Multi-view Application Framework for Hybrid Reality Display Environments. In *2014 IEEE Virtual Reality (VR)*, 2014.

[8] E. Gabriel, G. E. Fagg, G. Bosilca, T. Angskun, J. J. Dongarra, J. M. Squyres, V. Sahay, P. Kambadur, B. Barrett, A. Lumsdaine, et al. Open MPI: Goals, Concept, and Design of a Next Generation MPI Implementation. In *European Parallel Virtual Machine/Message Passing Interface Users' Group Meeting*. Springer, 2004.

[9] G. Humphreys, M. Houston, R. Ng, R. Frank, S. Ahern, P. D. Kirchner, and J. T. Klosowski. Chromium: A Stream-processing Framework for Interactive Rendering on Clusters. *ACM Transactions on Graphics*, 2002.

[10] G. P. Johnson, G. D. Abram, B. Westing, P. Navratil, and K. Gaither. DisplayCluster: An Interactive Visualization Environment for Tiled Displays. In *2012 IEEE International Conference on Cluster Computing*, 2012.

[11] A. Knoll, I. Wald, P. A. Navrátil, M. E. Papka, and K. P. Gaither. Ray Tracing and Volume Rendering Large Molecular Data on Multi-core and Many-core Architectures. In *Proceedings of the 8th International Workshop on Ultrascale Visualization*, UltraVis '13, 2013.

[12] T. Marrinan, J. Aurisano, A. Nishimoto, K. Bharadwaj, V. Mateevitsi, L. Renambot, L. Long, A. Johnson, and J. Leigh. SAGE2: A new approach for data intensive collaboration using Scalable Resolution Shared Displays. In *10th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing*, 2014.

[13] K. Moreland, W. Kendall, T. Peterka, and J. Huang. An Image Compositing Solution at Scale. In *Proceedings of 2011 International Conference for High Performance Computing, Networking, Storage and Analysis*, SC '11, 2011.

[14] K. Moreland, B. Wylie, and C. Pavlakos. Sort-last parallel rendering for viewing extremely large data sets on tile displays. In *Proceedings IEEE 2001 Symposium on Parallel and Large-Data Visualization and Graphics*, 2001.

[15] S. G. Parker, J. Bigler, A. Dietrich, H. Friedrich, J. Hoberock, D. Luebke, D. McAllister, M. McGuire, K. Morley, and A. Robison. OptiX: A General Purpose Ray Tracing Engine. *ACM Transactions on Graphics (Proceedings of ACM SIGGRAPH)*, 2010.

[16] B. Paul, S. Ahern, W. Bethel, E. Brugger, R. Cook, J. Daniel, K. Lewis, J. Owen, and D. Southard. Chromium Renderserver: Scalable and Open Remote Rendering Infrastructure. *IEEE Transactions on Visualization and Computer Graphics*, pp. 627–639, 2008.

[17] K. Reda, A. Knoll, K.-i. Nomura, M. E. Papka, A. E. Johnson, and J. Leigh. Visualizing Large-scale Atomistic Simulations in Ultra-resolution Immersive Environments. In *LDAV*, 2013.

[18] R. Tamstorf and H. Pritchett. Moana Island Scene. http://datasets.disneyanimation.com/moanaislandscene/island-README-v1.1.pdf, 2018.

[19] W. Usher, I. Wald, J. Amstutz, J. Günther, C. Brownlee, and V. Pascucci. Scalable Ray Tracing Using the Distributed Framebuffer. In *Computer Graphics Forum*. Wiley Online Library, 2019.

[20] I. Wald, G. P. Johnson, J. Amstutz, C. Brownlee, A. Knoll, J. Jeffers, J. Günther, and P. Navrátil. OSPRay – A CPU Ray Tracing Framework for Scientific Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 2017.

[21] I. Wald, W. Usher, N. Morrical, L. Lediaev, and V. Pascucci. RTX Beyond Ray Tracing: Exploring the Use of Hardware Ray Tracing Cores for Tet-Mesh Point Location. In *Proceedings of High Performance Graphics*, 2019. (To Appear), http://www.sci.utah.edu/~wald/Publications/2019/rtxPointQueries/rtxPointQueries.pdf.