Picowalls: Portable Tiled Display Walls from Pico Projector Arrays

Aaron Knoll Cody Hammock Jo Wozniak Nathaniel Mendoza Paul Navrátil Brandt Westing

Texas Advanced Computing Center, The University of Texas at Austin
Email: knolla,hammock,jwozniak,nmendoza,pnav@tacc.utexas.edu

Microsoft Corporation
Email: brandtw@microsoft.com

***Abstract*—We present picowalls, a method to create portable, high-resolution multi- projector displays driven by small, inexpensive "pico" projectors. We demonstrate a six-projector picowall system that can operate as either a front- or back-projected display device. Our modular system offers affordable and portable high-resolution display capability built from off-the-shelf hardware that can be deployed where conventional displays are impractical. We envision picowalls playing a strong role in outreach, and in scientific research applications benefiting from high-resolution collaborative displays on the field, outside of the visualization lab.**

I. Introduction

Tiled displays are now ubiquitous devices for visualization, outreach and exhibition involving high-resolution imaging. Though LCD panels have decreased in price, multi-panel displays are difficult to reconfigure and move, and expose visually disruptive seams or bezels. Multi-projector displays have proven less popular due to their higher cost per pixel, difficulty of setup and calibration, and space and lighting needs [17]. However, both panel and projector tiled displays face problems of portability and versatility, which are increasingly important in the outreach efforts for which they are most used in practice.

Pico projectors [5] are relatively new devices that generally weigh less than a pound and provide the highest resolution-to-price ratio among projections systems. They operate with low lumens and lightweight optics, but their short throw distance (typically 2–10 feet) make them an intriguing option for compact, high-pixel-density displays. Using small LED light sources and light-duty optics, pico projectors exhibit relatively low geometric distortion. Their small size enables use of lightweight mounts and simplifies transportation logistics. This combination of features makes pico projectors uniquely well-suited for installation in a backlit multi-projector system, even without edge overlap.

In this paper, we describe a method to construct picowalls: high-resolution displays from pico projectors using off-the-shelf mounting and computing hardware. This paper makes the following contributions:

- Introduces the concept of picowalls, modular back-projected arrays of pico projectors, providing a portable, scalable high-resolution display resource;
- Demonstrates a six-projector, six megapixel (MP) prototype from off- the-shelf components. The 8'×4' (107" diagonal) system offers resolution approaching that of a 4K display, at the fraction of the cost of 4K projectors and large 4K panels, and is easily portable; and
- Compares picowalls to other high-resolution display technology.

The rest of this paper proceeds as follows. In Section II we discuss work related to portable projection systems. We describe our picowall construction method in detail in Section III. We compare our prototype system to other options in Section V and we discuss future work and conclude in Section VI.

II. Related Work

Multi-projector displays became popular in the 1990's beginning with their adoption in the original CAVE environment at EVL [10], University of Illinois Chicago. Subsequently, planar tiled displays were installed at UNC Chapel Hill, Stanford, Sandia and Argonne National Laboratories in the USA, and the Fraunhofer Institute in Germany, among numerous other locations (see, e.g. [15]).

Beginning with the seminal work of Raskar and Brown [18] at UNC Chapel Hill, and Majumder and Stevens [15] at the University of Chicago, a significant body of research has been built around edge-blending and color-calibrating multi-projector arrays with overlap, summarized in e.g. [16]. Extending these techniques, seamless multi-projector calibration has been achieved for curved walls [20] and recently large CAVE-like environments [21].

While the techniques for seamless multi-projector display exist, implementations that integrate them into a single desktop environment are rare. Proprietary solutions (e.g. [8]) exist for blending several large screens vertically in Windows. The open-source Lighttwist project [6], [12] enables similar functionality in Linux using Compiz.

Not all multi-projector displays employ edge blending. The Active Mural at Argonne National Laboratory (e.g. [13]) remains in production, consisting of 24 720p projectors in a backlit configuration, projecting onto a thick acrylic. Projectors are placed at an appropriate distance from the target surface in a way that minimizes geometric distortion. Forgoing edge blending allows for using the full resolution of the component displays. The ActiveMural's portable sibling, the μ-Mural, employed short-throw projectors for a more compact rear-projected setup. While significant manual effort is required for proper alignment, one can achieve an effect similar to extremely thin bezels, with no visible overlap of screens. Our own work is inspired by this installation, and seeks to create

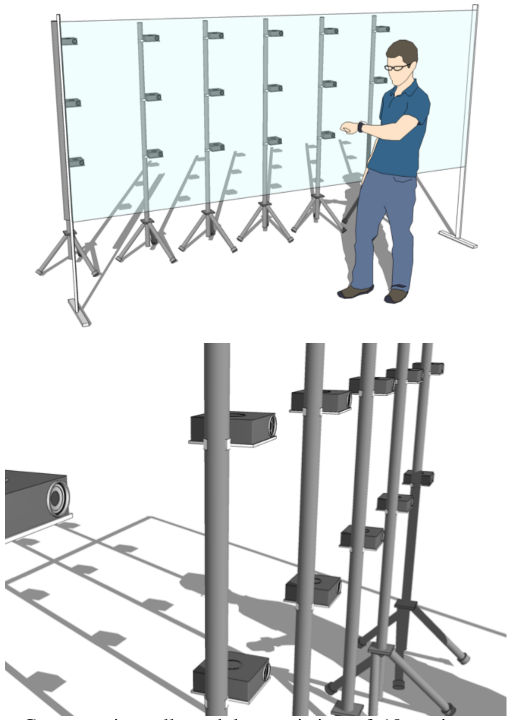

Fig. 1. Concept picowall module consisting of 18 projectors, driven by a single workstation with 6 outputs and six 3-way splitters. Projectors are mounted with lightweight, inexpensive photography equipment, designed for easy micro-adjustment.

a smaller-scale, less expensive, even more portable version of that equipment that is simpler to calibrate.

III. Picowalls

Picowalls create a functioning portable multi-projector display providing several megapixels of resolution. While previous multi-projector systems have focused on how to deploy multiple projectors for seamless displays in large, fixed installations, we are chiefly interested in creating a high-resolution display with portability, low weight, low cost and maximum usability.

Pico projectors provide the following properties:

- a low cost-per-pixel ratio ($400 per megapixel);
- lightweight optics with minimal barrel distortion from the lens;
- bright LEDs with long life (no replacement bulb costs);
- light (0.8 lb) and small (∼20 cubic inches);
- short projection distance (2–10 ft) and relatively wide throw ratio (3:2), which make up for low lumens output;
- small total space requirement (short throw distance).

We assert that by assembling many pico projectors into a tiled display, one can achieve high pixel density and acceptable brightness and contrast in a lightweight package with a compact installation. The immediate challenges in creating a portable multi-projector display are what to project onto, how to mount it and drive it. Our aproach entail to these challenges entails:

- Using off-the-shelf phototography equipment for all mounting equipment, of both the projectors and screen. Alignment is a delicate operation, requiring high precision and stiffness to deliver and preserve an aligned multi-projector image. The light-weight construction of each pico projector places particular importance on the rigidity of the mounting frame, but permits use of far lighter apparatus than would be required for arrays of larger projectors.
- Enabling rear projection, which maximizes pixel density and eliminates the problem of the user occluding projection beams. This requires screen material designed to stand closer to the light source (3–5 feet) than most fixed back-projected installations, exhibit good diffusion, and maintain the portability of our system. We note that front projection remains desirable for conference rooms and large walls, and our system should support both.
- Driving the largest practical portable projector display from a single workstation, enabling use of regular applications in Windows and Linux. However, larger distributed displays could be modularly assembled from single- workstation modules.

We originally envisioned picowalls as a larger effort involving multiple (5) modules of 18 projectors at 18 MP, which could be combined into a 90 MP distributed display using DisplayCluster [14]. Each module would be a stand-alone system driven by a single workstation with six video outputs, each output powering three 720p projectors via a splitter. An 18 MP module is shown in Figure 1.

In practice, we decided to construct a smaller prototype system to assess the viability of the larger-scale concept. The subsequent section and remainder of this paper show the implementation and findings of that effort.

IV. Six-Projector Prototype

The six-projector prototype is the first attempt at realization of our system concept. We desire a wide-format, 8'×4' display, similar in footprint to the Lasso touch display at TACC [22], but less expensive and more portable. Here, we describe our deployed 3840×1600 (6 MP) system capable of front- and rear-projection.

A. Projector

We chose the Dell M110 ultra-mobile projector [3], a 1280×800 (1 MP) pico projector. It uses a LED light source (20,000 hour life) delivering 300 ANSI Lumens, with a contrast ratio of 10,000:1, focused through a fixed f/2 lens. It is specified for projection distances of 3.18 – 8.48 feet, and has a reasonably wide throw ratio of 1.5.

The M110 functions well in practice. We were able to achieve in-focus images projecting as close as 2.5 feet. Though rated at 300 lumens, the M110 produces extremely bright images projecting from 3.5 – 4.5 feet, and exhibits crisp borders with no visible barrel distortion. The main disadvantages of the M110 are color fidelity and moderate fan noise (32 decibels in economy mode), both of which are acceptable given the price.

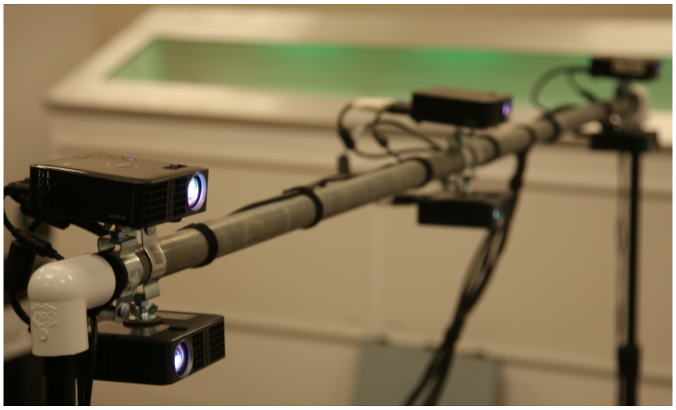

Fig. 2. Projector mount. We secure six projectors horizontally onto a single 6'×1.5" steel pipe, and use stainless steel brackets for individual mounts. Using microphone stands, the resulting construction is stiff. A similar outcome could be achieved with a sufficiently rigid photography backdrop kit.

B. Mount

The M110 accepts a 1/4"×20 camera tripod bolt, and given its weight placement on a tripod is logical. However, it was readily apparent that manual alignment would be difficult when adjusting projectors on separate tripods. To mount multiple projectors vertically on one tripod as envisioned in Figure 1 would require expensive articulating joints.

Our solution was to mount projectors on a rigid *horizontal* bar, using steel clamps and bolts from the hardware store designed to fit 1.5" PVC, as shown in Figure 2. Projectors can be fitted so that the beams rest directly on top of each other. A 6' bar allows for projecting onto a 90" wide screen. The M110 firmware provides keystone correction ensuring a perfectly rectangular image despite the slight verticle angle. There is no in-projector feature for flipping the image of the bottom projector, but this can be remedied in the video driver. We used microphone stands and PVC joints to support the bar from the floor. The entire mounting apparatus with 6 projectors and cables weighs roughly 20 pounds, and can be easily carried by one person. The mount enables extremely accurate alignment of six projectors, as shown in Figure 3.

C. Screen

Due to their high cost and difficulty of transit, we avoided rigid acrylic sheets conventionally used for back-projection. We instead opted for a Da-Lite Ultra Wide Angle flexible fabric screen [2]. This material allows for a viewing angle of up to 78 degrees, and is well-suited for multi-projector applications. For both a screen mount and enclosure for the entire rear-projected picowall, we chose lightweight 80/20 QuickFrame aluminum framing [1]. The total cost for both screen and frame was roughly $1,000.

Alternately, we experimented with even less expensive polycarbonate plastics commonly used in professional signage and often used for LED illumination applications. We tested products by 3M (the Envision line of graphic film) and Lexan (8A series polycarbonate graphics film), and noticed especially good contrast from the Lexan polycarbonate 8A13 film. A 48"×94" single sheet provides good diffusion and a crisp image, and cost roughly $50. Besides cost, an advantage of this material is that it can be easily rolled into a poster tube, but is potentially rigid enough to function as a touch screen. While the 1/16" screen was too thin and resulted in hotspots, we believe a 1/8" screen would be sufficient, and could potentially be rigid enough to support touch.

D. Workstation, Software and Setup

We drive our prototype picowall using a single Dell T7500 workstation and an ATI Radeon 5870 Eyefinity 6 GPU. The GPUs require active mini-DisplayPort adapters, which we include in the system cost. However, the M110s accept HDMI input, so the adapters can be eliminated if a different GPU is used. We have deployed both Windows 7 and Ubuntu 12.04 Linux on this machine, each capable of running common visualization applications such as ParaView [9].

Installation involves unpacking the frame, screen and mount, matching the cables to the correct projector, and manually aligning the projectors. Alignment by an experienced user takes roughly half an hour.

V. Discussion

In this section, we compare our six megapixel prototype to systems with similar resolution composed of display tiles and full-sized projectors. Below, we provide system configurations using the lowest online price for each component with sufficient technical capability.

The total retail cost of our system, including mount, screen and enclosure is conservatively $4,000. An older workstation and AMD Eyefinity 6 GPU can be acquired for $1,000. A single 4K projector (Sony VPL-VW1000ES, $25,000) would be highly portable, but currently costs over five times the full picowall system. Achieving a compact rear-projected setup with a single 4K projector would likely require the use of mirrors and sacrifice some portability. Inexpensive 1080p projectors (Acer H6510BD, $800) have a comparable price per pixel to the picowall, but would require heavier support apparatus. A single 84" diagonal 4K panel (LG 9600, $10,000) offers smaller viewing area, would be costly to carefully transport, and is still significantly more expensive than the picowall system. Multiple panel LCD's are extremely inexpensive and would provide higher pixel density and resolution (50" Seiki SE50UY04 4K TV, $1200) but would require heavy-duty mounting apparatus to construct a tiled display ($1500 for the 80/20 frame used in TACC tile displays [17]). A brief comparison is shown in Table I.

Tiled arrays of flat panels have become the *de facto* choice for high-resolution displays, with notable exceptions such as the 4k-projector Cornea system at KAUST [11]. We see this trend continuing for large, fixed installations [7], [17]. Panels offer low cost, better color contrast and stereo capabilities that are currently unmatched by projectors. Panel displays sport increasingly thin bezels, as demonstrated in the CAVE2 immersive system at EVL [4], [19]. With inexpensive 40" 4k panels roughly equaling the price of 1080p projectors, picowalls will not compete solely in price per pixel.

We believe picowalls can fill a gap in the current range of high-resolution displays, where there is not sufficient space for a traditional projection system and when the cost and framing of a tiled display system is impractical or impossible. A picowall module can potentially be transported in a suitcase; we envision these systems extending the reach of high-resolution

display	approx. total cost	display unit	price/unit	#units	total resolution (MP)	diagonal	portable
picowall	$4,000	Dell M110	$400	6	6	80–123”	yes
single 4K projector	$25,000	Sony VPL-VW1000ES	$25,0000	1	8 MP	100–150”	yes
1080p projector wall	$4,000	Acer H6510BD	$25,000	3	6 MP	80–150”	yes
single 84” panel	$11,000	LG 9600	$10,000	1	8 MP	84”	no
50” panel tiled display	$6,300	Seiki SE50UY04	$1,200	4	32 MP	114”	no

TABLE I. APPROXIMATE PRICE COMPARISON CREATING A $\geq$ 6 MP, 110” DIAGONAL DISPLAY.

displays outside their conventional places in visualization laboratories or CAVE’s, and fulfilling an important role of large displays: outreach. We believe picowalls have potential as vehicles for engaging K-12 students in schools, providing exhibits for museums and art galleries, and potentially assisting scientists with large spatial visualization problems on the field, particularly in the geosciences. The small space requirement for pico-driven rear projection (while retaining flexibility to use front projection), low cost of equipment, and light weight strongly encourage technologies such as this.

VI. CONCLUSION

In this paper, we have presented picowalls, a modular system for low-cost, high-resolution portable projection displays. We demonstrated a working six- projector picowall prototype that can be constructed from off-the-shelf hardware at the fraction of the cost of a single 4K projector or large single-panel display, and providing a significantly more compact and portable package than tiled panel or standard multi-projector displays.

In this work we wished to examine the “worst-case” scenario, with no software edge-blending and manual alignment of bezels to be as thin and seamless as possible. Under these circumstances, we believe the 6-projector picowall to be a serviceable display, though setup requires some patience on the part of the end-user. However, color matching and edge blending for a truly seamless display will be vital for systems larger than our prototype and for more widespread adoption of picowalls. While our pico projectors are closely color matched, there are still noticable variances across projector fabrication lots, which become more objectionable on larger, edge-blended displays. The newer AMD W600 GPU promises in-driver edge blending at a future date, presumably enabling in-OS seamless display under Windows. In Linux, we plan further experimentation with the LightTwist [6] edge blending framework for compiz. Incorporating more sophisticated large-scale camera-driven color and edge blending techniques, such as those of Majumder et al [15], [20], into an open-source display framework like DisplayCluster [14] would enable very high resolution projection independent of support by specific operating system or graphics hardware.

ACKNOWLEDGMENTS

We wish to thank Stephen Sofhauser and Dell Corporation for their generous provision of hardware, as well as Kelly Gaither and Jay Boisseau at TACC for their support of its development. We thank Mark Hereld at Argonne National Laboratory and Aditi Majumder at the University of California at Irvine for their help and input, and the anonymous reviewers for their comments.

REFERENCES

[1] “80-20 quickframe, http://www.8020.net/quick-frame-1.asp.”

[2] “Da-lite rear projection screens, http://www.da-lite.com/products.”

[3] “Dell m110, http://www.dell.com/ed/business/p/dell-m110/pd.”

[4] “Evl cave2, http://www.evl.uic.edu.”

[5] “Handheld projectors, http://en.wikipedia.org/wiki/handheld_projector.”

[6] “Lighttwist, http://vision3d.iro.umontreal.ca/en/projects/lighttwist.”

[7] “Reality deck, http://labs.cs.sunysb.edu/labs/vislab/reality-deck-home.”

[8] “Scalable display, http://www.scalabledisplay.com.”

[9] J. Ahrens, B. Geveci, and C. Law, “Paraview: An End User Tool for Large Data Visualization,” *the Visualization Handbook. Edited by CD Hansen and CR Johnson. Elsevier*, 2005.

[10] 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*, vol. 35, no. 6, pp. 64–72, 1992.

[11] T. A. DeFanti, D. Acevedo, R. A. Ainsworth, M. D. Brown, S. Cutchin, G. Dawe, K.-U. Doerr, A. Johnson, C. Knox, R. Kooima *et al.*, “The Future of the CAVE,” *Central European Journal of Engineering*, vol. 1, no. 1, pp. 16–37, 2011.

[12] J. Draréni, S. Roy, and P. Sturm, “Geometric Video Projector Auto-Calibration,” in *Computer Vision and Pattern Recognition Workshops, 2009. CVPR Workshops 2009. IEEE Computer Society Conference on*. IEEE, 2009, pp. 39–46.

[13] M. Hereld, I. R. Judson, J. Paris, and R. L. Stevens, “Developing Tiled Projection Display Systems,” in *Proc. IPT 2000 (Immersive Projection Technology Workshop)*, 2000.

[14] G. P. Johnson, G. D. Abram, B. Westing, P. Navratil, and K. Gaither, “DisplayCluster: An Interactive Visualization Environment for Tiled Displays,” in *Cluster Computing (CLUSTER), 2012 IEEE International Conference on*. IEEE, 2012, pp. 239–247.

[15] A. Majumder, Z. He, H. Towles, and G. Welch, “Achieving Color Uniformity across Multi-Projector Displays,” in *Visualization 2000. Proceedings*. IEEE, 2000, pp. 117–124.

[16] A. Majumder and B. Sajadi, “Advances in Large Area Displays: The Changing Face of Visualization,” 2013.

[17] P. A. Navrátil, B. Westing, G. P. Johnson, A. Athyle, J. Carreno, and F. Rojas, “A Practical Guide to Large Tiled Displays,” in *International Symposium on Visual Computing*, 2009.

[18] R. Raskar, M. S. Brown, R. Yang, W.-C. Chen, G. Welch, H. Towles, B. Scales, and H. Fuchs, “Multi-Projector Displays using Camera-Based Registration,” in *IEEE Visualization*, 1999, pp. 161–168.

[19] K. Reda, A. Febretti, A. Knoll, J. Aurisano, J. Leigh, A. Johnson, M. Papka, and M. Hereld, “Visualizing Large, Heterogeneous Data in Hybrid Reality Display Environments,” 2013.

[20] B. Sajadi and A. Majumder, “Scalable Multi-view Registration for Multi-Projector Displays on Vertically Extruded Surfaces,” in *Computer Graphics Forum*, vol. 29, no. 3. Wiley Online Library, 2010, pp. 1063–1072.

[21] ——, “Autocalibration of Multiprojector CAVE-Like Immersive Environments,” *Visualization and Computer Graphics, IEEE Transactions on*, vol. 18, no. 3, pp. 381–393, 2012.

[22] B. Westing, B. Urick, M. Esteva, F. Rojas, and W. Xu, “Integrating Multi-Touch in High-Resolution Display Environments,” in *State of the Practice Reports*. ACM, 2011, p. 8.

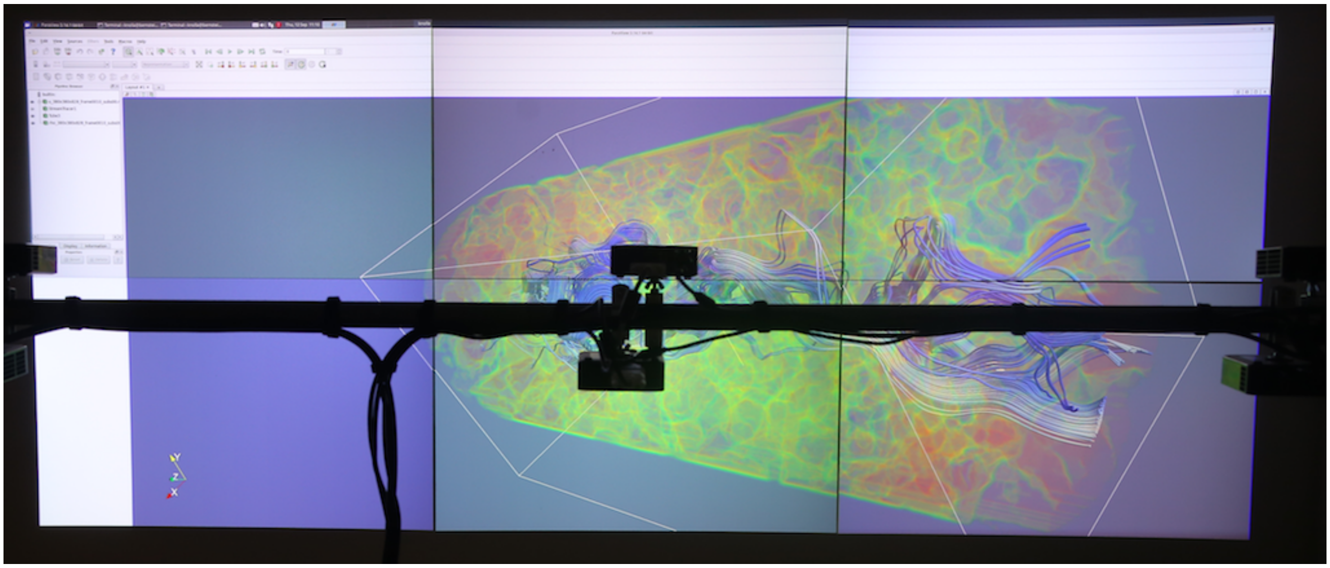

Fig. 3. Front-projected picowall prototype consisting of six 1280x800 Dell M110 projectors for a combined 3840x1600 resolution, driven by a single workstation with an ATI Radeon 5870 Eyefinity 6 GPU. Total weight of the projectors and mount is under 20 lbs.

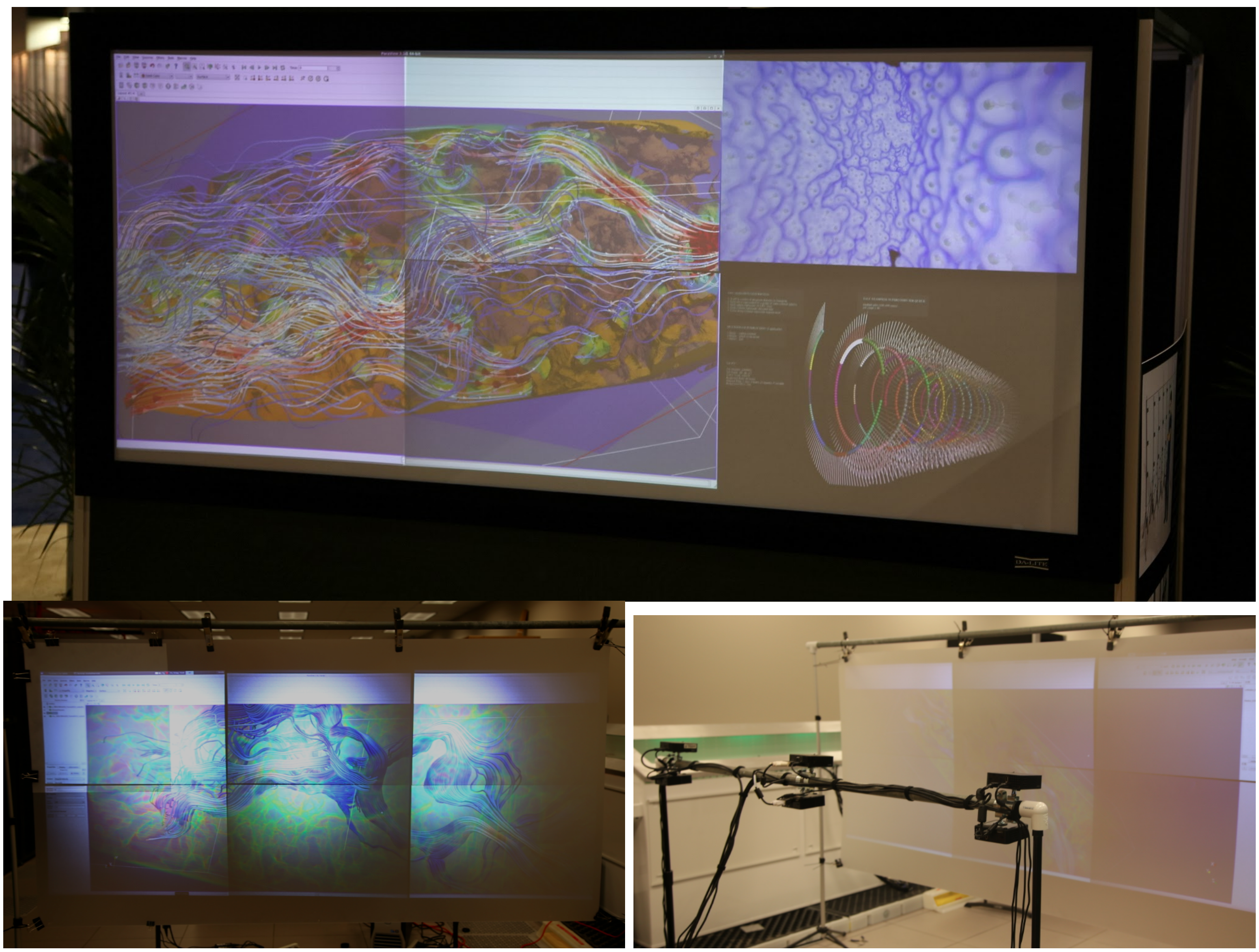

Fig. 4. *Top* Rear-projection setup with the Da-Lite Ultra Wide Angle screen, under fluorescent lighting at the SC2013 floor. By designing an enclosure from 80/20 aluminum framing, the picowall can achieve reasonable contrast in these environments despite low lumens. *Bottom left:* experimentation with inexpensive Lexan LED signage material. While hotspots were an issue, similar materials could ultimately provide an extremely low-cost screen with sufficient rigidity to enable touch. *Bottom right:* back view of the rear-projected picowall.