Chapter 21

The Utility of Virtual Reality for Science and Engineering

Kenny Gruchalla and Nicholas Brunhart-Lupo

In our daily usage of the large-scale immersive virtual environment at the National Renewable Energy Laboratory (NREL), we have observed how this VR system can be a useful tool to enhance scientific and engineering workflows. On multiple occasions, we have observed scientists and engineers discover features in their data using immersive environments that they had not seen in prior investigations of their data on traditional desktop displays. We have embedded more information into our analytics tools, allowing engineers to explore complex multivariate spaces. We have observed natural interactions with 3D objects and how those interactions seem to catalyze understanding. And we have seen improved collaboration with groups of stakeholders. In this chapter, we discuss these practical advantages of immersive visualization in the context of several real-world examples.

21.1 Introduction

Scientific visualization is the transformation of complex scientific data into visual images through computer graphics and data processing algorithms. The fundamental premise of scientific visualization is that the human mind excels at pattern matching and visual interpretation; we are readily able to identify patterns and anomalies in visual data, and we can contextualize those patterns with all our domain knowledge. A visual representation of data can engage more human cognitive machinery than looking at a list of numbers, and by doing so, we can gain a deeper understanding of the data in a shorter amount of time.

As an example, consider Anscombe's quartet (Table 21.1), which consists of four datasets synthesized by British statistician Francis Anscombe [Anscombe, 1973]. Each set is very simple, consisting of eleven two-dimensional points. If we apply standard statistical metrics on these sets, the results are almost identical. The mean of x and y for each of the four datasets is 9.00 and 7.50 respectively, the correlation between x and y are also the same with 0.816, and the linear regression line for the datasets is the same. A researcher using these metrics might then be led to assume that the datasets were similar. However, when we plot these four datasets (Figure 21.1), at a glance, we can immediately see that each is very different. There is a general linear relationship in the first set, a clear non-linear relationship in the second, a strong linear relationship with an outlier in the third, and the fourth has very different distribution being heavily skewed by an outlier. By plotting these data, we can instantly see the differences in their character and distributions. Of course, there are other statistical methods that can tease out these differences in a more quantitative manner, but these require a level of sophistication far exceeding the simple action of plotting these data. Anscombe's point is that without a visual understanding of your data, you may not know which statistical techniques to apply.

Table 21.1: Anscombe's Quartet: Data

1		2		3		4	
x	y	x	y	x	y	x	y
10.0	8.04	10.0	9.14	10.0	7.46	8.0	6.58
8.0	6.95	8.0	8.14	8.0	6.77	8.0	5.76
13.0	7.58	13.0	8.74	13.0	12.74	8.0	7.71
9.0	8.81	9.0	8.77	9.0	7.11	8.0	8.84
11.0	8.33	11.0	9.26	11.0	7.81	8.0	8.47
14.0	9.96	14.0	8.10	14.0	8.84	8.0	7.04
6.0	7.24	6.0	6.13	6.0	6.08	8.0	5.25
4.0	4.26	4.0	3.10	4.0	5.39	19.0	12.50
12.0	10.84	12.0	9.13	12.0	8.15	8.0	5.56
7.0	4.82	7.0	7.26	7.0	6.42	8.0	7.91
5.0	5.68	5.0	4.74	5.0	5.73	8.0	6.89

Mean	$\bar{x} = 9$	$\bar{y} \approx 7.5$
Variance	$\sigma_x^2 = 11$	$\sigma_y^2 \approx 4.12$
Correlation (x, y)	0.816	
Regression	$y = 3.00 + 0.500x$	

While Anscombe's quartet demonstrates the value of visualizing our data, to truly make the most of our very sophisticated pattern matching and visual interpretation capabilities, we should consider that these visual and cognitive abilities have evolved from our sense of place and embodiment. We understand our world by moving through it, interacting with it, and examining it from different perspectives. When we want to go somewhere, we walk. When we want something, we reach out and grab it. When we wish to see under something,

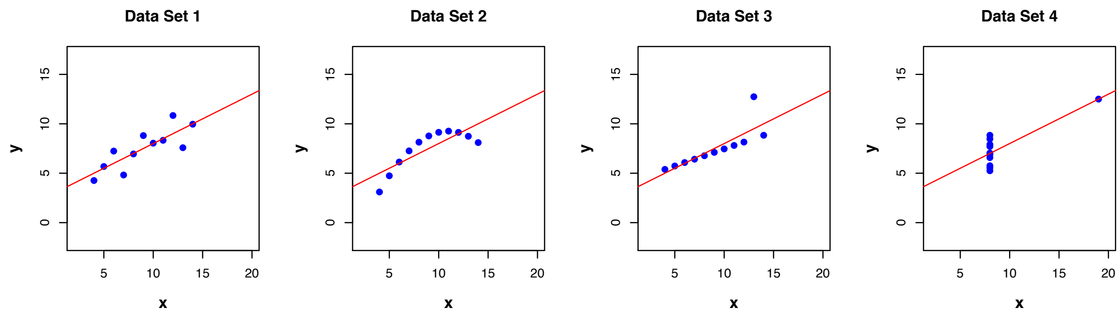

Figure 21.1: Anscombe's Quartet. The four datasets have nearly identical simple descriptive statistics (see Table 21.1), but are visually distinctive when plotted. The quartet provides a simple demonstration of the importance of visualizing data before analyzing it.

we crouch.

VR promises to bring that embodiment to the visualization and understanding of data. Here, a combination of hardware and software provides a psychophysical experience of being surrounded by a computer-generated scene, physically immersing users in a virtual world wherein they can explore complex spatial structures by looking around them, walking through them, and viewing them from different points of view. The medium of VR is built on rapidly evolving technology, moving in the past few years from large laboratory installations to commodity head-mounted displays (HMDs) and now mobile platforms. VR systems provide a head-tracked, typically stereoscopic, view into a virtual scene. Different VR systems provide different *levels of immersion*. Bowman and McMahan [Bowman and McMahan, 2007] define the *level of immersion* as an objective and measurable feature of a visualization system, measuring how close the system's visual output is to real-world visual stimuli. A system's level of immersion is dependent on a variety of factors including:

- head-tracking - the scene is rendered based on the physical location and orientation of the user's head
- stereoscopy - providing a depth cue by providing each eye a different perspective
- field of view (FOV) - the size of the visual field that can be viewed instantaneously
- field of regard (FOR) - the total size of the visual field surrounding the user
- resolution - the number of distinct pixels in each dimension
- frame rate - the frequency of generating images of the scene
- refresh rate - the frequency of the display hardware's redraw

- kinesthesia support - the awareness of the position and movement of one's own body.

CAVE-like [Cruz-Neira et al., 1993] environments are currently the state of the art and provide the highest level of immersion with head-tracked, stereoscopic images projected onto multiple surfaces in a room-sized installation that users can physically walk into (see Figure 21.2). Commodity VR HMDs (e.g., the HTC Vive) currently provide a lower level of immersion with stereo and head-tracking, but relatively low FOVs and resolutions, and with no view of one's body, kinesthesia is limited to proprioception. Augmented reality (AR) HMDs (e.g., the HoloLens), which augment the user's view of physical space by layering in a rendered scene, fully support kinesthesia but currently suffer from low resolutions, andd FOVs. The gaming industry revolutionized the field of visualization when they commoditized graphics processing units (GPUs). A similar transformation is approaching for immersive visualization with the commoditization of AR and VR headsets. The current state of the HMD technology is still inferior to state-of-the-art CAVE-style immersive environments. However, the level of immersion of the next generations of these HMD technologies could surpass these expensive high-end installations.

High-levels of immersion appear to provide cognitive benefits to the visualization of complex data by supporting natural body movements and well-practiced automatic brain function that facilitates reasoning in the virtual world. Additionally, the extra degrees of freedom afforded by VR can provide additional visibility into the relationships of complex multivariate data common to scientific and engineering analysis.

In this chapter, we explore some of the potential benefits of using immersive visualization for science and engineering supported by several real-world examples.

21.2 Background

We are not alone in believing that immersive visualization has benefits in the visual analysis of complex data. Scientific visualization has been a focal point for VR for many years [Bryson, 1996, van Dam et al., 2000, van Dam et al., 2002, Kuhlen and Hentschel, 2014]. And there is growing evidence that higher levels of stereoscopy, head tracking, FOV, and FOR working together can be beneficial. For example, empirical studies show improved perception and understanding of spatially complex data [Ware and Franck, 1996, Richardson et al., 1999, Schuchardt and Bowman, 2007, Ragan et al., 2013, Laha et al., 2014] inside immersive environments. Likewise, studies with complex 3D interaction tasks have shown improved task performance [Narayan et al., 2005, McMahan et al., 2006] in immersive environments. The extra degrees of freedom afforded by VR have been shown to improve understanding of high-dimensional data representations [Arns et al., 1999, Raja et al., 2004, Ni et al., 2006] when searching for or comparing complex abstract data. Furthermore, installations that support multiple users have been shown to improve collaboration [Narayan et al., 2005, D'Angelo et al., 2008, Marai et al., 2016]. These studies, and others like them, substantiate the benefits of immersive interfaces. However, these studies are limited to isolated tasks and how they might relate to scientific and engineering workflows is not always obvious.

The benefits of immersion in real-world settings is less examined in the literature, as conducting empirical experiments in these settings is difficult with many confounding variables. However, there are a few controlled studies on *real-world applications* that also show similar benefits from VR. The oil and gas industry was one of the earliest adopters, and a controlled study [Gruchalla, 2004] found significant benefits for immersion when comparing oil-well path planning activities in a CAVE-style immersive environment compared to a stereoscopic desktop environment. Immersion was shown to have significant benefits for biological data analysis in laser confocal microscopy data that emphasized understanding of spatial relationships [Prabhat et al., 2008].

While there are few controlled studies on real-world applications, there is a breadth of anecdotal evidence of real discoveries made with the aid of immersive technologies. For example, there have been discoveries made in biology [Brady et al., 1995], molecular biology [Gruchalla et al., 2008], geoscience [Kreylos et al., 2006], remote sensing [Gardner et al., 2003], forestry [Bohrer et al., 2008], and archaeology [Acevedo et al., 2001]. While the benefits of immersive virtual reality may be difficult to verify scientifically for science and engineering applications, the anecdotal discoveries made while using immersive virtual reality are suggestive of the utility.

21.3 NREL VR Use Cases

The National Renewable Energy Laboratory (NREL) is the U.S. Department of Energy's (DOE's) primary national laboratory for renewable energy and energy efficiency research. The NREL Insight Center combines state-of-the-art visualization and collaboration tools to promote knowledge discovery in experimental data, high-resolution microscopy, and large-scale simulation data. One of the primary tools used in the NREL Insight Center is a large-scale (CAVE-like) immersive virtual environment. In our day-to-day usage of this environment for scientific and engineering workflows, we have observed multiple discoveries and witnessed the practical benefits of immersive technology, which we describe here.

System

The immersive virtual environment at the Insight Center is a custom design, composed of six active stereoscopic projectors that illuminate two surfaces: a wall and a floor (Figure 21.2). The projected space is 5 m wide, 2.5 m high, and 1.75 m deep with 3540×1728 pixels on the wall, and 3540×1080 pixels on the floor. A six-camera Vicon$^{\text{TM}}$system optically tracks the whole volume. The system is driven by a single Linux server with dual 8-core Sandy Bridge processors, half a terabyte of RAM, and three NVIDIA Quadro M6000 GPUs. The primary input device is a commodity *Logitech*$^{\text{TM}}$ joystick augmented with optical markers to track its 3D position. In addition, we employ a variety of custom built input devices specialized to particular workflows. We handle all tracking and input control through VRPN [Taylor et al., 2001].

We support a variety of software applications in the space. Immersive ParaView [Shetty et al., 2011], FreeVR-enabled VMD [Sherman et al., 2013], and the commercial application Avizo provide scientists and engineers a pathway to move visualizations directly from their desktops to our immersive environment. We also support Unity-based applications, which provide a relatively easy programming model for scientists and engineers who wish to develop their own applications for the system. However, these tools are generally only used for preliminary investigations. The vast majority of the applications run in the system (and the applications detailed in this chapter) were custom built on our immersive software framework, *Isopach*, written in C++, and powered by Qt and OpenGL. *Isopach* is a high-performance scene-graph library and full stack application toolkit optimized for our multi-projector, multi-screen environment, and includes image handling, an object-component scene model, geometry operations, threading, and other utilities. By employing the most recent graphics API features (shaders) tuned to our hardware, we have a performance advantage over more general immersive software frameworks. It is also designed to facilitate coupling with other software, such as simulation codes written in C, R-based statistics scripts, and web data sources. The library provides a lower-level API compared to other frameworks, requiring more expertise to build a given visualization application, but allows the developer to uniquely tailor the user interface and experience for each investigation.

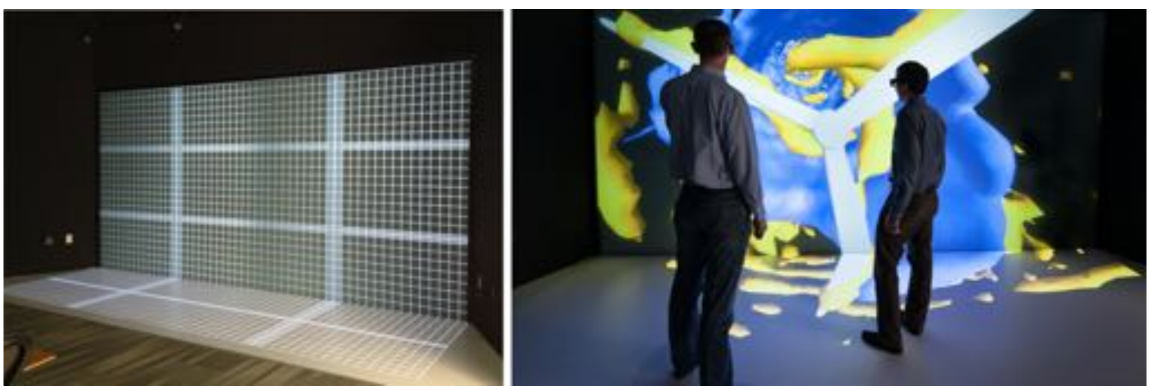

Figure 21.2: The immersive virtual environment at NREL Insight Center. Left: The system is an optically tracked space with a rear-projected wall and a front-projected floor. Right: Wind engineers standing inside the environment are evaluating the wake forming behind a wind turbine.

21.3.1 Improved Spatial Judgments

From our observations, one of the primary benefits of our immersive system is the improved ability for our users to make spatial judgments. Being able to physically move inside spatially complex datasets has allowed our scientists to identify structures — and the spaces between structures — that were not noticed or were impossible to notice using traditional desktop visualization.

One such discovery came when visualizing the morphology of organic photovoltaic (OPV) materials. These materials consist of interpenetrating networks of a polymer and fullerene materials, as can be seen in Figure 21.3. The polymer absorbs light, and the resulting excitation migrates, injecting a negative charge into the fullerene and leaving a positive charge behind in the polymer. These charges travel through the two material networks, ideally reaching electrodes to produce current. By examining the pathways for different morphologies, we can develop intuition about how modifying the materials will affect OPV device properties. Figure 21.3 is a typical representation of traditional analysis on these materials. While 2D renderings can be useful, the inner structure is largely occluded. Even when transparency is added, or matter is culled, the complex material network makes it difficult for the researcher to follow strands of material.

We built a visualization tool for our immersive system and invited the scientist leading these investigations to explore the 3D immersive version of these 2D renderings. When he stepped inside one of the morphologies, he uttered the three most exciting words in science, "Huh? That's funny." The visualization allowed him to physically explore the morphology. He could stand in the middle of his dataset, move to interesting places by walking and look behind the occlusions just by moving his head. In VR, depth is *depth*, and he could follow pathways with his finger from point to point. What he discovered was the heterogeneity of these morphologies that he could not easily appreciate in the desktop visualizations, features that the 2D perspective obscured. This new appreciation of his data was immediate and fostered changes to the statistical measures that were being applied to these materials. This observation was a real-world encounter of Anscombe's thesis; a qualitative understanding of the data helped the scientist develop his quantitative measurements.

We have seen similar discoveries in the visualization of molecular dynamics (MD) simulations of solar materials. MD simulations were being used to investigate how different polymer chains would stack inside the active layer of an OPV device. Based on x-ray diffraction imaging and traditional visualization of the MD results, researchers believed the stacking properties of two polymers to be qualitatively similar. However, when they examined these polymers using our immersive system (see Figure 21.4), they determined that only one exhibited a structure known as π-stacking while the other did not.

We have also seen users make spatial discoveries that were clearly relative to their bodies. We supported a project team that virtually constructed a large concentrating solar collector, a structure tens of meters in length, with curved mirrors that focus the light, using the resulting heat to generate electricity. These collectors are constructed in the field, requiring

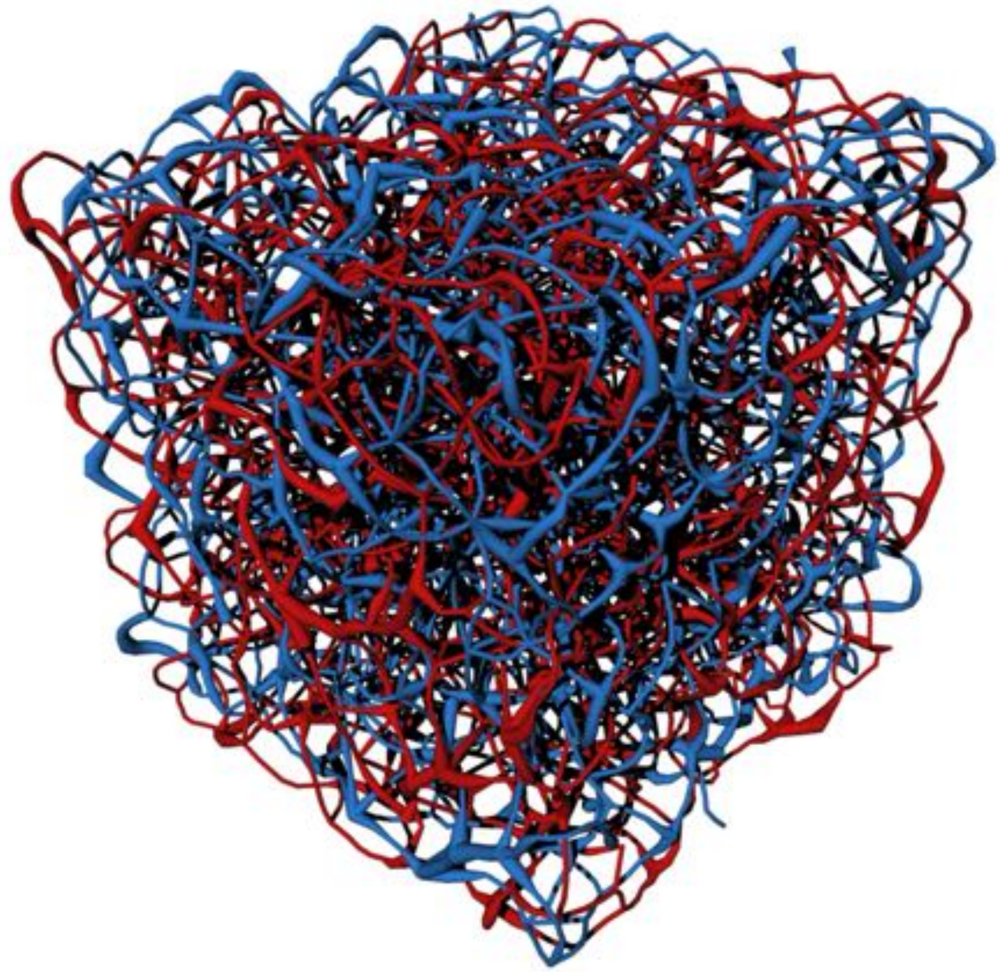

Figure 21.3: A simulated representation of a bulk heterojunction used in the active layer of organic photovoltaic devices (OPV), consisting of interpenetrating networks of polymer and fullerene material. Here a skeletonization of the polymer is shown in blue and a skeletonization of the fullerene in red. Understanding this structure and how electrons might transport through it, is a challenging problem. Using VR, scientists discovered structures in these materials that they had not seen using desktop displays.

Figure 21.4: Investigating polymer stacking in the active layers of OPV devices. Using VR, scientist were able to qualitatively distinguish stacking characteristics between materials that were not obvious with more traditional visualization techniques.

scaffold and supporting jig. The team wished to understand if there were flaws in the jig design which would complicate this assembly or challenge construction of the collector with the jig. The virtual assembly supplemented their traditional design and analysis using 3D CAD modeling tools and small-scale physical 3D models.

We presented the collector, its assembly jig, and assembly platforms to the project team at a 1:1 scale inside the immersive environment. We provided props to the user, consisting of a foam tube and a foam beam with trackers; the visualization tool attaches geometry to these tracked objects, so the users could move collector struts in the virtual space (see Figure 21.5). The application highlighted the collision of parts with the base structure as the user moved those parts into position.

In a single working session, the project team discovered nearly a dozen issues with the jig design. They were able to identify numerous places where connecting components would require dangerous extensions to reach, where beams and struts would likely collide with the scaffolding, and positions where construction workers would likely have difficulty manipulating a rivet gun.

At this point, the design team had already gone through more traditional steps of design and analysis. They had thoroughly modeled the structure to the threads on the bolts, they had 3D printed models on their desks, but only by bringing the model to human scale, and allowing them to explore the collector as if they would a real prototype were they able to uncover these issues.

This example demonstrates a unique capability provided by immersive visualization that can not be duplicated, or emulated, in traditional visualization. Users were able to ask and answer simple questions like "can I reach this?" Allowing users to test their creations without incurring significant fabrication costs and time investments is a powerful addition to the engineer's toolkit.

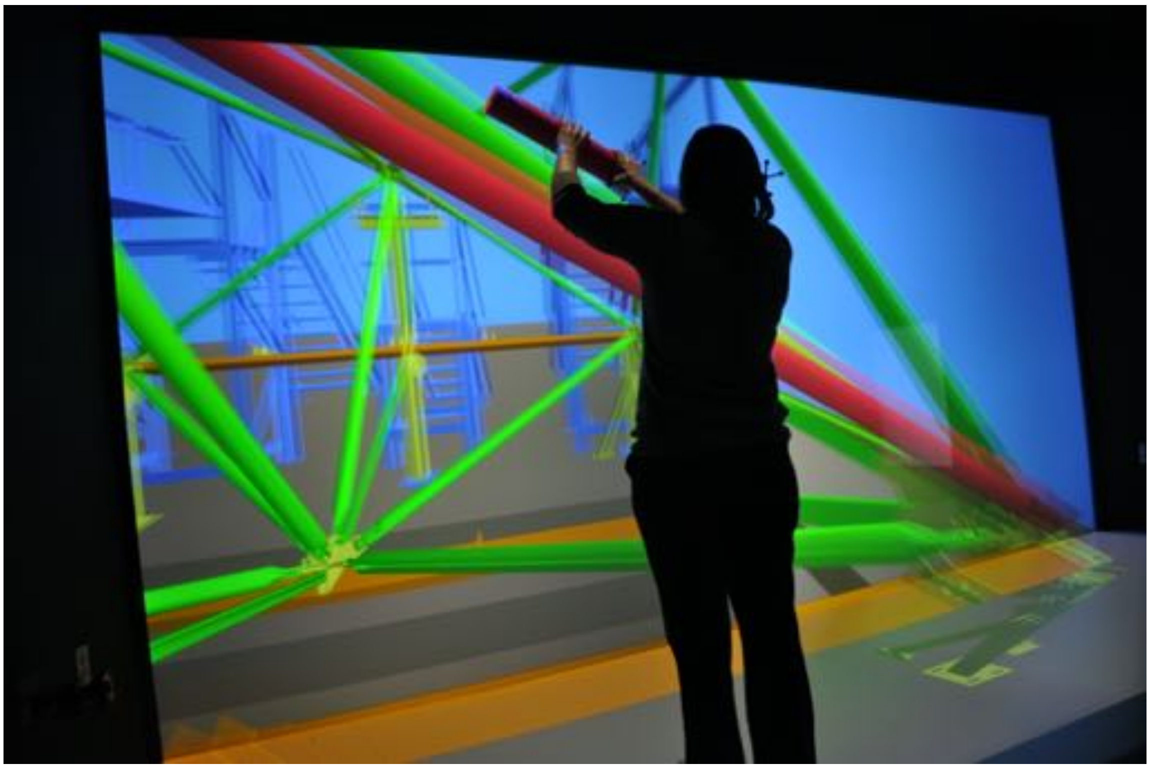

Figure 21.5: An engineer places a strut during the virtual assembly of a concentrating solar collector. The red strut in the figure is mapped to the prop held by the engineer. Using VR, engineers were able to identify design issues that they had not identified with their CAD/CAM tools and physical scale models.

21.3.2 3D Interaction

The virtual assembly of the concentrating solar collector also demonstrates the utility of being able to manipulate 3D objects directly in 3D space. The engineers were able to precisely move and place components of the structure to better understand the workflow and the complexities of assembling the collector.

We have also seen the utility of 3D interaction for analyzing computational fluid dynamics (CFD) data of simulated flow inside the cabins of electric vehicles. The efficiency of heating and cooling electric vehicles is an area of research at NREL, as these loads can have a significant impact on the driving range of an electric vehicle [Kiss et al., 2015]. The airflow inside vehicle cabins can be quite complex (see Figure 21.6), and developing a visualization that provides a clear view of that flow is a challenging problem.

VR provides a medium to interactively investigate the flow by directly seeding particles into that flow. We transfer the velocity vector fields from CFD simulations into the working volume of our immersive environment, and we render a partial mesh of the vehicle's body as context. The user can release massless particles into this flow with a touch of a button on the tracked joystick, injecting up to 20,000 particles into the velocity vector field by 'painting' with the controller (see Figure 21.7). These particles are then advected by the flow and change color to reflect the temperature at their current location in the volume. The particles diminish in size over a fixed amount of time, so as to not clutter the visualization. Further, we stretch the particles along the velocity vector; this helps the eye catch fast moving particles. The particles are rendered using instance rendering, a feature found in most modern graphics APIs, which renders all 20,000 particles in a single draw call, keeping the visualization interactive.

Before being introduced to the immersive virtual environment, the vehicle engineers would evaluate the flows through 2D cross-sections. This VR application provides the engineers a method to explore the air flows in a manner that is simply not possible in a 2D context. They can easily pick points to seed particles, and move their bodies to follow the flow of particles. Engineers were able to probe areas of interest directly and quickly isolate the features in this complex flow. The engineers reported discovering vortices and regions of high flow in the immersive context that they had not found in their previous non-immersive visualizations of the data.

21.3.3 High-Dimensional Data

As an immersive environment provides extra degrees-of-freedom, we have seen benefits toward the exploration of high-dimensional and highly multivariate datasets. In the very simplest case, consider the two-dimensional scatter plot, which is the mainstay of data analysis; in VR the direct analog is a three-dimensional scatter plot. We have mapped additional dimensions to point size and color, providing five-dimensional data directly in the immersive environment. Users can probe individual points and use interactive planes for additive half-space selection to isolate regions of interest (see Figure 21.8).

Going further, many data visualization techniques for even higher-dimensional data have analogs in a 3D environment. For example, we have generalized the two-dimensional parallel-coordinates visualization technique as parallel-planes in VR. In traditional parallel

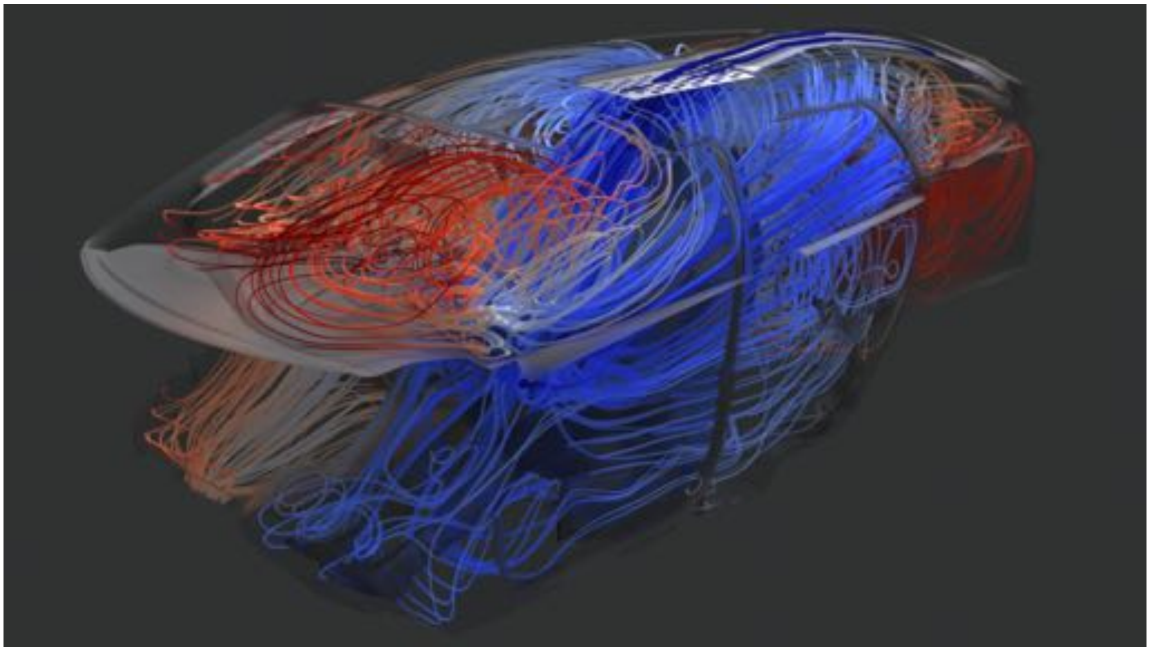

Figure 21.6: Streamline rendering of an electric vehicle simulation, displaying airflow inside the cabin. Note the mannequin's feet at the lower left of the image. Color represents relative temperature. The airflow inside the cabin is complex and difficult to understand.

coordinates, data dimensions are mapped onto coordinate axes as a series of parallel lines [Inselberg, 1985]. We map pairs of the multivariate dimensions onto a series of parallel 2D scatter plots and connect individual observations in the dataset with a polyline, as shown in Figure 21.9. This construct allows users to explore datasets with twelve or more variable dimensions in a convenient fashion. Regions of the rectangles can be "brushed" to highlight and select observations of interest. This brushing and selection action is used to explore existing data, but is also used to visually provide input parameter spaces to launch simulations or processes that provide additional data; it is in this manner that users can easily "paint" questions and have an attached model provide answers in near-real-time. We have observed that these immersive analytics tools can accelerate users' realization of insights about the simulation and its output [Brunhart-Lupo et al., 2016].

VR's extra degrees-of-freedom have also allowed us to re-imagine and bring new context to other highly multivariate datasets. For example, electric power distribution systems represent a significant visualization and analysis challenge, as they have a large number of temporally and spatially varying quantities (i.e., voltage, real power, and reactive power across three phases, solar irradiance, varieties of control equipment with different operational parameters and scenarios, and dynamically changing load). Even highly trained engineers

Figure 21.7: Inside the same vehicle as Figure 21.6, a user interactively explores the airflow inside an electric vehicle cabin, by directly seeding particles into the flow. Using this VR system, engineers were able to identify flow characteristics they had not discovered using desktop visualization tools.

have difficulty fully comprehending these interactions, especially between variables using traditional two-dimensional geographic representations.

To help address this challenge, we developed an immersive three-dimensional visualization technique for distribution networks by elevating the power lines as a function of their voltage and sizing them as a function of their power flow (see Figure 21.10). There are three phases of power in A/C distribution systems. Each line is "hung" in the vertical dimension by its per-unit voltage and shaped by the real and reactive power present on the line. By adding a degree of freedom, we have taken what is typically a four-dimensional visualization (i.e., network topology and two line variables mapped to width and color) and extended it to an eleven-dimensional space: three phases of voltage, three phases of real power, and three phases of reactive power embedded with the 2D network topology.

In addition to line information, we represent the state of other elements on the system. Voltage regulators are visualized as vertical cylinders, spanning their input and output voltages. Generation sources are spheres geographically positioned in the horizontal plane and positioned vertically by output voltage.

Users can manipulate floating 2D plots that provide details on demand; these are virtual billboards in the immersive space that the user can grab and re-position in three-space using the optically tracked joystick. A companion time-series view provides an overview

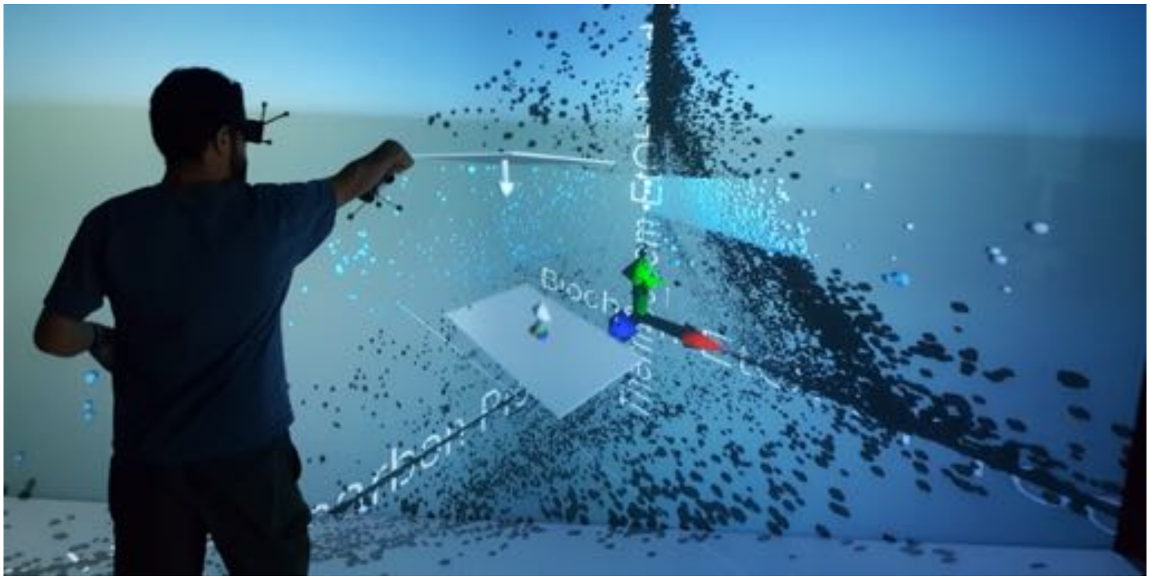

Figure 21.8: A user interactively exploring and selecting clusters in a five-dimensional dataset on a three-dimensional scatter plot. Half-spaces, created by the planes, define the user's selection.

of the study feeder's line loads and generation during a single day. This view provides the primary temporal interface for the three-dimensional views, allowing the user to set the current time or animate through time. Users can probe details of individual components by intersecting a component with the joystick and creating a three-dimensional tooltip with a button press. The tooltip provides both metadata (i.e., characteristics about the data itself) and time-series plots (e.g., time-varying variables applicable to the component).

This VR application has been used by power system engineers to evaluate complex control strategies on a distribution feeder [Palmintier et al., 2016] and provided novel visibility into the multivariate relationships in these data. The immersive visualization was used to support the traditional analysis of these power flow simulations, augmenting the power systems research engineers' typical workflow. Engineers would schedule time in our immersive environment to troubleshoot the simulation, posing questions about complex multivariate relationships that were not readily accessible using traditional two-dimensional displays and plots. Specifically, the immersive application was utilized to troubleshoot voltage imbalance between phases, as the immersive visualization provided topological context for the voltage profiles in all three phases. The engineers were readily able to identify gradual phase separations along the topology. The engineers also utilized the multivariate spatial information of the VR application to understand the location and cause of "over-voltages" on the system.

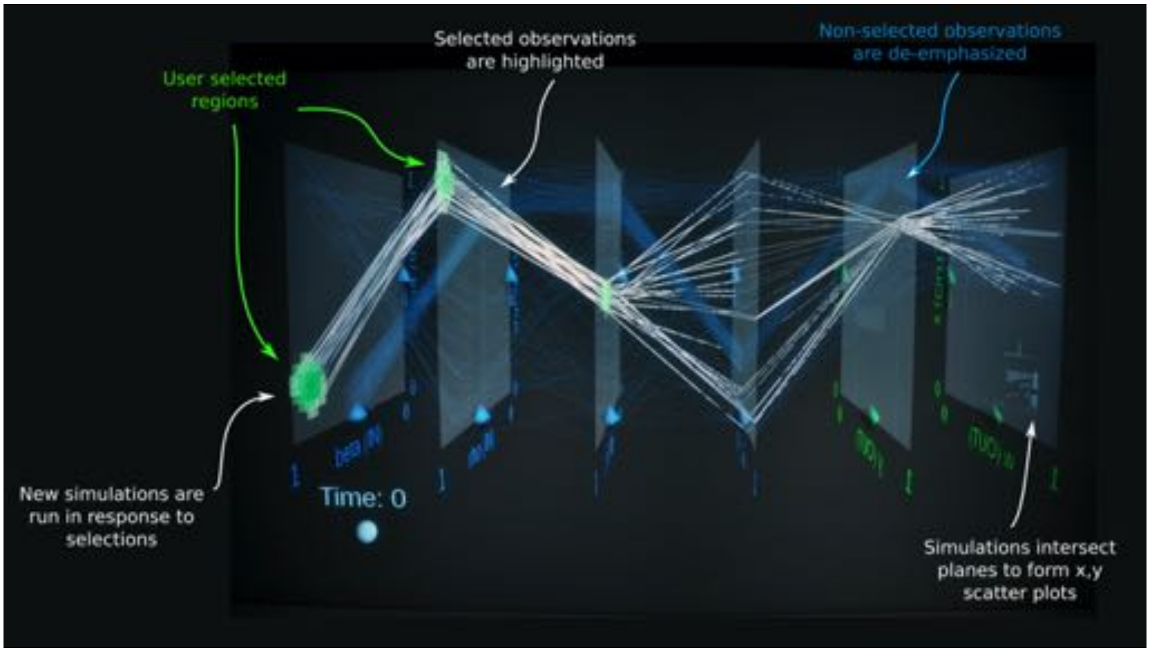

Figure 21.9: VR can support higher-dimensional visualization constructs, such as parallel planes that link observations on parallel 2D scatter plots in a high-dimensional parameter space.

21.3.4 Collaboration

One of the benefits of our large-scale system that we repeatedly observe is how the space seems to facilitate collaborative reasoning about data. The large scale allows multiple researchers to gather inside the environment simultaneously, which many teams have indicated they find more collaborative than crowding around a small computer screen or sitting around a conference table.

One example is financial and investment modeling. A number of researchers at NREL are exploring how market forces can impact investments in renewable energy. These problems are highly interdisciplinary, bringing financial analysts, market specialists, and industry experts together with modeling and simulation groups. Through multiple meetings, attended by these professionals and held in our immersive environment and supported by the on-demand simulation request framework discussed in the previous section (and displayed in the parallel-planes projection), we have observed a highly proficient, frictionless environment. A cluster would form around an individual chosen as the ad-hoc primary visualization user; the group would ask questions of the model, and new results displayed for discussion. Frequently, groups would spin off to talk in depth about a certain notable data point before rejoining the

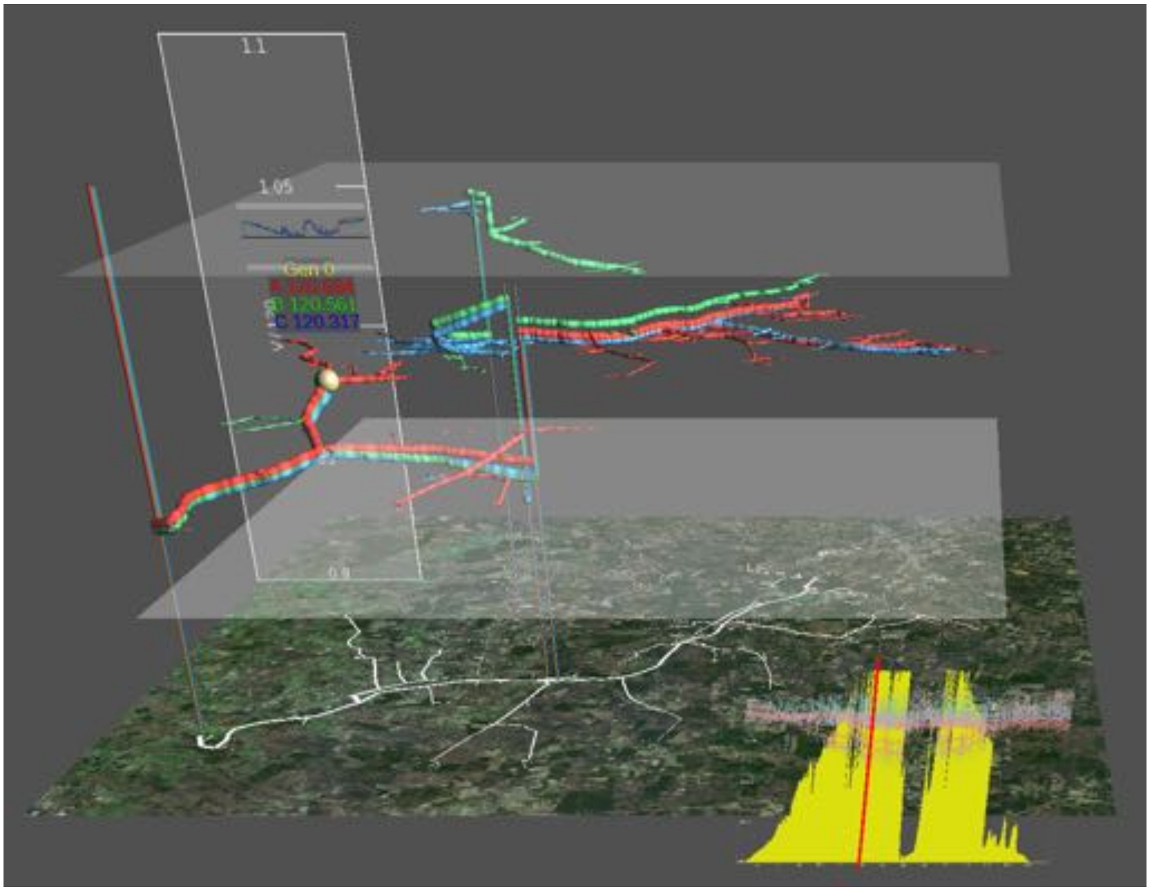

Figure 21.10: Three-dimensional visualization of a power distribution system, representing the highly multivariate space of a power flow simulation. Power system engineers used VR to augment their traditional analysis workflows.

main cluster for more questions-and-answers, replacing what would have been month-long conversations over email, and long-latency requests for new data. Though initially skeptical, the users reported enjoyment of the environment and noted the amount of research they could accomplish in a short amount of time.

In another example, we have been using the system for collaborative design and planning studies of the NREL campus (see Figure 21.11), where multiple stakeholders can gather and evaluate planning scenarios combining technical, economic, and policy perspectives. As before, we have facilitated these types of design and planning meetings by loosely coupling multiple simulation tools with our immersive, VR environment. For the NREL campus planning studies, this means an economic optimization model combined with an electrical power flow model of the campus to allow users to interactively manipulate the on-site power generation and electrical loads. Though in its early stages, we have already been able to discover opportunities for energy systems integration on our campus by bringing our site planners and leadership together in this environment, and have received requests to create similar models of other sites.

Our experiences in these kinds of studies are preliminary, but we are discovering that analysis can proceed at a rapid pace not only when immersive spaces allow collaboration between multiple users, but also when the visualization provides a substrate, either through simulation, machine learning, or statistical analysis, to let these users ask questions about their data, or request new simulations on the fly to test hypotheses. This machine-powered question and response format appears to be key in our future visualizations.

Figure 21.11: NREL campus planning study that allows groups of stakeholders to interactively evaluate the techno-economic impacts of design decisions.

21.4 Conclusion

In our daily usage of the large-scale immersive virtual environment at NREL, we have observed multiple practical benefits of immersive technology. We have witnessed discoveries made in VR that had gone overlooked using traditional data analysis methods. We have seen how researchers can expedite analysis through intuitive 3D interaction with their data. We have been able to embed more information into our analytics tools, allowing engineers to agilely explore complex multivariate spaces. We have seen groups of stakeholders bring their perspectives together on planning decisions.

VR can not and should not replace the entire visualization and analysis stack, but immersive visualization has its place as a valued tool in NREL's analysis stockpile and has augmented how some researchers do their science. For some NREL researchers, an immersive examination is now the first step in the data analysis workflow: a physical walk-through of the data, to get a qualitative understanding of the features, before developing the statistical or quantitative measures of those data. For others, it becomes part of an iterative debugging process to refine simulation models. Still, others use it to communicate and collaborate with a variety of audiences.

A transformation is approaching for immersive visualization. AR and VR are being commoditized by the entertainment industry with relatively low-cost HMDs, just as GPUs were commoditized more than a decade ago. While the level of immersion of these commodity systems cannot currently compete with the large-scale state-of-the-art immersive environments, like the one installed at NREL, their capabilities are rapidly advancing and will soon surpass these expensive high-end installations. As their capabilities improve, AR and VR will revolutionize analysis for many classes of complex scientific and engineering data.

21.4.1 Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Bibliography

[Acevedo et al., 2001] Acevedo, D., Vote, E., Laidlaw, D. H., and Joukowsky, M. S. (2001). Archaeological data visualization in vr: Analysis of lamp finds at the great temple of petra, a case study. In *Proceedings of the Conference on Visualization '01*, VIS '01, pages 493–496, Washington, DC, USA. IEEE Computer Society.

[Anscombe, 1973] Anscombe, F. J. (1973). Graphs in statistical analysis. *The American Statistician*, 27(1):17–21.

[Arns et al., 1999] Arns, L., Cook, D., and Cruz-Neira, C. (1999). The benefits of statistical visualization in an immersive environment. In *Proceedings IEEE Virtual Reality (Cat. No. 99CB36316)*, pages 88–95.

[Bohrer et al., 2008] Bohrer, G., Longo, M., Zielinski, D. J., and Brady, R. (2008). *VR Visualisation as an Interdisciplinary Collaborative Data Exploration Tool for Large Eddy Simulations of Biosphere-Atmosphere Interactions*, pages 856–866. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Bowman and McMahan, 2007] Bowman, D. A. and McMahan, R. P. (2007). Virtual reality: How much immersion is enough? *Computer*, 40(7):36–43.

[Brady et al., 1995] Brady, R., Pixton, J., Baxter, G., Moran, P., Potter, C. S., Carragher, B., and Belmont, A. (1995). Crumbs: a virtual environment tracking tool for biological imaging. In *Proceedings 1995 Biomedical Visualization*, pages 18–25, 82.

[Brunhart-Lupo et al., 2016] Brunhart-Lupo, N., Bush, B. W., Gruchalla, K., and Smith, S. (2016). Simulation exploration through immersive parallel planes. In *2016 Workshop on Immersive Analytics (IA)*, pages 19–24.

[Bryson, 1996] Bryson, S. (1996). Virtual reality in scientific visualization. *Commun. ACM*, 39(5):62–71.

[Cruz-Neira et al., 1993] Cruz-Neira, C., Sandin, D. J., and DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: The design and implementation of the cave.

In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '93, pages 135–142, New York, NY, USA. ACM.

[D'Angelo et al., 2008] D'Angelo, D., Wesche, G., Foursa, M., and Bogen, M. (2008). The benefits of co-located collaboration and immersion on assembly modeling in virtual environments. In *Proceedings of the 4th International Symposium on Advances in Visual Computing*, ISVC '08, pages 478–487, Berlin, Heidelberg. Springer-Verlag.

[Gardner et al., 2003] Gardner, J. V., Warner, T., Nellis, M. D., and Brandtberg, T. (2003). Virtual reality technology for lidar data analysis. In *Proc. SPIE*, volume 5097, pages 48–57.

[Gruchalla, 2004] Gruchalla, K. (2004). Immersive well-path editing: Investigating the added value of immersion. In *Proceedings of the IEEE Virtual Reality 2004*, pages 157–164, Washington, DC, USA. IEEE Computer Society.

[Gruchalla et al., 2008] Gruchalla, K., Dubin, M., Marbach, J., and Bradley, E. (2008). Immersive Examination of the Qualitative Structure of Biomolecules. In *International Workshop on Qualitative Reasoning about Physical Systems*, pages 36–41.

[Inselberg, 1985] Inselberg, A. (1985). The plane with parallel coordinates. *The Visual Computer*, 1(2):69–91.

[Kiss et al., 2015] Kiss, T., Lustbader, J., and Leighton, D. (2015). Modeling of an electric vehicle thermal management system in matlab/simulink. In *SAE Technical Paper*. SAE International.

[Kreylos et al., 2006] Kreylos, O., Bawden, G., Bernardin, T., Billen, M. I., Cowgill, E. S., Gold, R. D., Hamann, B., Jadamec, M., Kellogg, L. H., Staadt, O. G., and Sumner, D. Y. (2006). Enabling scientific workflows in virtual reality. In *Proceedings of the 2006 ACM International Conference on Virtual Reality Continuum and Its Applications*, VRCIA '06, pages 155–162, New York, NY, USA. ACM.

[Kuhlen and Hentschel, 2014] Kuhlen, T. W. and Hentschel, B. (2014). Quo vadis cave: Does immersive visualization still matter? *IEEE Computer Graphics and Applications*, 34(5):14–21.

[Laha et al., 2014] Laha, B., Bowman, D. A., and Socha, J. J. (2014). Effects of vr system fidelity on analyzing isosurface visualization of volume datasets. *IEEE Transactions on Visualization and Computer Graphics*, 20(4):513–522.

[Marai et al., 2016] Marai, G. E., Forbes, A. G., and Johnson, A. (2016). Interdisciplinary immersive analytics at the electronic visualization laboratory: Lessons learned and upcoming challenges. In *2016 Workshop on Immersive Analytics (IA)*, pages 54–59.

[McMahan et al., 2006] McMahan, R. P., Gorton, D., Gresock, J., McConnell, W., and Bowman, D. A. (2006). Separating the effects of level of immersion and 3d interaction techniques. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '06, pages 108–111, New York, NY, USA. ACM.

[Narayan et al., 2005] Narayan, M., Waugh, L., Zhang, X., Bafna, P., and Bowman, D. (2005). Quantifying the benefits of immersion for collaboration in virtual environments. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '05, pages 78–81, New York, NY, USA. ACM.

[Ni et al., 2006] Ni, T., Bowman, D. A., and Chen, J. (2006). Increased display size and resolution improve task performance in information-rich virtual environments. In *Proceedings of Graphics Interface 2006*, GI '06, pages 139–146, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

[Palmintier et al., 2016] Palmintier, B., Giraldez, J., Gruchalla, K., Gotseff, P., Nagarajan, A., Harris, T., Bugbee, B., , Gantz, M. B. J., and Boardman, E. (2016). Feeder voltage regulation with high-penetration pv using advanced inverters and a distribution management system: A duke energy case study. Technical Report NREL/TP-5D00-65551, National Renewable Energy Laboratory.

[Prabhat et al., 2008] Prabhat, Forsberg, A., Katzourin, M., Wharton, K., and Slater, M. (2008). A comparative study of desktop, fishtank, and cave systems for the exploration of volume rendered confocal data sets. *IEEE Transactions on Visualization and Computer Graphics*, 14(3):551–563.

[Ragan et al., 2013] Ragan, E. D., Kopper, R., Schuchardt, P., and Bowman, D. A. (2013). Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task. *IEEE Transactions on Visualization and Computer Graphics*, 19(5):886–896.

[Raja et al., 2004] Raja, D., Bowman, D. A., Lucas, J., and North, C. (2004). Exploring the benefits of immersion in abstract information visualization. In *In Proceedings of 8th International Immersive Projection Technology Workshop*, pages 61–69.

[Richardson et al., 1999] Richardson, A. E., Montello, D. R., and Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*, 27(4):741–750.

[Schuchardt and Bowman, 2007] Schuchardt, P. and Bowman, D. A. (2007). The benefits of immersion for spatial understanding of complex underground cave systems. In *Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology*, VRST '07, pages 121–124, New York, NY, USA. ACM.

[Sherman et al., 2013] Sherman, W. R., Coming, D., and Su, S. (2013). Freevr: honoring the past, looking to the future. In *Proc. SPIE*, volume 8649, pages 864906–864906–15.

[Shetty et al., 2011] Shetty, N., Chaudhary, A., Coming, D., Sherman, W. R., O'Leary, P., Whiting, E. T., and Su, S. (2011). Immersive paraview: A community-based, immersive, universal scientific visualization application. In *Proceedings of the 2011 IEEE Virtual Reality Conference*, VR '11, pages 239–240, Washington, DC, USA. IEEE Computer Society.

[Taylor et al., 2001] Taylor, II, R. M., Hudson, T. C., Seeger, A., Weber, H., Juliano, J., and Helser, A. T. (2001). Vrpn: A device-independent, network-transparent vr peripheral system. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '01, pages 55–61, New York, NY, USA. ACM.

[van Dam et al., 2000] van Dam, A., Forsberg, A. S., Laidlaw, D. H., LaViola, J. J., and Simpson, R. M. (2000). Immersive vr for scientific visualization: a progress report. *IEEE Computer Graphics and Applications*, 20(6):26–52.

[van Dam et al., 2002] van Dam, A., Laidlaw, D. H., and Simpson, R. M. (2002). Experiments in immersive virtual reality for scientific visualization. *Computers & Graphics*, 26(4):535 – 555.

[Ware and Franck, 1996] Ware, C. and Franck, G. (1996). Evaluating stereo and motion cues for visualizing information nets in three dimensions. *ACM Trans. Graph.*, 15(2):121–140.