Ten years Center for Immersive Visualizations - Past, Present, and Future

Elisabeth Mayer*
Leibniz Supercomputing Centre

Rubén Jesús García Hernández†
Ludwig-Maximilians-Universität München

Daniel Kolb‡
Leibniz Supercomputing Centre

Jutta Dreer§
Leibniz Supercomputing Centre

Simone Müller¶
Leibniz Supercomputing Centre

Thomas Odaker‖
Leibniz Supercomputing Centre

Dieter Kranzlmüller**
Leibniz Supercomputing Centre

ABSTRACT

Virtual Reality (VR) can be found in many fields. A majority of the time this involves the use of Head-Mounted Displays (HMDs). Their alternatives, large-scale immersive 3D screens and CAVE systems, can also be found in research and offer researchers high visual quality and collaborative VR experiences. This report covers the operation and learnings from maintaining a visualization center with large-scale immersive installations over the course of ten years.

Keywords: Virtual Reality, Large-scale Displays, Scientific Visualization, Visualization Center, Stereoscopic 3D, CAVE, Powerwall

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction devices—Displays and imagers; Human-centered computing—Visualization—Visualization systems and tools

1 INTRODUCTION

Virtual Reality (VR) has found application in many different fields [16, 20, 21] and has proven to be a useful tool in research [2]. It has also been adopted in Scientific Visualizations (SciVis) as a tool, as it offers numerous opportunities for viewing data [2] and helps viewers understand the results of simulations [7, 27, 29].

Bryson et al. defined VR for the use case of SciVis as a system that needs to be head-tracked and usually stereoscopic [2]; it needs a high-performance computer graphics system to deliver images and an option for users to give input. This applies to Head-Mounted Displays (HMDs) as well as to large immersive display systems such as the CAVE [6], which have been used in research since 1992 and offer a different viewing experience to HMDs. Their advantages include the ability to collaborate with other researchers in the same room, high-quality displays, and more immersive interactive experiences. Their limitations concern fixed locations and cost intensity.

We present findings and report on our experiences of supervising a visualization center with large-scale immersive displays for ten years. The center was created to offer researchers access to such VR installations. This paper examines the long-term use of the visualization center for virtual reality and presents our learnings, providing empirical knowledge to research teams who are about to establish a similar facility. By illustrating typical use cases this long-term report on the operational aspects, advantages and disadvantages of

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*e-mail: elisabeth.mayer@lrz.de
†e-mail: ruben.garcia@lmu.de
‡e-mail: daniel.kolb@lrz.de
§e-mail: jutta.dreer@lrz.de
¶e-mail: simone.müller@lrz.de
‖e-mail: thomas.odaker@lrz.de
**e-mail: dieter.kranzlmüller@lrz.de

our center could fill a gap in the existing VR literature. Augmented Reality devices or topics will not be covered in this paper.

We address the following questions: What are the lessons learnt from operating such a center for ten years? How have the workflows changed over time? And what may be the future of such a center?

2 RELATED WORK

2.1 Large scale Virtual Reality and Science

VR refers to an immersive, interactive, multi-sensory, viewer-centered, 3D computer-generated environment [24]. Here not only hardware, like HMDs are used but also alternatives like large-scale immersive displays [1]. Researchers were initially wary of using immersive displays and VR [3, 9, 18]. However, e.g., Duval et al. concluded that an immersive 3D display helps gain better insight into the data due to "the innate human capability to recognize and reason with 3D information" [9]. Researchers discovered that VR provided unique and effective ways to learn and that it proved to be highly motivating to learners [20]. Specifically the interactive aspect of VR overcame the boundaries between viewers and computer [24].

While HMDs can offer individual VR experiences and provide advantages as being affordable and transportable, this paper focuses on large-scale immersive displays. The original CAVE built by Cruz-Neira et al. can be described as one of the most iconic [6]: it is a room-scale cube that uses rear projection onto the walls to display a virtual world and a top projection for the floor. A major advantage of this system is the ability to collaborate in person, as a small group of people could be in the installation at a time. A majority of CAVEs today use back projection to generate the immersive space. In 1993 there were many use cases for CAVE systems in research, as these offered "strong sense of immersion and participation in the environment" [5]. Use cases ranged from visualizations of galaxies, a human head and brain, molecular dynamics and many more. What defines a CAVE or CAVE-like system is a room-scale area (not necessarily a cube), mostly using projection, that offers users an immersive experience with head-tracking for at least one user. However there are different types of CAVEs too [23]. Muhanna defined the difference between different large-scale immersive systems as follows: CAVEs are fully immersive room-based systems, whereas Powerwalls encompass non-room-based, partially immersive installations [23].

2.2 Virtual Reality Workflows

When creating applications for VR visualizations there have been various approaches. A standard example of a scientific visualization would be like Helbig et al. [14]. They created a workflow using meteorological data to visualize the raw data in VR. One of their main challenges was that the raw data were heterogeneous, different resolutions, dimensions, and structures. So an intermediate step was introduced and the data was unified. The typical simplified use case for a visualization center consists of the following: raw data is introduced, an intermediate step needs to be conducted to unify the data, and then the visualization is created.

There have been examinations in certain science domains, e.g., geoscience where their workflow has been reported on. Kreylos et al. [17] describe their workflow for scientific VR visualizations of geoscience data. Before getting started with a VR visualization, the requirements for the experience should be defined: the application needs to run in real-time, offer interactions with the dataset, and limit cybersickness.

3 THE VISUALIZATION CENTER

This section focuses on the visualization center and its development over ten years. The center consists of two installations that are situated next to each other (see Fig. 1).
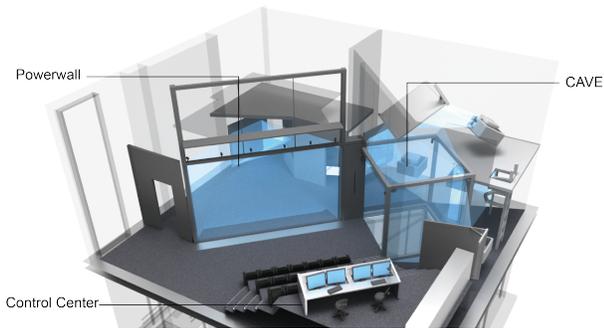
Figure 1: Layout of the visualization center with the Powerwall (left) and the CAVE (right).

The Powerwall: The planar projection surface has a size of $6\,m \times 3.15\,m$ and the projectors have a resolution of 4096×2160 *pixels*. Stereoscopy is achieved via polarization filters and passive stereo-glasses. For seating, 21 cinema-style seats are provided and the Powerwall is equipped with an optical tracking system.

The CAVE: is comprised of five walls with a size of $2.7\,m \times 2.7\,m$ each, forming a cube with one side missing. Each wall is projected onto by two active stereo projectors, achieving an overall resolution of 1920×1920 *pixels* per wall. For each wall one projector covers the top half and a second projector the lower half of the wall and a seamless blending zone is created between the projectors. Tracking is done also with an optical system and four cameras located in the corners near the ceiling of the CAVE. The perspective in the CAVE is only tracked for a single user, but the construction allows for up to five people to enter the CAVE at once for a collaborative experience. Due to the size of the room, we worked with mirrors to achieve the required projection paths (see Fig. 1).

Our report covers the ten years of operations, starting from 2012. We have broken this decade down into three phases (see Table 1). In our description of each individual phase, we cover a summary with an exemplary project of the phase.

3.1 Phase 1

In order to keep maintenance and development times low and to provide a stable service from the beginning two proprietary, commercial software products were mainly used: RTT Deltagen[1] (now: 3DExcite Deltagen), and Amira[2]. At that time most users were not familiar with the intricacies of VR methods, so the team was only involved in the data visualization process in an advanced stage of the projects. Either data were pre-processed with specialized software of the domain scientists providing the data and then imported as a geometric model into RTT Deltagen for immersive display or datasets could be converted into a visual representation with the standard visualization methods provided by Amira. In parallel, the

scene graph library OpenSG [25] (with an additional tool to manage distributed rendering, the CAVE Scene Manager [3], developed by Adrian Haffegee [12]) was adapted as a base for custom application development. The team itself consisted of three members who focused on general support of the hardware.

3.1.1 Example Project: Prototyping Project for Geosciences

A standard use case from phase 1 was, e.g. a prototyping project for geosciences. From 2011 to 2015, the team collaborated with a prototyping project aimed at creating a prototype e-Science environment to give experts access to data and models. A multi-model approach under the Meteorological Model Bridge was prepared for the CAVE: the 2011 flash flood that hit Genova and the surrounding region [13] The team was only involved in the last step of the project and received the following data: climate data on a 1-km and 5-km grid covering 24 hours in 48 timesteps, with each timestep containing $475 \times 475 \times 83$ data points. Here AmiraVR was used as it provided standard visualization tools like isosurface generation. This was advantageous because isosurfaces for each value of rain, snow, and sleet could be created.

3.1.2 Summary

During phase 1 it was vital to gather experiences concerning different aspects of running a visualization center. Up until that point the team had run a smaller projection device before (a so-called "Holobench" [28]). Problems included the occasional hardware failures, but also the amount of time it took when handling the CAVE or Powerwall.

This phase was dominated by commercial software. More than 50% of our projects were realized with RTT Deltagen, followed by AmiraVR. With commercial software, however, the user is always restricted to the available range of functions, limiting especially how interaction with and navigation in the model can be achieved. It was clear that customized applications were desired but could only be achieved by in-house development which led to a change in the approach in phase 2. Another lesson learnt was that being involved in a project from an early stage will facilitate the visualization as it allows influence on the choice of data formats and pre-processing steps, amongst other things.

3.2 Phase 2

By 2014 the user base had grown and expanded into additional science domains where Amira and RTT Deltagen could no longer provide the flexibility, support the variety of data formats, and handle the size of datasets. With the beginning of phase 2, the visualization team moved away from commercial software solutions and towards developing custom visualizations to meet the users' demands. At first, these applications were mainly based on third-party libraries like OpenSG and Equalizer [10] to handle the multi-display installations. In addition, a member of the visualization team started developing custom libraries to provide the full flexibility required for some visualization projects. Two libraries were created to cover two functionalities: One to provide a simple synchronization mechanism for multi-display installations, and the other for loading, managing, and rendering large-scale datasets. The visualization team had grown to five members. While only three had a background in computer science, all had intricate experience with the hardware and software.

3.2.1 Example Project: Visualization of Convection Streams

This project stems from the domain of geophysics and visualizes the temperature distribution within Earth's mantle over the course of about 200 million years. A large-scale dataset had been produced by running a simulation on a supercomputer that contains the time-varying data. The geophysicists required a VR visualization that would allow them to interactively explore their data in detail and in

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[1] https://www.3ds.com
[2] https://www.thermofisher.com/

[3] http://dev.invrs.org/documents/14

Table 1: Overview of the different phases during ten years of operating a visualization center.

	Phase 1	**Phase 2**	**Phase 3**
Duration	2012-2014	2014-2017	2017-
Hardware	CAVE, Powerwall	CAVE, Powerwall	CAVE, Powerwall, LED-Powerwall
Software	RTT Deltagen, Amira, OpenSG, Drishti	Equalizer, OpenSG, In-house libraries, Magnum Engine, ParaView, Amira, Covise	In-house library, Open Source Game Engine, Covise
Example Project	Prototyping tool for Geoscience fields Science Domain: Multiple	Visualizing Convection Streams Science Domain: Geophysics	Visualizing Rainfall in Bavaria Science Domain: Climatology, Hydrology

real-time as well as smoothly play the entire duration contained in the simulation data as an animation sequence. The established workflows and software could not fulfill these requirements. Therefore, this was the project that triggered the exploration of new workflows and custom application development [30].

The workflow started out similarly to phase 1 with a preprocessing step of the data. As the raw simulation dataset was not suitable for a real-time visualization due to its size, isosurfaces were precomputed from the dataset. This visualization first used OpenSG, this changed however due to the requirements and size of the data. Contrary to phase 1, however, we started developing a custom binary data format and software library, that allowed us to optimize the data storage and implement an efficient streaming of the data to graphics memory. Implementing the loading and managing of the data ourself allowed us to create more complex 3D data for each timestep without compromising performance. The result is a highly detailed, interactive visualization of the data.

3.2.2 Summary

Phase 2 saw the center moving away from commercial software solutions and towards custom-developed visualizations. This change was caused by highly specialized requirements of the growing user base, e.g., extremely large datasets, custom data formats, and various data types. The maintenance of developed software, however, requires low-level computer graphics and network programming knowledge. During this phase the team had become familiar with developing custom software as well as using the in-house libraries. As the desire for high-quality visuals grew the visualization team was involved in earlier project stages than during phase 1, when VR visualizations were often considered an afterthought. Further, at this point the team had started conducting their own research into VR, visualization, and user interaction.

At this point, game engines had already been used for scientific applications [11] and as developing and maintaining our libraries ourselves required a lot of basic know-how, we decided to explore game engines for use in multi-display applications for easier workflows, higher-quality visuals, and faster development times.

3.3 Phase 3

By 2017 HMDs gained popularity with the releases of HTC Vive and Oculus Rift [1]. With these, game engines surged in the field of VR, even though they had been used for scientific visualizations previously [11]. Advantages include cross-platform support, state-of-the-art rendering algorithms, benefiting from developments and maintenance of the code base by numerous other programmers, and the modular reusability of significant portions from prior visualizations for future projects.

The ongoing phase 3 is marked by the introduction of Unreal Engine 4 (UE4) to the visualization center's systems as well as a dedicated focus on scientific evaluation of implemented VR visualizations. Game engines had previously been used in CAVE systems [15], in that case, however, the CAVE did not support stereoscopy and was not equipped with a tracking system. With the development of the nDisplay plugin [4], it was possible to use UE4

for a CAVE and a Powerwall display setup, which only required the addition of tracking via VRPN [26].

To reduce considerable overhead in maintenance, phase 3 limited the operating system to Linux and discontinued support of previous Windows projects. Instead, several visualizations were recreated and rebuilt with the new Game-Engine-based workflow from various fields including art history and zoology. Nearing six years of continued use, the rendering cluster was upgraded with up-to-date hardware. During phase 3, we acquired an additional Powerwall based on LED technology (see Table 1). Due to its functional similarity to our projection-based Powerwall, we can export for all three installations with our current workflow. As of writing the paper the team consists of seven members with five members having experience with maintaining the hardware and software for the centre. Four of these people have computer science backgrounds and a further member has additional experience with design. The others prepare objects for the installations but don't directly work with them.

3.3.1 Example Project: Visualization of extreme rainfall events

In this project, an international collaboration investigates the effects of climate change on meteorological and hydrological events. This includes the transient climate simulation of a 50-member ensemble for the years 1950-2099, using the Canadian Regional Climate Model and the RCP8.5 scenario. The corresponding VR visualization compares three extreme rainfall events in Bavaria: one historical, which preceded the 1999 Pentecost flood, and two simulated future events. Each rainfall event is extracted from the project's dataset and consists of 200 timesteps spanning 60 hours of aggregated precipitation [19]. The magnitude of the aggregated rainfall is displayed using vertical height as well as colored isosurfaces. A 3D representation of geographical Bavaria provides further context and orientation.

With Unreal Engine 4.22 providing the necessary rendering quality and performance for CAVE visualizations, pre-processing and preparing the raw input data was the most laborious and time-consuming step of the workflow. The application uses three sets of data: A digital elevation model of Bavaria (EU-DEM v1.1), high-res satellite images by SENTINEL-2 serving as textures, and rainfall data originating from a scientific simulation executed on a HPC-system. Extensive preparation was required to convert this data to be compatible with Unreal Engine, which facilitated the final data composition, performance improvements like mipmaps, and rapid design iterations of visual aspects and user interaction.

3.3.2 Summary

While game engines managed to reduce workload by streamlining the visualization process, one bottleneck remained: converting raw data into uniform data for VR. A major issue of phase two was the diverse nature of scientific data, every science domain had its own data types, e.g., CSV, ASC, NetCDF, or even custom-developed data format for specialized, cutting-edge research. The visualization team was now also involved in the project from the beginning. Further, the advantage of using a customized plugin to display experiences in the CAVE and Powerwall let the team focus more on the visualizations

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[4] `https://docs.unrealengine.com/4.27/en-US/`

`WorkingWithMedia/IntegratingMedia/nDisplay/QuickStart/`

themselves than the process of bringing them into the installations. One disadvantage was to create a dependency on external software, especially as a few years after introducing UE4 and the plugin, support for OpenGL was removed from UE4 in favor of Vulkan, which caused issues with the display setup of the CAVE, effectively forcing us to rely on an older engine version.

4 DISCUSSION AND CONCLUSION

The center has been used consistently over the years. In phase 3 we started tracking the visitor count (see Fig. 2). We averaged ≈ 152 users monthly (both researchers and visitors) between January 2017 and December 2022. In early 2020 the center was closed due to the COVID-19 pandemic. As of the summer in 2020, restrictions were implemented due to health concerns, severely limited the number of simultaneous users. During the years of the pandemic, access to the center was restricted. We compared the average monthly users of the years 2017-2018 (258) with the average monthly users of two years affected by the pandemic 2020-2021 (39) and found a 85% reduction due to sanitary and health concerns. User numbers are recovering with an average of 126 monthly users during 2022 as opposed to an average of 31 monthly users during the year of 2021.

Figure 2: This graphic depicts the number of users at the center over the course of five years. The impact of the COVID-19 pandemic can be seen between March 2020 and June 2022.

4.1 Advantages and Challenges

One of the biggest benefits of such a visualization center is to have the hardware as well as a team of visualization experts in the same place. And having a team of visualization experts be part of projects from various science domains offers another benefit: reusability. Often, different science domains are confronted with similar challenges when it comes to visualizations. A single team supporting many projects is able to reuse existing code, workflows or tools and cut down development times. This enables domain scientists to focus on their scientific goals and less on visualizing their data.

Over the ten years VR has become a lot cheaper and more accessible with the introduction of relatively cheap commercial HMDs in 2016 and the subsequent rise in software support for VR. As indicated by the number of users (Fig. 2), however, the popularity of the large-scale installations has not been impacted negatively by the availability of HMDs. Many users report, that they consider systems like the CAVE or Powerwall to be beneficial to their work due to their large scale and their ease of accessibility. Some consider the isolation from the environment, that comes with the use of HMDs, to negatively impact the experience.

However, the main challenges of installations like the CAVE or Powerwall are their space requirements, complexity, cost, and the

effort required to maintain them. The monetary and time investment upfront is high, especially for high-quality equipment. In addition, the lack of mobility of such installations can be a deterring factor to users. Requiring physical travel to use the installations may be justified for events or longer sessions but is often seen as too time-consuming for short sessions or during day-to-day work.

4.2 Learnings

Creating visualizations for different science domains gave the team experience in handling various types and sizes of data. This makes it possible to create visualizations for many different fields. Two of the visualizations, where the center's team played a significant role have been honored at conferences specializing in visualizing extremely large datasets [4, 22].

Another major learning is that the team should be incorporated in the early steps of a visualization. Where previously, visualization and VR experts were only introduced in the last step of the process, now they are involved from the first step on, so the simulation.

The introduction of game engines showed immediate effects. We are now able to focus primarily on the user experience as well as the visual quality of the visualizations. Further, compared to phase 1, the visualization process has been sped up significantly. It is now possible to simultaneously create experiences for CAVE, Powerwall, and HMDs with little rework.

Our research for this paper returned only little research on location-based visualization centers. There had also been debate on if CAVE systems are still relevant [8]. A limitation of this report is that we can only report on what we have maintained, observed and learnt over the years. Our visitor numbers show the interest and active audience for such a center. We have not found an existing established scientific methodology to evaluate the added value of dedicated visualization centers. However, with the many science domains that have profited from our support, we hope many more can benefit from our report on the long-term use of such a center. As a research center, we are also looking for future use cases.

4.3 New Fields to Explore

The installations in the center are currently a closed system, so they cannot be accessed through external users, and the idea is to explore new fields to expand this.

On the software side, we currently base the majority of our developments on Unreal Engine. While this helps us to reduce development time and we can fully benefit from any developments to the multi-display plugin of UE4, the removal of OpenGL from UE4 has proven to be a severe limitation. As such, we are looking to expand our software portfolio to include other applications or libraries. With the addition of an LED-based display in 2018 we see several advantages of the LED technology. The advantages here include reduced maintenance, easier serviceability, very good brightness, and good color reproduction among other things. However, there are issues like dissipation of heat, which could lead to high temperatures in an enclosed space like a CAVE, and smaller defects like dead pixels being common. Overall, however, we consider LED technology, and especially the prospect of an LED CAVE, to be the next big step for our center.

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