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A Vision of Bringing Immersive Visualization to Scientific Workflows

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ABSTRACT

The process of data exploration is becoming an essential part of today's scientific workflows. A large number of immersive visualization environments are being explored to help researchers and experts to better understand the data and to offer intuitive interaction. Despite these benefits, shown by prior research, it is still uncommon to find them being applied to realistic scientific workflows. We argue that immersive visualization techniques will not be adopted until they can be easily integrated in the workflow of domain experts, and that specific efforts should be made to help the integration of novel and immersive visualization techniques with classically used software.

KEYWORDS

Immersive Analytics; Visualization; Interaction; Applications;

INTRODUCTION

In many practical application domains for visualization, the size of the used datasets grows tremendously. For example in high-energy physics, even after eliminating noisy and useless data, a typical

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Flow data example:

Even with only 128 points per direction of space, the final grid will have, in 3D, $128^3 = 2097152$ nodes. Outputs of simulations are multiple, making one snapshot 3 to 10+ times larger than the grid. Fluid mechanics is unsteady, it means that, commonly, thousands of snapshots are saved. As a consequence, saved data are, for the present illustration, larger than 6 GiB. Also, if the number of points per direction is simply doubled, then the size of the data is multiplied by a factor of 8.

collision experiment generates more than 10,000 new particle trajectories, each of them composed of dozens of points and each with spatial position and energy information. The physicists then analyze this massive data to find out strange outliers, with trajectories that are hard to explain by current physics theories. As another example, in fluid mechanics, researchers in academia and industry investigate multiple fields, for instance, velocity, pressure, concentration or temperature (to understand, e.g., combustion, understanding global warming, weather forecasting, flood risks). Multiple fields for time-dependent data are usually a few gigabytes large and can easily grow up to the terabyte range.

For research and engineering purposes, the exploration and analysis of data are thus becoming pivotal processes. In recent years and decades, various innovative interactive visualization environments, for example, the Responsive Workbench [12], occluded virtual reality (VR) glasses, and CAVE virtual environment [6], appeal to offer a better feeling of being visually immersed inside the data compared to traditional 2D screens. With such environments, it has been widely recognized in the literature that visualization enlightens users' understanding of and facilitates the interaction with the large and complex data. Many prior works argued that scientific data exploration tasks could take benefits of them (e.g., [2, 3]). However, in reality, they are rarely applied to scientific workflows.

In contrast to such purely VR visualization environments, previous literature (e.g., [1, 10, 11]) described a vision that desktops will not be totally replaced by such innovative visualization environments but rather be combined with others to make use of each environment and their inherent benefits. Here we further discuss this vision with a focus on scientific workflows. First we discuss the usage and benefits of immersive visualization for complex data exploration. Then, through our communication with researchers and a short analysis of related work, we expose why they are still not adopted by researchers. We emphasize the need to focus our effort in the visualization and HCI community towards combining and integrating immersive technologies with classical desktop workstations and software to benefit from Hybrid Virtual Environments (HVEs) for visualization purposes. Finally, we conclude our near-future research agenda highlighting several challenges for the interaction design in such hybrid environments.

IMMERSIVE VISUALIZATION FOR SCIENTIFIC DATA EXPLORATION

Using immersive environments for data exploration has been envisioned for a long time. Bryson [3], for example, explained that 3D VR environments and scientific visualization naturally match, not only because of the spatial properties of scientific data, but also the potential of real-world interactions leveraged by this combination. Early evaluation (e.g., [18]) concluded that visualization in stereoscopic view usually facilitates the understanding of complex line cluster and network graphs. Many recent works also confirm the advantages of immersive visualizations. For instance, Prabhat et al. [16] compared the performance of biological volume data exploration tasks in three environments. The environment with the highest immersion yielded the best results for both users' preference and

performance of understanding spatial relationship. Usher et al. [20] explored the use VR environments and 3D interaction techniques for experts to trace neural circuits in brain, finding this system effective and less frustrating compared to traditional tools. They argued that scientists are able to understand large and complex cases better with such setting. Hurter et al. [8] designed FiberClay, a system that visualizes massive 3D airplane trajectories through occluded VR glasses. They mention that thanks to their system, domain experts were able to discover new interesting patterns in the data, therefore concluding that such immersive systems have benefits for the data sense-making process. A recent survey [7, 15] also summarized many possible advantages brought by immersive analytics, including the possibilities of offering situated/embodied data exploration, spatial immersion, and collaboration. Based on the literature, it therefore seems that immersive visualization systems combined with 3D spatial input has benefits for data exploration and understanding.

LIMITATIONS OF IMMERSIVE ENVIRONMENTS FOR SCIENTIFIC WORKFLOWS

Despite the benefits offered by different immersive environments, and despite the fact that such environments are gaining popularity in many different areas (for example, augmented reality (AR) and VR systems have been already much used in education, art and tourism), it is hard to find them practically applied and integrated into real scientific and engineering workflows. Indeed, some inherent technical problems of the environments themselves, for instance possible occlusion, remain. However, based on the feedback and observations from domain experts, we believe that the adoption of immersive visualization environments are not only hold back by these fundamental reasons. Consequently, in this section, we quickly survey findings from the literature that highlight the limited rate of adoption of immersive technologies, before reporting the limitations of such immersive environments from experts' observations.

Limitations from the literature

One reason is that scientific work usually requires dense real-time computations [10]. Small and portable device cannot proper handle it, while large environment (like wall-sized screen and CAVE) has complicated setup and usually requires additional technique supports which limits their usage in laboratories. The need of constant calibration and maintenance is also a major drawback in such workflows. Apart from that, although many studies pointed out that visual analysis helps researchers and engineers to understand their data, scientific workflows are not limited to spatial aspects only. Abstract data such as statistical results play a pivotal role and the analysis of such data usually requires traditional plots such as histograms, charts, etc. Showing these elements simply as a billboard placed into stereoscopic 3D view is not necessarily always advantageous, and turning the plots into a 3D representation is often argued to be inefficient (e. g., [17]). Also, 3D spatial input sometimes fails to meet the interaction requirements of certain scientific tasks, which usually demand a high accuracy.

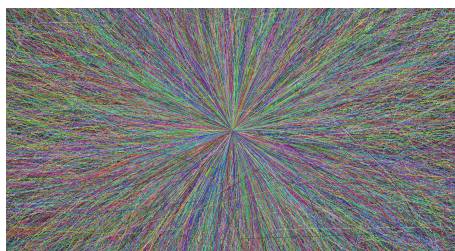


Figure 1: Display of particle trajectories generated by photon collision.

¹<https://atlas-vp1.web.cern.ch/atlas-vp1/home/>

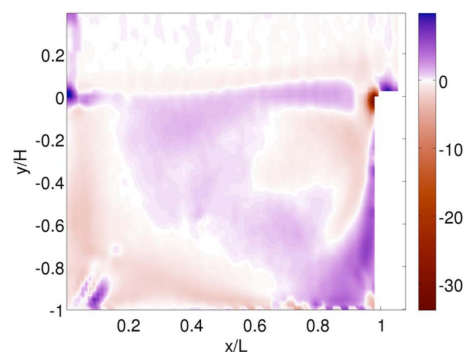


Figure 2: 2D-divergence field from experimental data (flow past a cavity).

A recent study [2] reported that domain experts mentioned that the traditional scripts-based input is still necessary for accurate and advanced analysis, and would rather combine the studied new interactive approach with traditional mouse and keyboard input.

Field observations

Through our observation and discussion with researchers working in fluid mechanics and high-energy physics, we work toward understanding people's resistance of applying novel immersive visualization environments to their workflows in practice. In particular, we work with experts in high-energy physics and our observations in this domain are similar to what Besançon et al. [2] reported about fluid dynamics. The desktop-based visualization software *Vitual Point*¹ used by Atlas team in CERN provides beautiful images of collision events, yet for the experts there are still a number of challenges. For instance, it is difficult to distinguish different events and the numerous trajectories; traces and trajectories are overlaid on each others (e. g., Figure 1). Although the physicists agree that stereoscopic output with intuitive and fluid input is inspiring to understand the global event, they expressed the need to find a way to support script writing-loading in such environments as well due to the fact that scientists do not explore the data in a random way. Many predefined views, settings, and interaction (like filtering on different parameters) are specifically designed by and for the scientists to carry out an analysis. Writing scripts with keyboards is still the easiest way to quickly adjust all these parameters with high precision.

Furthermore, one of the authors, a fluid dynamics researcher, also reports from his observations that several crucial needs are not fulfilled by the state-of-the-art visualization toolkits and new interactive systems. For instance, having access simultaneously to global and local metrics, and being able to compare the results within the visualization space is a fundamental task in fluid dynamics research. For instance, a common procedure is to verify the ergodicity of the flow: is the turbulence homogeneous at all scales, or do some parts of the data have a more specific behavior? The task is not only to discover it, but to *quantify* it. A second illustration is the investigation of the divergence field (e. g., Figure 2). It allows researchers, from experimental 2D snapshots, to understand some of the 3D properties of the system. From the simulation perspective, it also allows the researchers to verify if the simulation is accurate. In most scenarios, the flow rate crossing a plane of reference, say from the left to the right, has to be equal to the flow rate crossing the plane from the right to the left (if not, accumulation would occur, which leads to an explosion). The amount of fluids crossing the plane is hence, globally, zero. Note that it is not necessary the case locally, and understanding these behaviors are critical to understand the physics.

These examples illustrate that user-defined metrics are pivotal to understand the physics. The needs are not only expending the predefined settings and views, but to propose ways to interact and derive quantities from the use of the immersive environments. Based on these considerations,

our vision of bringing immersion to scientific workflows, is consistent with that of Isenberg [10], is that desktop should not disappear, but would rather be combined with immersive environments to augment its limited 2D output, thus help to better explore and understand complex dataset [1].

HYBRID 2D/3D VISUALIZATION ENVIRONMENTS (HVES)

Our observations indicate that a hybrid 2D/3D visualization environments could be highly appreciated for scientific workflows. In fact, the study of such HVEs to explore and to understand data is not a brand new topic. Bryson [3] made a point that “*Non-immersive interactive visualization systems implemented for the conventional desktop and mouse are effective for moderately complex problems. Virtual reality displays aid in the unambiguous display of these structures by providing a rich set of spatial and depth cues.*” It has been pointed out that immersion is not only offered by the data visualized in 3D, but also by the direct and intuitive interaction [4, 13]. This is largely supported in HVEs: using an additional tactile surface in stereoscopic visualization environments adds both various input (such as touch and tangible input) and output (a 2D space for information display and possible haptic feedback). In this submission, we focus more on the visualization aspect, discussing the benefits brought by using both 2D and 3D visualization. For such environments, one common design is to visualize a “god-like” global view on the 2D screen [9, 19] while users discover detailed information through immersive stereoscopic views. Thus users are able to discover data in details without losing the control/observation of the general context. Another method lets users perceive a global view of the data in 3D, and a slice or a small set of the data in 2D (for example, the interactive WIM [5]). Such approaches are common in scientific data exploration as a large portion of the scientific data (like flow fields or medical data) is volumetric. Exploring such dataset requires, in particular, visualization of slices, which is particularly suited for a 2D surface. A similar example is the one from Mandalika et al. [14] who designed a hybrid interface combining a zSpace VR system with a traditional desktop interface for radiology data exploration. In this paper, an interesting finding is that while students do faster in hybrid environments with stylus input, experts still perform the best in 2D using mouse in term of speed. This finding confirmed our hypothesis that desktop working environments should not be totally replaced for scientific workflows.

VISION AND RESEARCH AGENDA

Taking inspirations from previous work, we envision that a HVE that can be practically applied in today’s scientific workflows. It should be composed with at least a PC (with mouse, keyboard, and a screen—this could be a laptop as well) and an immersive output device. While general research questions about data visualization with novel/immersive environments are summarized in the literature (e. g., [4, 5, 7, 15]), in the remainder we describe our near future research agenda by reporting several challenges that focus on bridging immersive visualizations with current scientific workflows.

²For example, Microsoft's HoloLens.

Based on our experience with different immersive output environments, we believe that the use of non-occluded AR headsets² is currently a good solution to provide a common data exploration environment. Such AR headsets immerse users by projecting the data in a stereoscopic view. Compared with large immersive environments like responsive workbench and CAVE, AR glasses do not require complex setup and maintenance. Compared with occluding VR headsets, users are not separated from the real world, thus they have more freedom to perform tasks on the desktop, we consequently do not need to replicate existing tools completely in the virtual realm, and people can continue to interact with real-world objects (e.g., paper/pen, blackboard). We consider this last point as a major advantage as we observed researchers needing to take traditional notes in their current scientific workflows. The use of AR as a further output in addition to a PC thus provides an extension of the 2D screen with larger space. For domain experts to be able to perform their data analysis, it is thus important to clarify which elements can be visualized immersively, and which ones are better used on traditional screens. A challenge is thus how to make the visual transitions between different devices [10]. For example, a data exploration and analysis system should provide support to its users to decide what to show on each view as well as how to move a view from desktop to the AR view or in the opposite direction. In addition, existing AR headsets have intrinsic and unchangeable camera parameters and the data display should thus be well adjusted to match these specs. For example, while researchers in both particle physics and fluid dynamics often rely on orthographic projections of their 3D datasets, such views would be equivalent to a flat image in AR. Nonetheless, the projection parameters of AR headsets are equivalent to our normal vision, so that the disadvantages often associated with perspective projection of 3D data may not be as severe as for a general perspective projection. Further investigation is thus needed to understand how to best match the different views between the screen and the AR space.³

³For example, the view angle of Microsoft HoloLens is fixed to 18 degrees. In such limited view field, it is hard to visualize the dataset in 3D without proper adjustment of the model.

Second, our vision is not to create a novel environment and to replace current tools. Domains experts are familiar with the data analysis on desktops, the second challenge is thus to design the interaction technique compatible with scientific workflows. We thus need to design ways to interact with popular scientific software (e.g., Python, Paraview, and proprietary software such as MatLab, Virtual Point). While it is easy for experts to interact with them using keyboard and mouse, we need to investigate how to adopt the input to the AR space. More recent forms of input (e.g., tactile/tangible, voice, gestures) are often considered to be intuitive and natural. Yet, the question of whether they are suitable for generic or specific tasks in the context of existing scientific workflows is still open and requires investigation. This research does not only need to address the problems of mapping 2D input to 3D output but also how to create forms of control that is perceived by the intended users as fluid for both desktop and “hologram” representations.

A third challenge lies in the design of dedicated interaction techniques to support such hybrid environments—techniques that make specific use of both views and that seamlessly extend the

existing interaction metaphors that the experts are used to on their PC-based tools. We first need to determine which practical tasks require either the traditional or the AR views only, and design appropriate controls (likely captured by the PC) for the AR setting. We also need to support tasks that use both parts of the system and that that allow researchers to easily transition between them.

A forth challenge lies in collaborative scenarios scientists face on a daily basis. The sharing, discussion, and exploration of datasets together must be investigated, in terms of communication channels, interaction techniques, and efficiency both in co-located and distributed setups.

Finally, there are a number of practical challenges to consider. One of them is that we need interfaces to high-performance computing that is likely not done on the workstation that is used for interaction but on a remote server. Another one is the extension and further development of existing APIs such that existing tools can be extended to include AR components. Without answers such practical questions the adoption of new interaction designs will ultimately remain slow.

CONCLUSION

We described our vision of a practical way to bring immersive visualization environments to scientific workflows. We believe that traditional desktop workstations are still highly required to support the complex data processing and analysis tasks. At the same time, AR glasses could be used to augment the traditional screen to improve complex data understanding. By focusing on how to merge the two environments and handle their interaction through an extensive programming effort, we believe that we could improve the adoption rate of techniques and systems developed by the visualization communities into domain experts' workflow.

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