Visualizing Plasma Physics Simulations in Immersive Environments

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Abstract: Plasma physics simulations create complex datasets for which researchers need state-of-the-art visualization tools to gain insights. These datasets are 3D in nature but are commonly depicted and analyzed using 2D idioms displayed on 2D screens. These offer limited understandability in a domain where spatial awareness is key. Virtual reality (VR) can be used as an alternative to conventional means for analyzing such datasets. This study presents PlasmaVR, a proof-of-concept VR tool for visualizing datasets resulting from plasma physics simulations. It enables immersive multidimensional data visualization of particles, scalar, and vector fields. The study includes user evaluation with domain experts where PlasmaVR was employed to assess the possible benefits of immersive environments in plasma physics visualization. Participants manifested a high level of engagement when using the prototype, considering it more enjoyable than conventional means. The participant's perception of the usefulness of VR in plasma simulations also increased after experiencing the prototype.

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1 INTRODUCTION

Plasma is a physical state of matter where a significant fraction of particles is charged (Fridman and Kennedy, 2021). These particles, usually electrons and ions, interact via long-range forces and sustain rich, collective motion, waves, and instabilities (Piel, 2010). Modeling these systems requires complex simulations that can be performed using Particle-in-Cell (PIC) codes (Ljung et al., 2000). An example of such a code is the fully relativistic, massively parallel OSIRIS PIC code (Fonseca et al., 2002) used to generate the data presented in this work. The datasets obtained from these simulations consist most notably of particle data (e.g., position, momentum, energy), scalar field data (e.g., energy density), and vector field data (e.g., electric and magnetic fields) (Fitzpatrick, 2022). The generated datasets are 3D in nature but commonly depicted and analyzed by resorting to 2D idioms (Munzner and Maguire, 2015).

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While there are applications to create and analyze 3D idioms for plasma physics (Ahrens et al., 2005; Bethel et al., 2016), these mostly use conventional visualization and interaction means (2D screen, keyboard, and mouse), which are not particularly engaging (Guo et al., 2017). In that sense, virtual reality (VR) can be used as an alternative to these conventional means in the analysis of plasma simulations. VR has been known to offer improved depth and spatial relationship perception (Guo et al., 2022; Vienne et al., 2020), which are fundamental for obtaining insights into 3D plasma morphology. It provides a different perspective that results from the users' immersion in the physical constructs they are trying to observe (Millais et al., 2018). Likewise, VR can potentially increase user engagement by offering more immersive and enjoyable experiences.

This study presents PlasmaVR, a VR interactive prototype tool to visualize the data resulting from plasma physics simulations. The tool provides researchers with an immersive environment for exploring scientific datasets using natural interaction. It enables multidimensional data visualization of particles, scalar, and vector fields. The tool includes specific functionalities for data annotation and segmentation.

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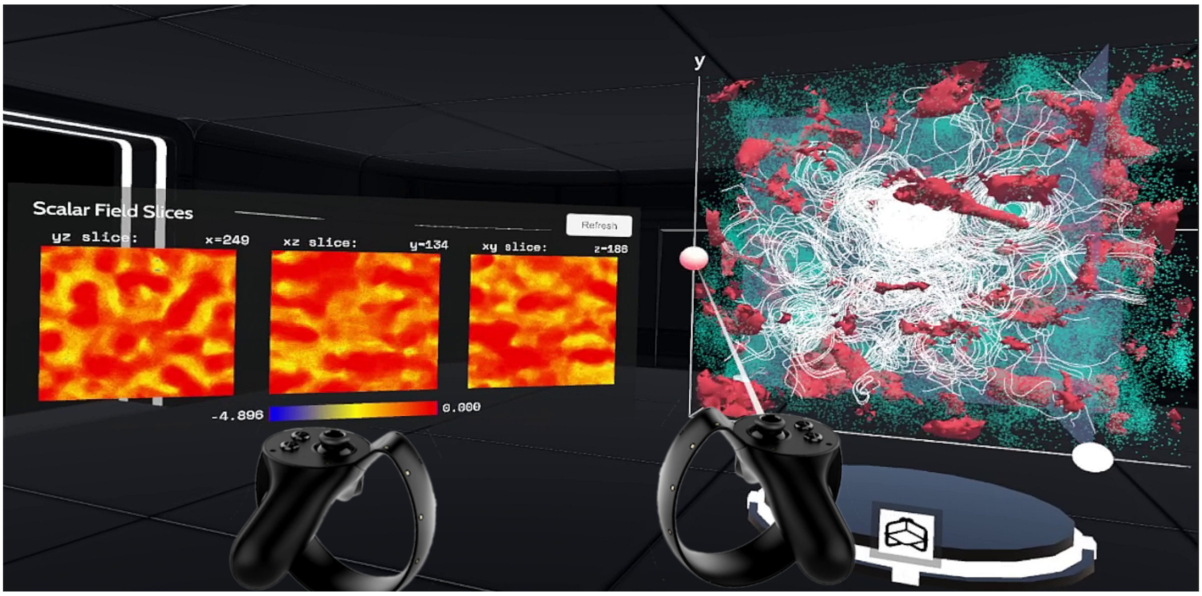

Figure 1: The immersive environment (mockup) of PlasmaVR emulates a sci-fi-themed laboratory. The idiom and the slicing planes control mechanism are visible on the right of the figure. The resulting slices are on the left of the figure.

It allows multiaxial dynamic slicing of the 3D idioms with a real-time representation of corresponding scalar 2D energy heatmaps (Figure 1).

2 RELATED WORK

Immersive technologies have been widely accepted as an aspect of paramount relevance and a future trend in scientific visualization (Gallagher, 2023). In that scope, extended reality (XR) has been applied in a wide range of domains, including in research studies related to natural, formal, and social sciences (Korkut and Surer, 2023; Mathur et al., 2023; Fombona-Pascual et al., 2022; Yeung et al., 2021).

The application of XR technologies to plasma physics data visualization has also been addressed in previous research work. An example is the system developed by Foss et al. (Foss et al., 2018), where plasma simulation data was visualized in an augmented reality (AR) environment. This work focuses on the scalar data obtained from plasma simulations and uses isosurfaces for its representation. The visualization is presented in a time-varying format, and as such, 3D models corresponding to the timesteps were pre-rendered and then displayed in sequence to create an animation. The system is limited in what concerns interactivity, as possible user interaction mainly consists of walking around the visualization. However, researchers who tested the system found the possibility of observing the isosurfaces from different perspectives in an AR environment very valuable. The integration of plasma physics simulations with VR was equally explored by Danielová et al. (Danielová et al., 2019). They proposed a system that allows researchers to visualize plasma simulation datasets. The web-based system offers a new perspective on complex interactions of intense laser beams with various forms of targets. It enables the analysis of particles and fields and the modification of environmental properties to enhance spatial features.

Ohtani et al. (Ohtani et al., 2010; Ohtani et al., 2011b; Ohtani et al., 2011a) used a CAVE system for visualizing plasma simulation results and device data. They addressed the virtual representation and interaction with magnetic field lines, particle trajectories, and isosurfaces of plasma pressure. The study focused on the virtues of VR in understanding the three-dimensional positional relationship between plasma elements. In that scope, researchers also addressed in a later work (Ohtani et al., 2016) how VR promoted users' understanding of dust particle positioning in plasma simulation experiments. They concluded that VR could improve understanding of the relative positional relationship between the dust particles' trajectories and the magnetic field's structure. In an earlier study, Hayashi (Hayashi, 2001) had also already conceptualized how CAVE systems could be used to simulate nonlinear phenomena in plasmas. Ohno et al. (Ohno et al., 2006) had previously presented VFIVE, a VR visualization software for CAVE systems, capable of representing scalar and vector data. Lastly, the application developed by Brás (Brás, 2022), which was used as a base for the current study, uses VR headsets in the scope of scientific visualization of plasma physics simulations.

The present study builds upon visualization and interaction concepts addressed in earlier work and further explores the potential of immersive environments in plasma physics scientific visualization. In particular, it fills in the gaps concerning the usefulness and usability of VR in that scope. While Foss et al. (Foss et al., 2018) and Ohtani et al. (Ohtani et al., 2010; Ohtani et al., 2011b; Ohtani et al., 2011a) used CAVE and AR systems, we set out to find out how a system capable of a potentially more immersive experience (designed for VR headsets) could perform in that sense. Also, unlike the study conducted by Foss et al. (Foss et al., 2018), we used an interface with integrated analytics features. These features share some of the characteristics of the work developed by Danielová et al. (Danielová et al., 2019) but were designed natively for VR interaction instead of the web interface proposed by these researchers.

3 SYSTEM OVERVIEW

PlasmaVR is an interactive tool for scientific visualization and exploration of datasets that result from plasma physics simulations in an immersive environment. The tool was born from the need of the Group of Lasers and Plasma (GoLP) (at Instituto Superior Técnico (IST), University of Lisbon) researchers to have an improved depth and spatial relationship perception when analyzing 3D plasma idioms. The general requirements for PlasmaVR were established from interviews with these researchers. They included animated visualization of the changing dynamics of the simulated systems (particle positions, scalar fields, and vector fields - Figure 2) and playback control over these animations. They also included the ability to perform dynamic time-dependent annotation and slice and segment the 3D idioms into 2D energy heatmaps.

The system aggregates two complementary modules: the data processing and VR modules. The first aims to process the high volume of raw data from plasma simulation experiments. This raw data is generated in the HDF5 (The HDF Group, 2007) format, and the processing module transforms it into a model that can be used inside the graphical engine (Unity). This module can process point clouds as well as scalar and vector volumes. The second module handles the representation of the different virtual elements inside the immersive environment and the user interaction.

When the users put on their VR headsets, they are inserted into an environment that simulates a sci-fi laboratory-themed room. This virtual room is where the plasma exploration takes place (Figure 1). In the center, the chosen type of plasma structure fluctuates above a platform and can be animated, rotated, resized, sectioned, or annotated. The user can move around the room, enter inside the plasma structure, slice it, and observe the intricacies of its morphology.

PlasmaVR uses a floating panel (which can be shown or hidden) attached to the left VR controller to access the different features. It includes buttons that lead to the playback control, slicing, rotation/resizing features, annotation, and the immersive environment configuration. The first of these features is the playback control, which incorporates play/pause buttons and a timeline. This timeline can be used to jump to a specific frame in the idiom's animation or observe step-by-step modifications of the plasma structure.

When analyzing the idioms, the users can rotate and resize them to view the data from different angles and perspectives. The rotation of the idioms is performed with a mapping to the controllers' motion. When the rotation mode is activated, a virtual model of a hand holding a sphere appears in place of the model of a standard controller. This sphere works as a 'proxy' for the 3D idiom. The user can then press the controller trigger to grab the sphere and rotate it with their virtual hand. The idiom follows the sphere's rotation with three degrees of freedom.

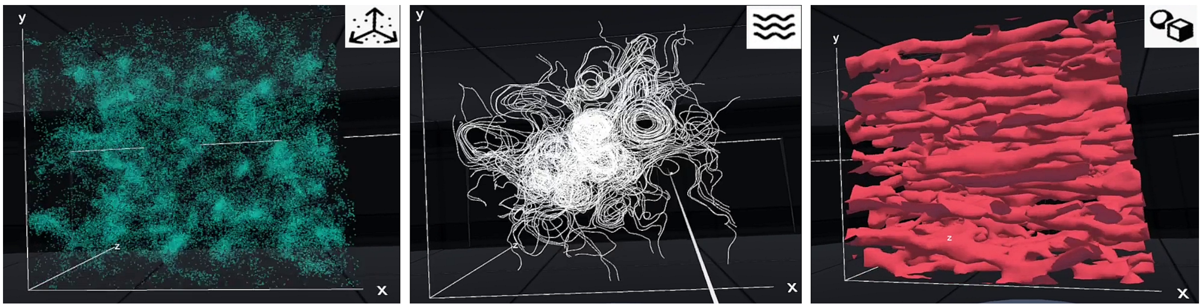

Figure 2: Particles (left), streamlines (center), and isosurfaces (right) idioms represented in the immersive environment and corresponding symbols used in the interface (top-right corners).

PlasmaVR also includes a slicing feature, which is directed at producing formal results of data analysis. To extract the slices, the users can move small spherical handles attached to each axis of the 3D plasma idiom. These handles are, in turn, linked to planes that bisect the idiom and will move along its respective axis. The position of each plane determines the sections that will be extracted (Figure 3). A 2D panel displays the heatmaps corresponding to the bisection from the three planes. This real-time multiaxial representation of energy heatmaps allows the researchers to document how the values change inside the represented fields.

When analyzing a plasma idiom, researchers may want to highlight specific aspects of what is happening in the simulation. However, annotating something in a 3D idiom using a keyboard, mouse, and 2D screen may be tedious and counterintuitive. Thus, researchers usually either make 2D annotations or generate and move 3D objects (e.g., arrows) to the area they want to highlight. On the contrary, 3D annotation fits particularly well within the PlasmaVR environment and interaction. The annotation feature takes advantage of VR's increased depth and spatial relationship perception. The researcher can enter inside the plasma structure and make geometrically complex and precise 3D annotations, thus highlighting valuable simulation insights. Due to the ability to draw freely in 3D, it is easy to draw annotations like in Figure 4 (right), where the purple annotation wraps around a volumetric protuberance in the structure, thus providing information more comprehensively. The annotations can be aggregated in groups, and their colors can be customized using the annotations menu (Figure 4, left), accessible from the main panel. This feature is also adapted to the dynamic nature of the plasma idiom. Because the plasma structure representation changes with time, the users can select a specific time frame where the annotation will be visible. This possibility allows researchers to make dynamic annotations that track, for example, the path of a particular anomaly as the plasma animation progresses.

4 EVALUATION

Domain experts from GoLP interacted with the application and performed a set of predefined tasks. An array of objective metrics was recorded during this interaction. They were then asked to answer questionnaires concerning the prototype's usability and usefulness. This section details how that evaluation was carried out.

4.1 Methodology

The study was conducted with an experimental group of five domain experts, from which informed consent was obtained. As plasma researchers, the participants were ideal to measure the possible benefits of PlasmaVR in the visualization of the data resulting from plasma physics simulations. The hardware consisted of an Oculus Quest 2 VR headset with a pair of controllers. The headset was connected to a desktop computer with an Intel Core i7-8700 CPU @ 3.20GHz processor, 16GB of RAM, and a NVIDIA GeForce GTX 1060 3GB graphics card. A monitor, keyboard, and mouse were also used (for filling out questionnaires).

The participants were asked to perform a set of three tasks that were designed to be realistic and, at the same time, would allow them to have contact with the extended scope of the prototype's functionalities. In the first task, the participants were required to draw a wide circle of a specific color surrounding a predrawn isosurface idiom and then define a time interval for when the annotation would be visible in the

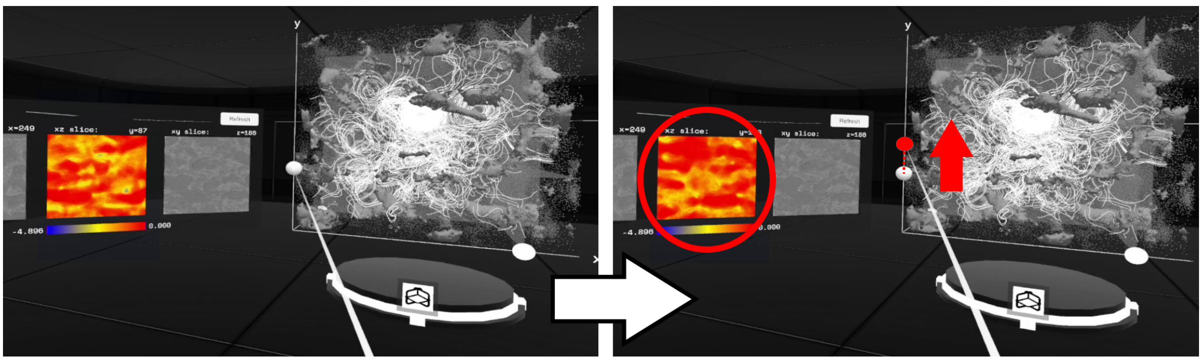

Figure 3: The three intersecting planes can be moved along its axis to generate the corresponding slices. In the example of the figure, moving the handle of the horizontal plane up the YY axis (red arrow and small red circle) results in the real-time update of the corresponding energy heatmap for the XZ slice (large red circle).

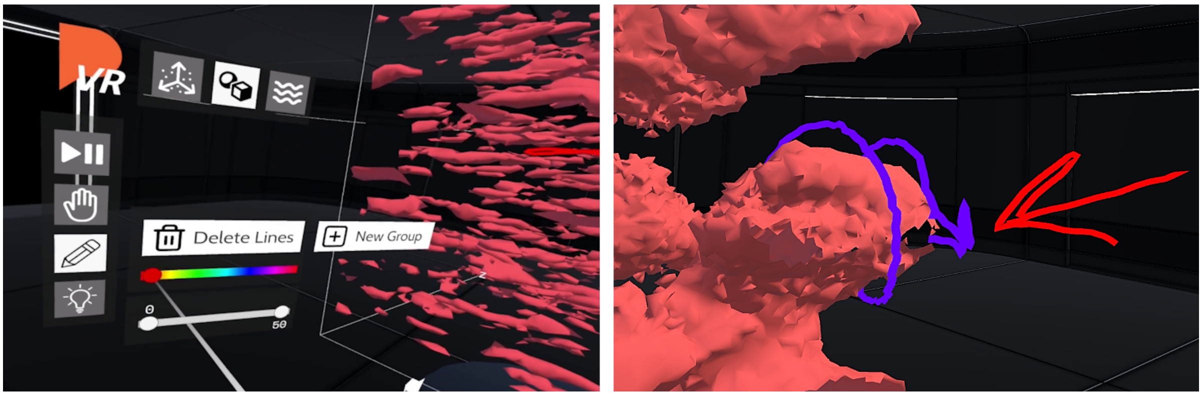

Figure 4: The annotations menu allows users to define its characteristics, including the range of animation frames where they will be shown (left). Users can do 3D annotations to highlight relevant portions of the idioms (right) (Brás, 2022, p. 35).

simulation. This task was aimed at testing the annotation and the corresponding timeline performance. Namely, it was introduced to assess the spatial perception within the immersive environment by testing how easy and intuitive it was to use the annotation tool to draw in space. It equally allowed the assessment of how the participants would perform in changing the color of an annotation element and specifying a timeline interval within the simulation using the interface panels.

For the second task, the participants were asked to rotate the isosurface to have the y-axis pointing towards the right. This more straightforward task was aimed at testing the rotation functionality's performance. In particular, in assessing how the proxy rotation would perform in terms of precision in relation to the VR controller's movement. This performance would indicate how well the rotation mechanism transmitted depth perception to the user.

In the third task, the participants were asked to find the portion of an isosurface with the lowest charge density value. This task was designed to assess the analytics performance of the prototype. It required participants to use the slicing tool to extract the energy heatmaps to be able to figure out the portion with the lower density. Such a sequence of operations adequately estimated how well spatial relationship was perceived in the isosurface visualization. Likewise, it provided a good indicator of how well users can match this 3D visualization of data with the 2D representation in slices. After completing the three tasks, the participants were asked to complete a 10-item System Usability Survey (SUS) (Brooke, 1995) questionnaire.

4.2 Results and Discussion

The group of five participants was composed of researchers with ages ranging from 18-50 years old. All had experience with plasma simulations and OSIRIS/PiC Codes (20% more than five years, 60% between one and five years, and 20% less than one year experience). Most (80%) had earlier experience with using VR technologies.

To assess the suitability of the prototype for different types of tasks, a set of objective metrics, such as completion time and number of errors, were analyzed. Regarding the time participants took to complete each task type (annotation, rotation, and slicing, as described in the previous section), the rotation task corresponded to a shorter (mean time in minutes ± standard error) completion time (1.32 ± .153) when compared to annotation (2.87 ± .321) and slicing (3.50 ± .224).

While the slicing task had a marginally higher completion time, it corresponded to a much lower (mean number of errors ± standard error) number of mistakes (0.60 ± .179) than the annotation task (1.80 ± .219). This difference may indicate that the prototype is better fitted to handle analytics tasks than annotation tasks. The rotation task had similar errors (0.60 ± .110) to the slicing task.

To assess the usability of PlasmaVR, the participants were asked to complete a ten-question standard SUS questionnaire with a five-level Likert scale for agreement (1: Strongly disagree and 5: Strongly agree) after interacting with the prototype. An average SUS score of 75.5 (SD = 5.5) was obtained. Such a score can be paired with a rating of 'Good' (Bangor et al., 2009) or 'B' (74.1 - 77.1) (Lewis and Sauro, 2017). Although the small number of participants impacts the accuracy of the usability evaluation (< 35% accuracy, based on the sample size threshold proposed by Tullis and Stetson (Tullis and Stetson, 2004)), the majority had a positive perception and found the system usable.

We also wanted to identify the specific aspects where the system performed well and where it could be enhanced in the scope of future development efforts. With that objective, the SUS questions were broken down into eight categories. These reflect the different usability areas that were addressed. The categories include cohesiveness (how well-integrated the prototype's features are), learnability (how easily it can be learned), and intuitiveness (how simple and easy to use). They also include concision (how uncomplicated the interface is), reliability (how few inconsistencies are in the prototype), and comfort (how non-frustrating its use is). Furthermore, they include trustworthiness (how confident participants were using the prototype) and usage intention (how much participants expected to use it). Results show that the aspects that performed better (mean (standard error); median (interquartile range) for the SUS score) were cohesiveness (3.40 (.110); 3.00 (1.00)), learnability (3.33 (.067); 3.33 (0.67)), intuitiveness (3.20 (.167); 3.00 (1.00)), concision (3.20 (.167); 3.00 (1.00)), and reliability (3.20 (.089); 3.00 (0.00)). Aspects that performed below average include comfort (2.80 (.089); 3.00 (0.00)) and trustworthiness (2.60 (.110); 3.00 (1.00)). The lowest contribution came from usage intention (1.80 (.089); 2.00 (0.00)). These results are illustrated in Figure 5.

The results are mainly within a relatively narrow range. The aspects that performed better are those related to the overall experience with the prototype and how simple and easy the system is to use. Participants found the interface reliable, well-structured, and cohesive. A good level of learnability was also observed, which seems to be a direct consequence of how intuitive the participants considered the interface.

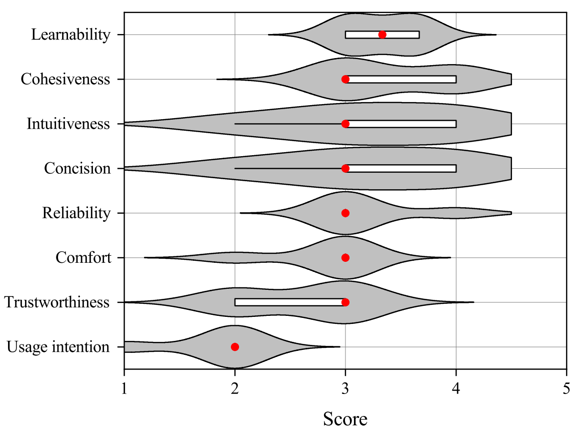

Figure 5: Distribution of participant's score for each usability category.

These results align with the participants' increased perception of the usefulness of VR after testing the prototype, which will be addressed further.

Nevertheless, participants found that while the prototype was reliable, they did not feel entirely confident using it. This apparent contradiction might be justifiable by interaction limitations pointed out by participants (e.g., difficulties in doing a full rotation of the idiom using a single controller motion, which will be discussed later). The most unexpected result, however, was the one corresponding to usage intention, which achieved the lowest score of all categories. This lower classification might result from the more localized role in their workflow that some researchers identified as the main scope of the prototype. More specifically, some participants positioned its usefulness in a faster preliminary visualization of the plasma physics data as a first step before moving to a more exhaustive analysis using conventional means.

Additionally, we wanted to determine if the participant's perception of the usefulness of VR in plasma simulations had changed after experiencing the prototype. Before using the prototype, the participants were divided on the usefulness of VR in plasma simulations. Indeed, only 40% agreed that VR would be useful in helping their workflow, 20% neither agreed nor disagreed, and 40% disagreed (five-level Likert scale for agreement, 1: Strongly disagree and 5: Strongly agree). After using the prototype, participants' perception changed to much more positive values, with 60% strongly agreeing on the usefulness of VR in plasma simulations, 20% agreeing, and 20% neither agreeing nor disagreeing. This substantial shift in opinion regarding the usefulness of VR in plasma simulations suggests that the user experience with the prototype was impactful and meaningful to the participants. As such, it is consistent with a high level of engagement despite the lower usage intention previously addressed.

We also enquired users about the aspects of the prototype they thought would contribute to making VR application useful in their workflow. 20% strongly agreed, and 80% agreed that VR could be used to display data effectively. 60% strongly agreed, 20% agreed, and 20% neither agreed nor disagreed that VR was useful for highlighting relevant information. 20% strongly agreed, 40% agreed, 20% neither agreed nor disagreed, and 20% disagreed that VR improved the data exploration experience. Lastly, 80% strongly agreed, and 20% agreed that VR was a more enjoyable way of exploring plasma simulation data than conventional means. It's worth highlighting that the highest of these scores corresponds to the way participants found PlasmaVR enjoyable, which is, once again, compatible with a high level of engagement.

4.3 Limitations and Future Work

When analyzing the results from this work, the rationale behind a few methodological decisions and their corresponding limitations should be considered. The first of these limitations is the small sample size used in the study, which makes it harder to assert statistical significance. In that sense, the study could have been carried out with more participants by extending the sample selection to encompass non-expert users or physics researchers from areas other than plasmas. We chose instead to restrict the sample selection to domain experts, which allowed us to ensure a consistent baseline among the participants regarding plasma experiments data analysis knowledge. Likewise, we opted for using a more controlled experimental environment instead of, e.g., making the application available online and asking users to download and execute the application by themselves.

Another methodological issue that limits the scope of this study is the absence of a comparative assessment of conventional analysis means with VR, namely by using an experimental control group. As such, assumptions regarding improvements in performance or usability can only be substantiated by participants' feedback (collected using questionnaires) and not by differences in measured performance metrics. Nevertheless, while not in the scope of this study, such comparative assessment can be addressed in future work.

There are several opportunities to expand this study beyond its current scope. Potential future research directions may include overcoming some of the limitations mentioned above. Such improvements may mean extending the experimental group to include researchers from plasma physics research units other than GoLP. They may also imply, e.g., the comparison of PlasmaVR with augmented reality and desktop versions of the prototype to further assess the advantages and limitations of immersive environments in plasma physics simulations.

5 CONCLUSION

This work presents a novel prototype tool for visualizing plasma physics experiment datasets in VR. The tool enables a multidimensional data visualization environment where users can travel around and inside animated representations of plasma based on time-dependent data. It allows them to observe the structural variations in morphology over time from several points of view. The work shows the different characteristics of the tool, including its architecture, raw data processing capabilities, and user interface functionalities. It addresses its evaluation with a group of domain experts consisting of plasma physics researchers. This evaluation is carried out using a set of objective and subjective metrics. These metrics are collected during testing through direct measurement and after testing using questionnaires. The collected metrics are used to support the research questions, which aim to ascertain the usability and usefulness of VR in plasma physics visualization. The findings suggest that applying VR technologies to plasma physics visualization can result in a usable experience. The results also support the hypothesis that VR can be useful in plasma physics visualization.

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REFERENCES

Ahrens, J., Geveci, B., and Law, C. (2005). Paraview: An end-user tool for large-data visualization. In *Visualization Handbook*, pages 717–731. Elsevier.

Bangor, A., Kortum, P., and Miller, J. (2009). Determining what individual sus scores mean: Adding an adjective rating scale. *Journal of Usability Studies*, 4(3):114–123.

Bethel, E. W., Childs, H., and Hansen, C. D., editors (2016). *High Performance Visualization: Enabling Extreme-Scale Scientific Insight*. Chapman & Hall/CRC Comutational Science Series. CRC Press, Chapman & Hall Book, Boca Raton London New York, first issued in paperback edition.

Brás, D. (2022). A virtual reality platform for scientific visualization of plasma physics simulation. Master's thesis, Instituto Superior Técnico, University of Lisbon, Portugal.

Brooke, J. (1995). Sus - a quick and dirty usability scale. *Usability Eval. Ind.*, 189.

Danielová, M., Janečka, P., Grosz, J., and Holý, A. (2019). Interactive 3d visualizations of laser plasma experiments on the web and in vr. *EuroVis 2019 - Posters*, page 3 pages.

Fitzpatrick, R. (2022). Charged particle motion. In *Plasma Physics: An Introduction*, volume 1, pages 15–41. CRC Press, Boca Raton, 2nd edition.

Fombona-Pascual, A., Fombona, J., and Vázquez-Cano, E. (2022). Vr in chemistry, a review of scientific research on advanced atomic/molecular visualization. *Chemistry Education Research and Practice*, 23(2):300–312.

Fonseca, R. A., Silva, L. O., Tsung, F. S., Decyk, V. K., Lu, W., Ren, C., Mori, W. B., Deng, S., Lee, S., Katsouleas, T., and Adam, J. C. (2002). Osiris: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators. In Goos, G., Hartmanis, J., van Leeuwen, J., Sloot, P. M. A., Hoekstra, A. G., Tan, C. J. K., and Dongarra, J. J., editors, *Computational Science — ICCS 2002*, volume 2331, pages 342–351. Springer Berlin Heidelberg, Berlin, Heidelberg.

Foss, G., Solis, A., Bhadsavle, S., Horton, W., and Leonard, L. (2018). Plasma simulation data through the hololens. In *Proceedings of the Practice and Experience on Advanced Research Computing*, pages 1–2, Pittsburgh PA USA. ACM.

Fridman, A. A. and Kennedy, L. A. (2021). Plasma in nature, in the laboratory, and in industry. In *Plasma Physics and Engineering*, pages 3–14. CRC Press, Boca Raton, 3rd edition.

Gallagher, R. S. (2023). Future trends in scientific visualization. In *Computer Visualization: Graphics Techniques for Engineering and Scientific Analysis*, volume 1, pages 291–303. CRC Press, Boca Raton, 1st edition.

Guo, J., Wang, Y., Du, P., and Yu, L. (2017). A novel multi-touch approach for 3d object free manipulation. In Chang, J., Zhang, J. J., Magnenat Thalmann, N., Hu, S.-M., Tong, R., and Wang, W., editors, *Next Generation Computer Animation Techniques*, volume 10582, pages 159–172. Springer International Publishing, Cham.

Guo, M., Yue, K., Hu, H., Lu, K., Han, Y., Chen, S., and Liu, Y. (2022). Neural research on depth perception and stereoscopic visual fatigue in virtual reality. *Brain Sciences*, 12(9):1231.

Hayashi, T. (2001). Computer simulation of nonlinear phenomena in plasmas. *Computer Physics Communications*, 142(1-3):49–54.

Korkut, E. H. and Surer, E. (2023). Visualization in virtual reality: A systematic review. *Virtual Reality*, 27(2):1447–1480.

Lewis, J. and Sauro, J. (2017). Can i leave this one out? the effect of dropping an item from the sus. *Journal of Usability Studies*, 13(1):38–46.

Ljung, P., Dieckmann, M., Andersson, N., and Ynnerman, A. (2000). Interactive visualization of particle-in-cell simulations. In *Proceedings Visualization 2000. VIS 2000 (Cat. No.00CH37145)*, pages 469–472,, Salt Lake City, UT, USA. IEEE.

Mathur, M., Brozovich, J. M., and Rausch, M. K. (2023). A brief note on building augmented reality models for scientific visualization. *Finite Elements in Analysis and Design*, 213:103851.

Millais, P., Jones, S. L., and Kelly, R. (2018). Exploring data in virtual reality: Comparisons with 2d data visualizations. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–6, Montreal QC Canada. ACM.

Munzner, T. and Maguire, E. (2015). *Visualization Analysis & Design*. A.K. Peters Visualization Series. CRC Press, Boca Raton London New York.

Ohno, N., Kageyama, A., and Kusano, K. (2006). Virtual reality visualization by cave with vfive and vtk. *Journal of Plasma Physics*, 72(06):1069.

Ohtani, H., Kageyama, A., Tamura, Y., Ishiguro, S., and Shohji, M. (2011a). Integrated visualization of simulation results and experimental devices in virtual-reality space. *Plasma and Fusion Research*, 6:2406027–2406027.

Ohtani, H., Ohno, N., Mizuguchi, N., Shoji, M., and Ishiguro, S. (2010). Simulation data analysis by virtual reality system. *Plasma and Fusion Research*, 5:S2109–S2109.

Ohtani, H., Shoji, M., Ohno, N., Suzuki, Y., Ishiguro, S., Kageyama, A., and Tamura, Y. (2016). Visualization of dust particle data with plasma simulation results using virtual reality system. *Contributions to Plasma Physics*, 56(6-8):692–697.

Ohtani, H., Tamura, Y., Kageyama, A., and Ishiguro, S. (2011b). Scientific visualization of plasma simulation results and device data in virtual-reality space. *IEEE Transactions on Plasma Science*, 39(11):2472–2473.

Piel, A. (2010). *Definition of the Plasma State*, pages 29–43. Springer Berlin Heidelberg, Berlin, Heidelberg.

The HDF Group (2007). Hdf5 user's guide.

Tullis, T. S. and Stetson, J. N. (2004). A comparison of questionnaires for assessing website usability. In *Proceedings of the Usability Professionals Association (UPA) 2004 Conference*, pages 7–11. Usability Professionals Association (UPA).

Vienne, C., Masfrand, S., Bourdin, C., and Vercher, J.-L. (2020). Depth perception in virtual reality systems: Effect of screen distance, environment richness and display factors. *IEEE Access*, 8:29099–29110.

Yeung, A. W. K., Tosevska, A., Klager, E., Eibensteiner, F., Laxar, D., Stoyanov, J., Glisic, M., Zeiner, S., Kulnik, S. T., Crutzen, R., Kimberger, O., Kletecka-Pulker, M., Atanasov, A. G., and Willschke, H. (2021). Virtual and augmented reality applications in medicine: Analysis of the scientific literature. *Journal of Medical Internet Research*, 23(2):e25499.