Digital-LHD: LHD Visualizer for Head-Mounted Display Systems

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We developed a virtual reality visualization program, Digital-LHD, for modern Head-Mounted Display (HMD) systems. Digital-LHD provides an immersive environment for the interactive visualization of plasma data related to the Large Helical Device (LHD). Its predecessor, Virtual-LHD, was developed for CAVE systems, which were limited in accessibility due to their cost and size. The newly developed Digital-LHD utilizes Unity and C# to offer interactive 3D visualization. Digital-LHD includes features such as isosurface rendering, magnetic field line tracing, particle trajectory visualization, and new functionalities like local arrow glyphs and a plasma pressure color contour. The enhanced interactivity and intuitive GUI have improved the user experience. Digital-LHD enables fusion plasma researchers to perform immersive visualizations with HMDs, providing a more accessible and cost-effective solution.

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1. Introduction

Virtual Reality (VR) technology has been employed to visualize three-dimensional data generated by simulations and experiments in plasma physics. The National Institute for Fusion Science (NIFS) installed a room-sized VR system known as CAVE in 1997. At NIFS, a variety of VR visualization software for the CAVE system has been developed. This paper specifically focuses on one such software, Virtual-LHD (Virtual Large Helical Device) [1]. Initially designed as an interactive three-dimensional visualization tool within the VR environment provided by the CAVE system, Virtual-LHD places significant emphasis on interactivity [2]. The input data for Virtual-LHD is sourced from HINT [3], a magnetohydrodynamic (MHD) equilibrium code for plasma in the LHD. Virtual-LHD aims to facilitate a three-dimensional analysis of pressure, temperature, and magnetic fields, leveraging the CAVE's interactive capabilities to their fullest extent. Virtual LHD was applied, for example, to the analysis of ion particle motions in LHD. The performance was enhanced later by incorporating a 3-dimensional acoustic system into Virtual LHD. The ions' position and velocity were considered in the virtual Doppler effect [4].

Virtual-LHD was subsequently enhanced to visualize the vacuum vessel of the LHD [5, 6]. In this update, polygonal data from a CAD program was integrated into Virtual-LHD

objects using the Fusion VR middleware [7]. Additionally, a new feature for visualizing dust particle motions was incorporated in this revision.

Over the past two decades, Virtual-LHD has been a cornerstone of research at the National Institute for Fusion Science, significantly contributing to scientific outreach and advancements in LHD device research. As one of the oldest VR application programs dedicated to scientific research, it has had a profound impact. However, the high cost and substantial size of CAVE systems have limited the accessibility of Virtual-LHD to a broader range of simulation researchers.

In recent years, the advent of Head-Mounted Displays (HMDs) has revolutionized the VR landscape. With the modern HMD, the user can virtually change its position and direction (Euler angle) and interact with a VR object in real time using controllers. The quality of the VR experience is comparable to that of the CAVE system. They also come with the added benefits of affordability and compactness, thereby democratizing access to immersive VR experiences.

Motivated by this technological shift, we embarked on developing an HMD version of Virtual-LHD, named Digital-LHD, which required an almost complete rewrite of the original program's source code. Transitioning from C and OpenGL to C# and Unity, this new iteration of Digital-LHD has been designed to effectively utilize the interactive environment of modern HMD technology.

The purpose of this paper is to describe the technical procedures involved in developing an HMD version of

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Virtual-LHD. It focuses on the challenges encountered and the innovative solutions implemented to achieve efficient visualization in a modern HMD system environment.

Before going into the details of the development of Digital-LHD, we will briefly review related studies.

Visualization programs using HMDs based on game engines have been developed for various fields, including plasma physics [8], geophysics [9], and other broader areas [10]. The general-purpose visualization library VTK (Visualization Toolkit) [11] is also available for use with HMDs [12]. There have been efforts to integrate VTK into various applications [13]. Since VisIt and ParaView are based on VTK, they can also be used in HMD systems. We developed VOIR [14, 15], an HMD version of VFIVE [16-18], using Unity [19]. VFIVE is a general-purpose visualization software for CAVE systems, primarily used for computational fluid dynamics. Unity, a game engine, enables the development of software for HMDs. VisAssets [20] provides a programming environment with Unity for HMDs. CLCL is a library that allows software developed with CAVELib to run on HMDs [21]. For a recent review of visualization with HMDs and other VR systems, refer to [22].

2. The CAVE Systems and HMDs

The CAVE system [see Fig. 1(a)] is a large room-shaped VR device where the walls and floor serve as screens for 3D images. The user enters the room wearing stereoscopic glasses and uses a controller called wand. The position and orientation of both the glasses and the wand are tracked. The wand typically has three buttons and a joystick, allowing the user to interact with the VR space. While multiple people can use the CAVE system simultaneously by wearing non-tracked stereoscopic glasses, only the person with the tracked glasses will see the image without distortion.

HMDs are goggle-type VR devices worn on the user's head [see Fig. 1(b)]. Scientific visualization using HMDs has a long history [23, 24]. The two major HMD systems, Oculus and HTC VIVE, come with two controllers: one for the left hand and one for the right hand. Each controller is equipped with a trigger button, a grip button, and a joystick. Modern HMDs possess position & angle tracking systems for the goggles and the controllers.

3. Digital-LHD

The original version of Virtual-LHD is application software developed for CAVE systems. This software provides interactive visualizations of LHD plasma data generated by the HINT code. It was programmed in C language using CAVELib and OpenGL. Building on the original Virtual-LHD code, we developed an HMD version using Unity and its OpenXR plug-in. This new iteration is programmed in C#. Utilizing OpenXR allows the code to be versatile across multiple HMD systems without requiring modifications to the source code.



Fig. 1. VR devices used for scientific visualization. (a) CAVE system. (b) HMD (Oculus Quest2) and its controllers.

We have implemented the same visualization methods as in the original CAVE version: isosurface rendering of plasma pressure, magnetic field lines, Poincaré map of magnetic field lines, drift-particle guiding center motion, and dust particle display functionality.

As new visualization features, we also implemented local arrow glyphs, a color map of plasma pressure in the poloidal cross-section, and test particle motion. Users can interactively control parameters related to these methods using the HMD system's controller.

Three-dimensional fly-through, a critical feature for an immersive VR environment, is also implemented. Users can freely navigate the virtual space, including the helical coils, using the joystick on the controller.

The visualization methods and related features of Digital-LHD are described in the following subsections. The hardware used for these descriptions is an Oculus Quest 2 (HMD) connected via OculusLink to a laptop computer (Windows 11 Pro, CPU: Intel Core i7-11800H, GPU: NVIDIA GeForce RTX 3050 Laptop GPU, main memory: 16.0GB).

Digital-LHD is lightweight software. The VR operations are quick and smooth, even though the laptop is relatively low-performance for VR purposes.

3.1 Menu function

A problem with the original Virtual-LHD was its lack of a sophisticated GUI. In developing Digital-LHD, we leveraged our experience in GUI development for HMD from VOIR [14] to introduce a new, easy-to-use GUI.

The original Virtual-LHD had an almost one-to-one correspondence between wand buttons and visualization methods. The introduction of a GUI, composed of virtual menu panels and beams, has enhanced the flexibility, allowing for an increase in the number of visualization methods.

The new menu function allows users to intuitively select visualization methods within the HMD's VR space. Figure 2 shows a snapshot of the GUI menu.

3.2 Display of 3D models

It is important to display 3D model data of the LHD, including the helical coil pair and the vacuum vessel with ports, in the VR space. In Digital-LHD, the 3D model data in FBX format are loaded by Unity. Figure 3 shows a snapshot of the 3D models: the vacuum vessel in dark blue and the helical coils in yellow. Strictly speaking, the helical coils are directly coded using triangle sequences in Unity, while the vacuum vessel is modeled in FBX format by CAD software. Unity processes automatic shadowing for both types of 3D models; note the shadow on the virtual floor in the checkerboard pattern. The shadow enhances the sense of reality and, therefore, the efficiency of visual analysis in the VR space.



Fig. 2. The menu system of Digital-LHD.

The shadowing feature was missing in the original CAVE version of Virtual-LHD.

3.3 Visualization methods

3.3.1 Isosurface rendering

An isosurface of the plasma pressure constructed using the marching cubes algorithm is displayed. The user of Digital-LHD can interactively change the isosurface level by vertically moving a handheld controller. This kind of intuitive control of the visualization parameter is a characteristic feature of three-dimensional visualization in VR space. Figure 4 shows an isosurface of plasma pressure (pink) with the virtual handle of the level controller (a bluish cone with white indicators).

3.3.2 Local Arrows

"Local Arrows" is a visualization method for vector fields implemented in VFIVE (Fig. 5). We have incorporated this method into Digital-LHD. When the trigger button is pressed, a beam is emitted from the controller, and the magnetic field around the tip is visualized using multiple arrow glyphs. By moving the controller while holding down the trigger button, the position of the arrows changes, allowing the user to examine the vector field in the region of interest.

3.3.3 Magnetic field lines

A major visualization method for magnetic fields in the LHD is drawing field lines. Taking full advantage of the immersive and interactive environment of HMDs, the user



Fig. 3. Vacuum vessel (dark blue) and the helical coils (yellow) of LHD.



Fig. 4. Isosurface rendering function. A blue cone with white spheres serves as the GUI for changing the isosurface level.



Fig. 5. Local Arrows. The user can change the position of the arrows' center.

can specify a seed point for a magnetic field line using a controller (Fig. 6). The numerical integration of the field line tracing is performed using a sixth-order Runge-Kutta method. When the user presses the trigger button on the right controller, a virtual beam appears. The tip of the beam serves as the potential seed point. The field line tracing begins when the user releases the trigger button. The user can observe the field line as it grows while the numerical integration progresses.

3.3.4 Poloidal Slicer

To visualize the poloidal distribution of pressure, a color contour in a poloidal cross-section is displayed when the user selects the "Poloidal Slicer" visualization method from the menu (Fig. 7). The poloidal angle of the cross-section can be adjusted by moving the controller horizontally.

3.3.5 Poincaré map of magnetic field lines

The user of Digital-LHD can display a Poincaré map of multiple magnetic field lines simultaneously (Fig. 8). Numerical integration for 20 magnetic field lines is automatically performed using the sixth-order Runge-Kutta method when the user specifies a poloidal angle. The cross-section of the magnetic field lines, or Poincaré map, in the LHD is calculated. The cross-section points are superimposed on the color contour of the pressure.

Most visualizations in Digital-LHD, such as isosurface rendering, are performed in real time. The only exception is the Poincaré map. It takes about 6 seconds to complete a map because it invokes heavy numerical integrations. We will accelerate the Poincaré map by making use of threadparallelization in future development.

3.3.6 Visualization of plasma particle trajectories

It is also possible to visualize trajectories of ion motion. The user can control the initial conditions of the particle. The beam emitted from the controller specifies the initial position and direction. The initial speed is adjustable through an interactive user interface similar to the isosurface level controller. The ion motion is numerically integrated using the Buneman-Boris method. Users can observe the ion's Larmor gyration motion under the LHD's magnetic field in real-time. It is also possible to show the guiding center's trajectory, which is numerically integrated using the Runge-Kutta method. Figure 9 shows a trapped bounce motion.

3.3.7 Dust particle display function

Dust is one of the key factors that degrade the confinement of plasma. Dust particles, peeled off from the divertor



Fig. 6. Magnetic field lines. Two magnetic field lines (light blue and magenta) in the LHD are presented. The seed points can be changed intuitively in Digital-LHD.



Fig. 7. Plasma pressure distribution visualized by "Poloidal Slicer".



Fig. 8. Poincaré map of magnetic field lines in a poloidal cross-section, displayed with the color contour of pressure.



Fig. 9. Trapped bounce motion of an ion released by a user.



Fig. 10. Experimentally measured dust particle motions. The sequences of spheres represent the dust particle trajectories, with different colors for different particles. The white sphere indicates the initial position.

plates or vessel walls, enter the plasma core and reduce its temperature. Some dust motions are directly measured by stereoscopic fast framing cameras installed in the LHD [25]. The measured trajectories are saved as time-sequence data of the dust particle positions. The loaded data can be displayed as a sequence of small spheres; see Fig. 10. Different dust particles are represented by different colors. A trajectory and velocity are illustrated by a sequence of spheres, with the initial position depicted in white. Dust trajectories can be superimposed with other visualization items, such as magnetic field lines (light blue in Fig. 10) and the CAD data of the vacuum vessel. One can observe multiple dust particles accumulating in localized spots within the vacuum vessel.

4. User Feedback

We had one of the researchers involved in the LHD experiments try out Digital-LHD. This researcher had prior experience using the Virtual-LHD program on the CAVE system at NIFS. After using Digital-LHD for about two hours, the researcher provided the following feedback:

Regarding the comparison with CAVE, there were several positive comments. For example: (i) The sense of immersion is higher than with the CAVE. Various experimental ideas could come to mind. (ii) Digital-LHD provides better image experiences when looking up. (The CAVE at NIFS does not have a screen on the ceiling.) (iii) Digital-LHD also provides natural image experiences when looking downward. (The CAVE casts the user's shadow on the floor.)

On the other hand, some issues were pointed out regarding the user interface. The most important observations were: (i) The state transitions of the menu are somewhat difficult to track. (ii) Buttons and joysticks are too many to operate swiftly.

We would address the former issue by adding a click sound when selecting. We would address the latter problem by reducing the number of buttons and improving the menu system.

5. Summary

We have developed Digital-LHD, a virtual reality visualization software for modern HMD devices. Digital-LHD is a rewritten version of Virtual-LHD, originally designed for CAVE-type VR systems. Digital-LHD is written in C# using Unity, whereas Virtual-LHD was written in C with OpenGL. Various visualization methods implemented in Virtual-LHD can now be utilized in advanced VR environments with modern HMDs. Fully interactive analysis of LHD-related data is now possible without the need for a room-sized and expensive VR apparatus like CAVE. Additionally, some new visualization features have been added to Digital-LHD, such as a menu, color slices in poloidal cross-sections, local arrows, and test particle orbits. Digital-LHD will provide a costeffective environment for advancing fusion plasma research in the future.

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