Eurographics Conference on Visualization (EuroVis) 2017
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Short Paper

Spatial Interaction for the Post-Processing of 3D CFD Datasets

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Figure 1: *Interactive slicing of a CFD dataset using a tablet as spatial interaction device*

Abstract

Virtual Reality visualizations are often used for the evaluation of three-dimensional datasets generated by Computational Fluid Dynamic (CFD) simulations. Several different tracked devices, such as pointers or data gloves, have been employed for spatial interactive post-processing and navigation. However, users utilizing these devices often achieve inaccurate results performing interactive slicing of datasets, a common technique during the assessment of CFD datasets.

In our approach, we propose spatial interaction using tablets, which more closely resemble cutting planes, for planar surface extraction in VR environments. In contrast to traditional tracked devices, inside-out tracking of the environment can be achieved using the rear camera of the tablet, helping to make expensive external tracking systems expendable. A user study among novice and expert VR users supports the notion that tablets can be a fast and accurate alternative to traditional spatial input devices in VR environments.

Categories and Subject Descriptors (according to ACM CCS): Information Interfaces and Presentation [H.5.2.]: User Interfaces—Interaction styles

1. Introduction

Numerical simulations and assessment of resulting datasets are constantly gaining importance in product design and optimization workflows in many different fields of engineering. VR environments such as powerwalls and CAVEs [CNSD93] play an important role in interactive post-processing of these datasets. By defining immersive spatial 3D interaction spaces, single users or groups of users are enabled to navigate and interact with data in a natural way, often in a scale 1:1 environment.

In large scale VR environments, multiple stereoscopic displays or projection systems are used to provide visual experiences. Highly accurate optical tracking systems enable the system to perform spatial localization of various objects in the interaction space. By using head tracking, the virtual environment can adapt to user movement and change in orientation. Tracked interaction devices such as pointers, styluses, data gloves or fly sticks are made available, which allow various application dependent spatial interactions to be carried out on the scene or dataset.

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DOI: 10.2312/eurovisshort.20171136

Interactive post-processing of Computational Fluid Dynamics (CFD) simulation data is often performed in VR environments to assess various properties of the flow, such as the distribution of pressure or velocity. Slicing of the computational volume to filter a 2D subset from a 3D dataset is a routine task which has to be performed continuously. Commonly used interaction devices seem to complicate this task as it is hard for users to accurately estimate the up-vector of a forward pointing stylus or wireless presenter.

To address these issues, we developed *TabSlice*, an approach to perform spatial interactions using tablets. *TabSlice* primarily aims at making it easier for novice and advanced users to extract planar 2D geometries from 3D datasets with enhanced accuracy. By introducing a planar interaction device into the VR environment, accurate slicing in a 3D interaction space can be performed more easily Our main contributions to the field are (I) a user study supporting this claim, (II) further exploration of the ability of tablets to act as magic lenses [BSP*93] on datasets in VR environments building on previous results by Stoev et al. [SSS01], Jeon et al. [JHKB10] and Sörös et al. [SSRG11], and (III) a technical solution for low cost inside-out tracking, i.e. tracking of the external environment using a tracking device, using tablets as interaction devices in virtual environments.

2. Related Work

After the introduction of magic lenses as the see through interface by Bier et al. [BSP*93], several interactive systems acting as information lenses to virtual or physical objects have been described. Fitzmaurice presents a palmtop device featuring a 6D input sensor responding to user gestures and movement near physical objects [Fit93, FZC93]. Tsang et al. later build on this "window in hand" metaphor with Boom Chameleon [TFK*03], an LCD touch panel mounted on a boom arm, permitting the user to freely navigate and annotate a 3D scene displayed on the panel.

Stoev et al. describe magic lens interaction above tables displaying virtual scenes [SSS01]. They use head tracking as well as hand tracking to provide perspectively correct rendering of 3D data onto pads carried by the user to perform two-handed navigation techniques such as *grab-and-drag* and *eyeball-in-hand*.

Ma et al. present a method for navigation of 3D models with their tangible interface iNavigator [MLJ03], where they project cross-sections of building plans onto physical glass planes held perpendicular to a tabletop device. Their *cutting-plane-in-hand* metaphor is later extended by Hirota et al. to planes that allow free positioning in physical space. Hirota et al. introduce cross-section projector, a method for the interactive slicing of volumetric data and projection of the extracted cross section onto user manipulated screen panels [HS07]. Hashimoto et al. build upon this work allowing for the visualization of maps containing both different zoom levels as well as level of detail information onto screen panels according to the distance between the panel and a spatial reference position [HTKI08]. Spindler et al. later classify these methods as the exploration of *volumetric information space*, *zoomable information space* and *layered information space* [SSD09].

Miguel et al. have proposed a see-through the lens interface using a PDA (Personal Digital Assistance) for supporting spatial manipulation within an immersive display [MOKT07], where selection of virtual objects can be performed with either a live or freeze view on the mobile system. Olwal et al. exploit the high display resolution of a tracked mobile phone to do spatial focus+context visualization, allowing for touch interaction on the focus display in otherwise touch incapable environments [OF09]. Tiefenbacher et al. present techniques for 3D manipulation on spatially tracked mobile touch devices in a CAVE environment [TPR14], providing additional touch-enabled menu interaction on the mobile device.

Inside-out tracking has been used on mobile devices to navigate virtual scenes on displays and tabletops, e.g. by Jeon et al. [JHKB10] who use mobile phone cameras to track markers using ARToolkit [HO04]. Sörös et al. employ tablets and mobile phones to act as magic lenses by performing remotely computed natural feature detection on the surrounding environment [SSRG11]. In their work, multi-touch input on the interaction devices may also be mapped to actions concerning the underlying volume visualization system.

3. Magic Lenses for Powerwall Interaction

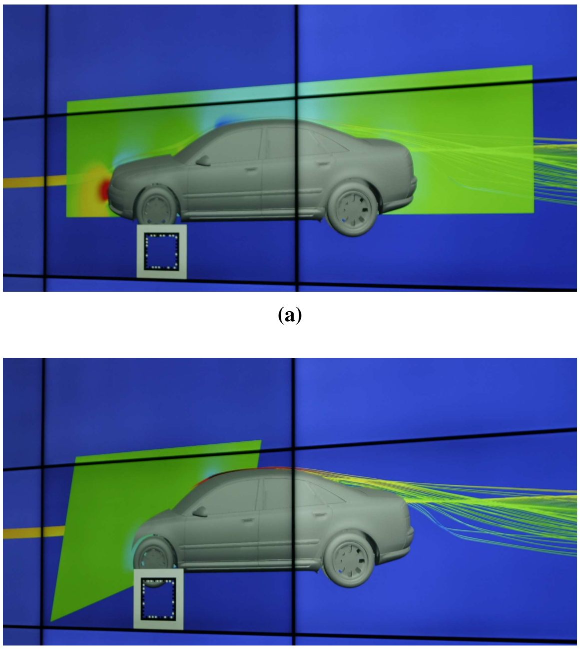
Spatial magic lens applications primarily focus on the navigation of 3D scenes. Progressive methods for volumetric exploration, such as described by Hirota et al. [HS07] and Hashimoto et al. [HTKI08], permit only the extraction of relatively small parts of a reference volume confined to the space of the magic lens. In addition to the magic lens metaphor explored by the aforementioned works, we propose the expansion of the extracted slice to the complete cutting plane inside the interaction space that is able to be covered by the VR environment. By using tablets as spatial interaction devices in virtual environments, touch input on the display can be performed e.g., to select, highlight or annotate specific parts of the virtual data.

3.1. Interaction Device Tracking

Traditional head tracking and interaction device tracking is performed by using highly accurate as well as highly expensive outside-in optical tracking systems, i.e., tracking of active or passive markers by an external system. Cameras used for the tracking of optical targets span an interaction space usable for navigation and interaction with the dataset. Usually, multiple buttons are available on the interaction device enabling the user to select between different modes of interaction or to perform specific actions on the underlying scene. With the processing power available in today's mobile systems, rendering of 3D data as well as image recognition algorithms on high resolution video data can be performed directly on the mobile device. This enables mobile devices to act as magic lenses in VR installations performing accurate inside-out tracking for spatial localization of the interaction device relative to the surrounding environment.

3.2. Continuously Slicing CFD Datasets

Methods for interactive post-processing of CFD data that are considered in this work involve continuous slicing of the dataset at varying locations and orientations (see Figure 2) also adjusting the perspective towards the displayed scene simultaneously.



(a)

(b)

Figure 2: *Visualization of a CFD dataset showing extracted cutting planes through the computational volume. Color-coding is used to visualize pressure.*

Slicing of CFD simulation data appears to be a similar operation as slicing of volumetric datasets as described in previous workAlthough the outcome seems to be identical, the specifics are rather different. First, when post-processing a CFD simulation, the actual data consists not only of multiple distinct variable fields on–often unstructured–grids but also includes several polygonal meshes that represent static or animated parts of the surrounding machinery. These geometric data provide additional clues to the user about the positioning of data in the dataset and have to be made available to the magic lens device. Second, due to the complexity of unstructured data, actual slicing of the dataset has to be performed by a parallel post-processing system on remote computing resources [NKA12], and transferred back to the attached VR environment and magic lenses. Depending on the complexity of the dataset, real-time surface extractions following user interactions with more than 30 extractions per second are possible.

4. System Architecture

The *TabSlice* system being introduced in this paper is a modular tracking system (also see Figure 3) that can be connected to tracker-based VR systems, such as OpenCOVER [WSWL02], which can be used in powerwall or CAVE environments. Mobile devices (*Magic Lens* in Figure 3) containing high-resolution cameras, such as tablets or mobile phones, are used to either track markers or natural features of the environment. For optical tracking, we make use of *Vuforia*, a mobile Augmented Reality (AR) framework originating from the Studierstube project [SFH*02]. The display of the mobile device is used for rendering the same scene that is currently displayed in the VR environment, albeit with a different viewpoint, taking into account the position of the mobile device and the perspective of the user. Image recognition algorithms executed on the mobile device perform localization and computation of the orientation of the device relative to the coordinate system of the interaction space.

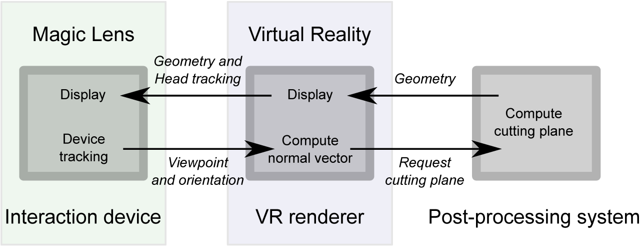


Figure 3: *Overview of the* TabSlice *system architecture*

This information, along with head tracking information received from the VR renderer (see Figure 3), can be used to adapt the viewpoint on the mobile device, enabling a magic lens overlay onto the VR environment, as shown e.g. by Baričević et al. [BLT*12]. In addition, position and orientation of the mobile device is continuously transmitted to the VR renderer. The VR renderer then uses position and orientation of the device to calculate position and normal vector of a cutting plane through the dataset.

COVISE [Wie96], a system for the post-processing of numerical simulation data (see Figure 3) then slices the dataset accordingly, generating a triangle mesh representing the cutting plane, and sends this data to the VR renderer for display in the virtual environment. In turn, the VR renderer transmits the data back to the magic lens device for display.

Despite the distributed architecture, computationally expensive cutting plane extraction and communication through Wi-Fi, latencies of less than 80ms from user interaction to final rendering can be achieved, measured using a prototypical version of the *TabSlice* system. Due to the relatively low amount of bandwidth available on the wireless network, the magic lens device may be forced to skip some of the generated triangle meshes, depending on the size of the extracted surfaces.

5. User Study

To obtain feedback towards the usability of the presented approach, we performed a summative, within-subject user study to compare a *TabSlice* prototype to traditional, pointer-based VR interaction on powerwalls. Two potential shortcomings of our approach were identified beforehand. First, the inaccuracy of the inside-out marker tracking due to optical properties of the employed tablet cameras, and second, potential user fatigue due to the usage of comparably heavy interaction devices. As a result, specific emphasis was put towards the evaluation of accuracy of the cutting plane extraction.

5.1. Participants

Thirteen unpaid test subjects, six male and seven female, voluntarily participated in the study. Three of the participants can be

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considered to be experts in both fluid dynamics and virtual reality applications. Four of the remaining ten participants had visited VR systems before, the other six had only rudimentary awareness of VR interaction and VR systems in general.

5.2. Setup and Tasks

The VR environment used in the evaluation consisted of a powerwall composed of nine 55 inch displays arranged in a 3x3 configuration, an ART TRACKPACK optical tracking system used for head tracking as well as pointer tracking, a wireless presenter for pointer interaction fitted with targets used for tracking and a 10 inch Android tablet featuring a 5 megapixel rear camera, which was used in the *TabSlice* prototype. The usable interaction space in front of the powerwall was a cube of approximately 300 cm X 250 cm X 300 cm (width X depth X height). A single square marker was used for inside-out tracking of the tablet displayed on the powerwall with a size of 25 cm X 25 cm.

The tasks given to the participants originated in the domain of mechanical engineering, namely the post-processing of CFD data simulating air flow around a car. The given tasks had to be performed both using the traditional pointing device in form of the wireless presenter, as well as a tablet using the *TabSlice* system. After a 20 minute introduction and training session using both interaction devices, the actual task where quantitative measurements were performed took between five to ten minutes.

Quantitative data concerning accuracy, namely the deviation of the normal vector of the surface created by user interaction from the normal vector that was requested by the conductor of the study, were automatically gathered in the background during interaction. These quantitative measurements where conducted to assess the accuracy of both interaction methods, to be able to evaluate the prototypical tablet interaction system towards our primary assumption that traditional pointers are a suboptimal method to perform cutting plane extraction in a virtual environment.

5.3. Procedure

At the beginning of each session, 20 minutes of preparation and individual training was arranged, using the two interaction devices for ten minutes each. Training VR interaction involved slicing the dataset at various positions given by the conductor of the study and estimating color-coded values mapped onto the extracted cutting plane signifying air pressure. Users were presented with the possibility to read color values from the cutting plane displayed either on the magic lens or on the powerwall. As this part of the study was primarily meant to help users get accustomed to the VR environment and VR interaction, performance of the participants was not evaluated in the analysis.

In the second part of the study, quantitative data concerning the accuracy of the user interactions was acquired. The conductor of the study required the participants to perform slicing through the dataset at specific angles (e.g. *"vertically slice the dataset from the front to the back of the car"*) for a total number of five repetitions, with different viewpoints towards the car's geometry. During the study, participants were allowed to move inside the interaction space in front of the powerwall but had to stay inside an approx. 180 cm radius around the marker for the *TabSlice* system to give accurate tracking results. Throughout the study, users were encouraged to set their own pace performing the required interactions, determining themselves if and when satisfying results were achieved. Two-handed interaction using the tablet was recommended to achieve better stability and accuracy.

5.4. Results and Discussion

The data acquired from the different groups (novice and expert users) differ somewhat so that we analyze them separately. Due to the small number of test subjects and the disparity in knowledge about VR interaction, standard deviation and standard error rates are high throughout both groups.

For both groups, quantitative accuracy of cutting plane extraction was higher using the *TabSlice* system. Surprisingly, the experts were unable to achieve higher accuracy than novices when using the traditional pointer device but outperformed them when using the tablet, which was an unfamiliar VR interaction device for both groups before participating in the study. Regarding the performance of the interaction, the VR experts were able to achieve satisfying results considerably faster using the tablet, where it took the group of novice users even longer using this interaction method than using pointer device interaction. These initial test results seem to support our original hypothesis that tablets can be an intuitive and accurate method for the interactive extraction of cutting planes using spatial interaction in virtual environments.

6. Conclusion and Future Work

We introduced *TabSlice*, an approach for spatial interaction in VR environments using tablets serving as magic lenses to extract planar surfaces from 3D datasets. The main contributions of this work are an expansion of the magic lens to allow for the display of cutting planes to the extent covered by the VR environment, a technical solution for low-cost inside-out tracking using tablets in virtual environments, and a method providing enhanced accuracy performing interactive planar slicing in 3D interaction spaces. We implemented prototypes of the *TabSlice* system that allowed us to evaluate our approach performing interactive post-processing of a CFD dataset in a powerwall environment. An initial study with a group of both expert and novice users was performed that lead to confirmation of a gain in accuracy when using the *TabSlice* system compared to traditional methods of interaction. In future work, we plan to support simultaneous use of markers for exact localization and natural feature tracking as well as usage of the internal gyroscope for smaller periods of time when no marker is visible for the tablet's camera. Another topic of research is the combination of two handed spatial interaction systems such as *TabSlice* in VR with cheaper motion sensing input devices that rely on skeletal mapping for head tracking. We also plan to extend our user studies to longer periods of interaction to further investigate user fatigue as well as evaluating collaborative multi user scenarios featuring multiple tablets as interaction devices in VR environments.

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