# Slice WIM: A Multi-Surface, Multi-Touch Interface for Overview+Detail Exploration of Volume Datasets in Virtual Reality

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# Abstract

We present Slice WIM, a method for overview+detail visualization of volume datasets that explores the potential of new interfaces made possible by a virtual reality (VR) environment made of two display surfaces: an interactive multi-touch table, and a stereoscopic display wall. Slice WIM displays a miniature version of the 3D dataset within a head-tracked stereoscopic view such that it appears to float directly above the multi-touch table. Multitouch gestures on the table are then used to navigate through the dataset and to set slices (cutting planes) through the data. Leveraging the unique table+wall hardware setup, horizontal slices through the data are projected (like a shadow) down onto the table surface, providing a useful 2D data overview to complement the 3D views as well as a data context for interpreting 2D multi-touch gestures made on the table. We demonstrate several strategies for interacting with 2D "shadow slices" on the table surface as a method for controlling the WIM and exploring volumetric datasets. Applications of the interface to explore two different volume datasets are presented, and design decisions and limitations are discussed along with feedback from both casual users and domain scientists.

### 1 Introduction

From high-resolution 3D structures extracted from medical imaging data to computational simulations of blood flow through the heart, volumetric scientific datasets are particularly challenging to visualize and explore, especially given the unprecedented spatial resolution that is possible with today's data collection and simulation tools. For example, our collaborators are now studying the small-scale flow patterns around the hinging mechanism of mechanical heart valves implanted within patient-specific anatomical models (Figure 1) [Keefe et al. 2010]. Whereas coarse simulation of blood flow has been possible for many years, it is only recently that simulation technology has advanced to the point that it can capture physiologically-accurate detailed local flow features (e.g. flow structure around the hinging mechanism of each valve leaflet) [Simon et al. 2010]. These new data provide tremendous opportunities for new discoveries, however, they are extremely challenging to interpret.

I3D 2011, San Francisco, CA, February 18 – 20, 2011.

© 2011 ACM 978-1-4503-0565-5/11/0002 \$10.00



**Figure 1:** The Slice WIM interface. To the user, a miniature version of the 3D data appears to float in the air above the table surface. (A digital rendering has been superimposed on the photograph above to demonstrate this effect.) A slice through the data is projected (like a shadow) onto the table below, where multi-touch gestures are used to quickly navigate and explore the data. This user is exploring a high-resolution simulation of blood flow around a mechanical heart valve positioned within a patient-specific model of the left ventricle and aorta. The colored lines visible on the stereoscopic display wall are streamlines describing the flow.

Immersive virtual reality (VR) visualization has proven useful for analyzing biomedical fluid flows in the past [Sobel et al. 2004; Everts et al. 2009; Hentschel et al. 2008], however, these approaches are limited when analyzing data at multiple scales. The typical strategy adopted for analyzing small-scale flow features within VR environments is to"shrink oneself" to the size of a blood cell to zoom in on the local data. At this small, zoomed-in scale, the local flow features are visible and the head-tracked, stereoscopic VR environment facilitates the process of identifying local flow patterns. The problem is that, at this small scale, the grounding context provided by the surrounding anatomy and larger-scale flow features cannot be seen. This makes it easy to become lost within the virtual environment and also makes understanding relationships between local features and global features (e.g. changes in local flow patterns in response to patient-specific anatomical variations) very difficult. Thus, current approaches to visualizing and exploring high-resolution volume datasets in VR do not appropriately support overview+detail data analysis.

In visualization research, maintaining context while focusing on a subset of data is not a new problem. However, since prior work on overview+detail visualization has primarily been conducted within desktop/non-immersive visualization settings, it is not clear how to interpret and apply the core findings (e.g. the importance of multiple coordinated views [Baudisch et al. 2002], the benefits of complementing 3D displays with 2D displays [John et al. 2001; Tory

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et al. 2006]) to interactive VR applications.

Within the VR research community, the existing interfaces that are closest in spirit to overview+detail visualization techniques are based on the World in Miniature (WIM) metaphor [Stoakley et al. 1995; Pausch et al. 1995]. Although several valuable extensions to VR-based WIM techniques have been introduced recently [Wingrave et al. 2006; Trueba et al. 2009], these have been applied only to architectural models and cityscapes. Determining how best to utilize WIMs to navigate and explore complex scientific volume datasets, while supporting both overview and detail views of the data, remains an open problem.

In this paper, we present Slice WIM, a new World in Miniature VR interface that addresses this problem while also exploring the new potential of interfaces that combine multi-touch input with VR. Slice WIM uses the hardware configuration pictured in Figure 1. This semi-immersive VR configuration consists of a vertical headtracked stereoscopic display positioned behind a multi-touch table display. (It is now practical to construct such hardware at relatively low cost [Coffey et al. 2010].) The importance of the hardware for interactive techniques, such as Slice WIM, is that just as in a CAVE [Bryson 1996] or Responsive Workbench [Kruger et al. 1994], it supports stereoscopic viewing of a 3D model in such a way that the model appears to float in the air above the horizontal surface. However, in contrast to other VR configurations, the horizontal surface here is a multi-touch table, enabling a number of new interaction techniques to be explored. For example, Slice WIM utilizes the metaphor of manipulating 3D objects that float above the table by touching their "shadows" projected on the table.

In demonstrating and developing this metaphor in the context of scientific datasets, Slice WIM builds upon a growing body of work that explores the use of multi-touch interfaces for 3D scientific visualization. In addition to recent commercial popularity, researchers have documented several important advantages of multi-touch interfaces, including effective selection of on-screen targets [Kin et al. 2009], improved user awareness in collaborative interaction tasks [Hornecker et al. 2008], and improved feedback for virtual and real-world interactions [Robles-De-La-Torre 2006]. However, it is only recently that these advantages have begun to be realized in the context of visualizing 3D data [Yu et al. 2010]. Thus, the contributions of our work include: (1) A new VR WIM interaction technique that specifically addresses the challenges of exploring scientific volume data (e.g. supporting both overview and detail views, linking 2D and 3D data displays within a VR environment). (2) A demonstration of a new approach for utilizing multi-touch input to explore 3D scientific data. (3) A demonstration of two applications of the Slice WIM interface to different types of scientific volume data. (4) A discussion of design lessons learned and current limitations grounded in feedback from both casual users and domain scientists who used Slice WIM to explore their own datasets.

The remainder of the paper begins with a discussion of relevant related work. The Slice WIM interface is then described, followed by a description of the applications of Slice WIM to (1) a medical imaging dataset and (2) a computational fluid dynamics dataset. Then, we present a discussion of design lessons, current limitations, and user feedback.

# 2 Related Work

Our work builds upon three main areas of related research described in the following sections.

### 2.1 Overview+Detail Visualization

A wealth of research in both the scientific and information visualization communities has addressed overview+detail visualization (e.g. [Baudisch et al. 2001; Baudisch et al. 2002; Baldonado et al. 2000; Cockburn et al. 2008]). However, almost all of this prior work has targeted desktop and/or non-immersive visualizations, using strategies such as multiple coordinated views arranged in separate windows (e.g. [Butkiewicz et al. 2008; Flider and Bailey 2004; Piringer et al. 2004]). Slice WIM aims to incorporate design lessons from this prior work while reinterpreting them to apply to virtual environments. For example, Slice WIM presents multiple closely coordinated views of the 3D data [Baudisch et al. 2002] and mixes 3D visualizations with complementary 2D visualizations of the same data [John et al. 2001; Tory et al. 2006], however, rather than implementing these data displays as side-by-side windows on a desktop, they are implemented as a head-tracked, stereoscopic display linked with a 2D multi-touch table display.

#### 2.2 World-In-Miniature Interfaces

World-In-Miniature (WIM) interfaces have been used extensively in VR. Introduced by Stoakley et al. [1995] and Pausch et al. [1995], the core WIM concept is to provide a small (e.g. handheld) model of the virtual environment that can act as both a map and an interaction space as the user explores the large-scale environmentessentially a world within a world. Operations that are difficult to perform in the large-scale world (navigating a great distance, selecting/manipulating an object that is far away) can be done easily in the WIM. To this core concept and related interaction techniques, researchers have more recently added features to support scaling and scrolling the WIM for use in very large environments [Wingrave et al. 2006] and automatic selection of optimal WIM views, including handling issues of occlusion, for use in complex architectural models where the 3D structure of the model can be analyzed algorithmically [Trueba et al. 2009]. Although this recent research has focused on architectural/geospatial applications, scale and occlusion are also important considerations when working with scientific volume datasets. Our work uses a gestural touch interface to both set cutting planes within the WIM (addressing occlusion issues) and scale, rotate, and translate the WIM (addressing scaling and scrolling). In the future, as our ability to analyze features in volumetric scientific datasets improves, we believe combining the interfaces we introduce with more automated WIM viewing strategies inspired by recent related work may be a particularly effective for quickly and effectively exploring volumetric datasets.

It is often natural to think of WIMs as resting on a surface, either a handheld prop [Stoakley et al. 1995], the floor of a CAVE environment [LaViola et al. 2001], or as several investigators suggest, a table [Stoakley et al. 1995; Wigdor et al. 2006]. Slice WIM uses a table, but extends previous approaches by specifically considering volumetric data, which do not include a ground plane. We introduce a new metaphor for manipulating a 3D WIM floating above the table by interacting with its "shadow" projected onto the table.

Outside of VR, a desktop-based implementation of the WIM metaphor provides inspiration for our intended applications to scientific visualization. Li and Hanson [2006], designed a mouse-based WIM interface for exploring astronomical data. These data present similar overview+detail visualization challenges because of their extreme scale and sparsity.

### 2.3 Touch and Tabletop Interfaces for 3D Visualization

Although touch and tabletop interfaces have a long history of use in 2D applications, it is only recently that the fluid, gestural styles of

interaction typically afforded by these interfaces have begun to be leveraged for exploring 3D data [Yu et al. 2010; Benko and Feiner 2007; Valkov et al. 2010; Grossman and Balakrishnan 2006]. A common theme in this area of research is overcoming the perceptual problem that occurs when using a stereoscopic multi-touch display: as the user reaches out to touch the surface, her hand occludes her view of the display, ruining the illusion of an object floating on top of the display. As opposed to using an augmented reality display [Benko and Feiner 2007], a true 3D display (this technology is still emerging) [Grossman and Balakrishnan 2006], or adjusting the parallax to a non-physically-realistic value as the user reaches out to touch the display [Valkov et al. 2010], we introduce a new lightweight solution to this problem in the form of a multi-surface hardware configuration that allows for viewing an unobstructed object floating in space and touching its shadow.

This approach is motivated in part by the success of prior desktop interfaces that utilize the metaphor of manipulating 3D objects via "interactive shadows" [Herndon et al. 1992]. Perceptual research reinforces the validity of this approach. It is now well known that 2D views of 3D scenes provide complementary information to users, and, depending upon the task, judgments based on these 2D views can be more accurate than those based on 3D views [John et al. 2001]. Further, combining 2D and 3D views can be particularly effective for supporting accurate spatial judgements in complex 3D environments [Tory et al. 2006].

Slice WIM adopts the strategy of interacting with 3D data that exists in a 3D space above the interactive surface. This is related to (and perhaps most accurately described as the inverse of) techniques that project data onto a physical prop held above a table (e.g. [Spindler et al. 2009]). Slice WIM also builds upon prior successful strategies for linking a 2D display with a 3D display, for example linking pen-based interaction on a tracked tablet with a wall-size 3D display [Hachet and Guitton 2002].

# 3 Slice WIM

This section describes Slice WIM in detail. First, a more complete description of the VR hardware utilized is presented. Then, we describe in turn the visual components of the interface and the gestures and widgets used to manipulate Slice WIM.

#### 3.1 Hardware: Multi-Surface, Multi-Touch VR

Slice WIM utilizes a multi-surface, semi-immersive VR environment. As shown in Figure 1, the surfaces connect at a right angle. The horizontal surface is a multi-touch display, driven by a 1024x768 resolution projector. The hardware uses the FTIR-based method for detecting touches on the surface [Han 2005]. The vertical surface is a 1280x720 resolution, 7'x4' rear-projected headtracked stereoscopic display. Five NaturalPoint OptiTrack cameras are mounted around the room to provide head-tracking data. Tracking and touch servers send event data over a network connection to the VR application running on a single computer with two display outputs, one for each projector.

#### 3.2 Overview: WIM Visuals and Slices

Slice WIM is composed of several visual components, each diagrammed in Figure 2. As in traditional WIMs, Slice WIM includes a miniature 3D copy of the world that serves both as a map and an interaction space. In Slice WIM, this *miniature world* is positioned so that it appears to float above the table. As in many traditional WIMs, Slice WIM also provides a visual indicator within the miniature world of the user's current location. However, rather



**Figure 2:** Visual components of the Slice WIM. In this diagram, the 3D "dataset" being visualized is simply a blue sphere.

than displaying a miniature avatar for the user, Slice WIM displays a miniature rendering of the physical display hardware. A small green rectangle (the view window) outlines the position of the vertical display screen relative to the miniature world, and a small red rectangle does the same for the table surface. Each of these rectangles lies within a plane (one vertical, one horizontal), and the primary means of interacting with the WIM is manipulating these two planes (slices through the data). As the user adjusts these planes or moves the 3D data relative to the planes, as described in section 3.3, the three linked data views (2D widgets on the table, 3D miniature world, and 3D detailed world) update accordingly. The bottom edge of the view window is always constrained to rest on top of the horizontal slice through the data, which may be thought of as a ground plane, while the vertical slice through the data defines the plane of the view window. The large view of the 3D detailed world displayed on the stereoscopic vertical screen is defined precisely by the position, orientation, and scale of the view window relative to the miniature world, an example of which is shown in Figure 3.

#### 3.3 Driving the WIM: Multi-Touch Interactive Shadows

Multi-touch interaction on the table is used to control two widgets that are not part of traditional WIMs: (1) a *shadow widget* displays a parallel projection of the 3D miniature world, and (2) a *slice widget* displays handles and controls that can be used to adjust both the vertical and horizontal slices described in the previous section. As both widgets refer to 3D objects the user sees floating above the table, a convenient way to understand these is to think of them as "interactive shadows". We describe each of the widgets in turn.

The shadow widget is a parallel projection of the 3D miniature copy of the world onto the table surface. When interacting with the environment users quickly interpret the projection as a shadow. To reinforce this metaphor, we often render the projection to look precisely like a shadow, however, we have also explored visualizing data on top of the shadow. (This aspect of the design is described in greater detail within the application case studies in section 4.)



**Figure 3:** The view from the user's perspective during a data navigation task. The user has positioned the window within the left ventricle with the heart rotated to provide a straight-on view of the mitral valve. The orientation of the dataset (tilted to the right and back) required to achieve this view can be seen clearly by the position of the 3D dataset within the WIM, the location of the view plane within the left ventricle cavity can be seen clearly in the shadow projection, and the detailed geometry of the mitral valve is visible in the large-scale view of the data (left of the WIM).

Touching and manipulating the shadow widget causes the 3D miniature copy of the world to move in a corresponding way. During this manipulation, the view window follows along with the 3D miniature world. Thus, the primary reason for performing this interaction is to translate, scale, and/or rotate the miniature world relative to the multi-touch table. Following the multi-touch gestures defined by Coffey et al. [2010], these interactions are performed by touching the table with one or multiple fingers and then performing the gestures illustrated in Figure 4. As shown in part (a) of the figure, a single point of contact provides translation in the horizontal and depth dimensions (the height of the 3D object above the table remains fixed), and two points of contact are used to scale and to rotate about a vertical axis. Rotation about the other two axes in space is also supported. To do this, the gestures in Figure 4b are used. These gestures require a slightly different constraint than the gestures in Figure 4a. In this case, if the view window were to remain in a fixed position relative to the miniature world, the view window would rotate so that the bottom slice is no longer parallel to the table. Since this would create a mismatch in the orientation of the view window and the physical display, we decouple the view window from the rotation of the miniature world in this situation. Moving two points of contact together either left or right relative to the user in a direction roughly parallel to the plane of the vertical display rolls the miniature and detailed worlds about an axis perpendicular to the vertical display, and moving two points of contact together in the depth dimension (toward or away from the vertical display) tilts the miniature and detailed worlds toward or away from the user about an axis parallel to the vertical display.



**Figure 4:** The set of multi-touch WIM reorientation gestures used in the Slice WIM. Gestures that translate, scale, and rotate the WIM in the plane of the table surface are shown in (a). Gestures that change the up direction by tilting and rolling the environment are shown in (b).



Figure 5: The slice widget used for precise positioning inside the WIM. Independent handles are used to position the window to the world inside the miniature world. Additionally, the height of the horizontal slice can be adjusted up or down by dragging a thumb near the double arrow shown in red.

The second important widget is the slice widget. Figure 5 shows a closeup view of it. The thick green line is the projection of the view window onto the table. A small yellow arrow also points in the viewing direction. The circular areas at each end of the widget are handles that can be grabbed and manipulated by the user. To adjust the view, the user touches and moves these handles. Each handle can be moved independently, or using two-fingers, both handles can be moved at the same time. As the handles on the widget are moved, the view window floating above the table moves along with it, slicing through the miniature world, clipping the 3D geometry to the plane of the view window as it goes, and updating the large detail view accordingly. Note that this interaction sets not only the position and orientation of the view window relative to the miniature world, but also its scale. As the two handles are moved closer to each other the width of the view window shrinks relative to the miniature world. In the large, linked view of the detailed world, this has the effect of zooming into the dataset.

As a shortcut, if the user wishes to keep the center point of the view window fixed and rotate the viewing direction around this point, this can be accomplished by touching the rotation icon at the center of the widget with one finger and moving a second finger placed anywhere else on the table around this point.

All of these interactions control the vertical slicing plane; it is also important to be able to adjust the height of the view window, which is done by adjusting the horizontal slice that acts as a ground plane for the view window. With at least one of the slice widget handles active, an additional point of contact, typically from the thumb, moved vertically on the table changes the current height of the horizontal slice. The red double-sided arrow in Figure 5 reminds the user of this control and illustrates a typical location for a thumb touch, below and slightly to the left of the right handle, for when the the right index finger is touching the right handle of the widget.

Together, this combination of slicing metaphors, shadow widgets, and multi-touch controls makes possible a particularly fluid style of exploring volumetric datasets. This is best conveyed through the video accompanying this paper.

#### 3.4 Additional Design Decisions

We designed Slice WIM through an iterative process; several additional important design decisions came to light during this process. First, to avoid cluttering the display, we only show the 3D portions of the WIM (miniature world and view window outline) when the user is interacting with the WIM. Three seconds after the user lifts her finger from the table, this part of the WIM slowly fades out of view, becoming more and more transparent. When the user next touches the table, the 3D portion of the WIM comes back into view. The gradual fade is critical to avoiding a distracting pop in/out effect. Second, we found that establishing a strong correspondence between the physical space of the display and the horizontal and vertical slicing metaphor used in the WIM is critical to the success of the technique. This correspondence is reinforced in the current implementation by drawing the window to the world and the table as virtual objects within the WIM and using a consistent color coding scheme for these objects and the widgets used to manipulate them (green=vertical slice, red=horizontal slice).

Additional discussion of user feedback and lessons learned through the design of Slice WIM is included in section 5. Building on the basic interface described to this point, the following sections present specific applications of Slice WIM, including variations on the design described above that can be used to enhance the role of the table as a data display.

# 4 Exploratory Visualization Applications

This section describes the use of Slice WIM in two VR scientific visualization applications. The first visualizes data collected from medical imaging of the human heart and surrounding anatomy. In this application, details of the geometry, including understanding the specific shape of each of the cavities of the heart is the primary focus. The second visualizes dense, time-varying data from a supercomputer simulation of blood flow through the heart. In this application, understanding intricate details of the flow patterns formed as blood rushes past an implanted mechanical heart valve is the primary focus. We describe how Slice WIM can be utilized and augmented to analyze each of these different types of data.

### 4.1 Visualizing 3D Anatomy from Medical Imaging

In this application, the data come from a CT scan of a human heart. From these data, we extract an isosurface that captures the 3D geometry of the heart tissue as a triangle mesh. The triangle mesh comprises the 3D scene rendered in both the detailed and miniature world views. Figure 3 shows Slice WIM applied to this dataset.



**Figure 6:** In medical imaging datasets, the complexity of the anatomical geometry renders a typical shadow projection useless. Instead, for the shadow widget projection, a slice is rendered from the raw CT data. The orientation shown here (visible in the top) is much easier to interpret with the raw CT slice (right) as opposed to a traditional shadow (left). Additionally, the CT slice conveys the intricate internal structure of the heart.

A specific challenge that arises when exploring these data is understanding context. For example, consider viewing the scene in Figure 3 without the aid of the WIM, that is, just using the tan colored detailed world view shown in the background of the figure. This geometry is very difficult to interpret: spatial relationships are complex, the shape is organic and includes high variation in curvature, and the data include noise and anomalies that are distracting. When we zoom into these data it is very easy to become lost. This confusion is minimized considerably by using the WIM as an overview visualization while exploring the anatomy in detail. The miniature world portion of the WIM provides the 3D geometrical context needed to interpret the global orientation of the dataset.

This application also explores an interesting variation of the basic Slice WIM interface. Rather than displaying a simple shadow of the miniature world on the table, the shadow is replaced by a image slice through the raw CT data. We implement this using 3D texture mapping and the original CT volume data. Figure 6 illustrates the additional information that this strategy can add for this dataset compared to using just a shadow.

### 4.2 Visualizing High-Resolution Simulations of Cardiovascular Flows

In this application the data come from a custom high-resolution simulation of blood flow through a mechanical heart valve positioned within a patient-specific model of the left ventricle and aorta (Figures 1 and 7). The 3D scene displayed in the miniature world is a triangle mesh describing the bounding anatomical geometry for the left ventricle and aorta. The detailed world view also includes this mesh and, in addition, displays many colored streamlines in order to depict the details of the flow field.

Similar to the previous application, the shadow widget is augmented with an interesting data display. In this case, a color map is used to depict the simulated pressure within the heart. Again, the data are displayed on the table surface and calculated based on



**Figure 7:** Slice WIM in a fluid flow simulation inside of a left ventricle and aorta. The 3D miniature part of the WIM (top image) is similar, but the shadow widget projection shows a pressure map slice (bottom image) overlayed on a traditional shadow.



Figure 8: 3D vortical flow structures.

the horizontal slice that passes through the geometry as depicted in the WIM. Our implementation uses 3D texture mapping to render the color map. Comparing the two applications, one important difference in the data display here is that we render the pressure data on top of a true shadow (a parallel projection of the bounding triangle mesh onto the table). We found this was necessary because the geometry is such a strange shape that some slices only intersect the geometry is small areas. Figures 7 and 9 depict this clearly. The shadow is needed both to provide context for interpreting the pressure data and 3D information in the form of an outline.

The streamline-based visualization in Figure 8 illustrates the type of detailed 3D data views that scientists and engineers require to analyze today's computational fluid dynamics data. Notice, for example, the vortical structures that are clearly evident in these visualizations. When the view is zoomed in enough to read these data in detail the larger flow features and bounding anatomy are no longer visible. By providing multiple coordinated views of the data at different scales, the Slice WIM makes it possible to maintain the



**Figure 9:** Several views of the shadow widget projection consisting of a 3D shadow outline and a pressure map slice. In one orientation (left), the alternating high and low pressure pockets formed by the incoming blood flow of the mitral valve are visible. In another (right), the v-shaped pocket of low pressure on one side of the closed valve is visible next to the high pressure on the other side.

global context necessary to interpret these local flow features.

### 5 Discussion

This section presents additional lessons learned during the design of Slice WIM along with initial user feedback.

### 5.1 Alternative Designs Considered

An alternative WIM design that we considered departs from the shadow metaphor and instead positions the miniature world within the physical plane of the table, displaying a stereo view on the table surface. We were initially drawn to this design because we believed that using the table itself as a horizontal slicing plane would be a metaphor that would be readily understood by users. However, we determined that this design would present several problems: First, since the data that interest us are volumetric, we need to be able to see what lies inside the data. If the miniature world were placed on the table itself, it would be very difficult to see any of the internal structure of the world, since the view would always be limited to a bird's eye perspective. In addition, the type of 2D data displays that we developed in both the applications to augment the shadow widget, would not work in the configuration where the WIM is positioned directly on the table. Second, this configuration would suffer from the same perceptual issue mentioned earlier in the discussion of related work-when interacting with the table the user's hand would obscure the display, ruining the stereo effect. For these reasons, we believe the current design offers a number of immediate advantages, including making it practical to include both 2D and 3D data displays within a WIM and making it possible to effectively utilize multi-touch input to interact with a 3D WIM.

### 5.2 Perceptual Considerations and Future Work

Through formative user testing, we determined that users often felt uncomfortable when the miniature world appeared too close to their eyes, however, when they pushed the miniature world away this also moved the shadow widget away, toward the back of the table where it is less comfortable to reach. We determined that this issue can be easily solved by applying a slight offset and downscale to the miniature world, moving the miniature world farther away from the user's head, but keeping its shadow close to her hands. Scaling the miniature world down slightly relative to the shadow also helps. Our implementation uses an offset of 0.5 ft. and a scale factor of 0.75. After several months of use, we are surprised that no users have noticed this offset and scale without being told. Thus, it seems to significantly improve usability without introducing a perceptual mismatch between the miniature world and its shadow. Inspired by this finding, in the future, one avenue of research that we plan to investigate is developing a better understanding for the perceptual issues surrounding manipulating interactive shadows of 3D objects. We believe this may be an area where smart use of perceptual illusion can enhance 3D user interfaces.

### 5.3 User Feedback

Informal formative user testing played a critical role in the development of Slice WIM. For example, in early design tests, most new users were apprehensive to start using the interface. After implementing features that reinforce the slicing and physical space metaphors used in the interface (e.g. adding visual handles to the slice widget and highlighting the view window border on both the miniature view and the detailed view), we found that new users are now much more willing to begin using the interface. Recently, many users have even starting interacting with the tool before an initial explanation of the technique is finished.

We have also recently conducted a small pilot study of Slice WIM (N=8) based on a 3D search task inspired by the medical imaging application described earlier. Participants were asked to find a small blue target that we placed on the inner surface of the heart geometry. To complicate the task, we added many green distractor targets. For this initial study, the sample size was limited and the participants were primarily from computer science backgrounds and were therefore not representative of the primary intended audience for the tool, however, the initial feedback we received is promising. All users reported that the interface was well suited for the task at hand. Users were observed to quickly understand the relationship between the shadow widget and the miniature world. Users also quickly learned to utilize head tracking to view the 3D scene, including the WIM, from different vantage points. Most users adopted the following strategy to complete the task: First, they used the shadow widget to familiarize themselves with the shape of the anatomy and position and orient the miniature world to their liking. Then, they grabbed the slice widget handles with two fingers and began to quickly explore the data by slicing through it. As they moved the slice widget, they looked at both the detailed view window and the 3D miniature to locate the target point. If the target was not found, they adjusted the 3D miniature to view the environment from a different orientation, repeating the process until the target was located.

When asked what they would like to change about the interface, two users reported that the widgets were sometimes difficult to reach on such a large table; they suggested limiting the interaction space to a smaller region. Three users commented that the technique required concentration and suggested that some form of tactile feedback might enable the widgets to be used more effectively when not looking at the table. One user reported that the miniature world was in the way, suggesting that moving it to the side may help.

The researchers who have provided us with data for the applications described earlier have also used Slice WIM. The most compelling feedback we have received from these users comes in the form of a collaborative data exploration session that we recently had. We asked the computational fluid dynamics researcher who simulated the blood flow dataset if he could describe an interesting aspect of the data to us. He started by asking if we could put the dataset into an orientation where the mitral valve is at the top. We quickly did this using the shadow widget. Then, he asked us to zoom in to focus the view on the top portion of the left ventricle. We did this by using the slice widget to reposition the view window and using the thumb gesture to move the view window up relative to the dataset. From this vantage point, he was able to clearly point out to us a donut-shaped vortex that we had not noticed before. In the future we are keen to apply Slice WIM to new datasets that may provide

new opportunities for discovery. For example, a second group of collaborators, mechanical engineers, have expressed interest in installing a visualization tool using Slice WIM at their own lab.

# 6 Conclusion

We have presented Slice WIM, a multi-surface, multi-touch interface for overview+detail exploration of scientific volume datasets in virtual reality. Slice WIM addresses current limitations of VR visualizations of volume data; although current strategies support detailed spatial analysis of local data features, it is easy to become lost and disoriented in these immersive visualizations and it is also difficult to perform analysis at multiple scales (e.g. interpreting local data relative to global patterns). Slice WIM presents a solution to these problems that builds upon successful desktopbased overview+detail visualization strategies (e.g. multiple linked 2D and 3D views) and the successful VR WIM metaphor. Feedback from both expert and casual users informed the design of Slice WIM and suggests the promise of new interfaces that utilize a multi-surface, multi-touch VR framework combined with interactive shadow widgets. We believe that as our ability to collect and simulate datasets at high resolutions continues to rapidly increase, interfaces, such as Slice WIM, that support exploratory visualization at multiple scales will become increasingly important.

### 7 ACKNOWLEDGMENTS

This work was supported in part by the Minnesota Supercomputing Institute for Advanced Computational Research; the University of Minnesota Grant-in-Aid of Research, Artistry and Scholarship program, and the National Institutes of Health (RO1-HL-07262).

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