Interactive Slice WIM: Navigating and Interrogating Volume Data Sets Using a Multisurface, Multitouch VR Interface

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Abstract—We present Interactive Slice World-in-Miniature (WIM), a framework for navigating and interrogating volumetric data sets using an interface enabled by a virtual reality environment made of two display surfaces: an interactive multitouch table, and a stereoscopic display wall. The framework addresses two current challenges in immersive visualization: 1) providing an appropriate overview+detail style of visualization while navigating through volume data, and 2) supporting interactive querying and data exploration, i.e., interrogating volume data. The approach extends the WIM metaphor, simultaneously displaying a large-scale detailed data visualization and an interactive miniature. Leveraging the table+wall hardware, horizontal slices 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 multitouch gestures made on the table. In addition to enabling effective navigation through complex geometries, extensions to the core Slice WIM technique support interacting with a set of multiple slices that persist on the table even as the user navigates around a scene and annotating and measuring data via points, paths, and volumes specified using interactive slices. Applications of the interface to two volume data sets are presented, and design decisions, limitations, and user feedback are discussed.

Index Terms—World in miniature, virtual reality, multitouch, overview+detail, volume visualization, 3D user interface.

1 Introduction

Complex volumetric data sets are common to many fields in science and engineering and are routinely generated today via imaging, experimental data capture, and/or simulation. As the size and complexity of these data increase, data analyses become increasingly difficult. For spatially complex data, visualization via virtual reality environments has proven useful due to the increased spatial understanding that typically results from head-tracked stereoscopic viewing [14], [19], [33], [39]. However, navigating through spatially complex volumetric data sets within virtual environments remains a challenge. Effective interfaces for selecting, querying, and otherwise interrogating volumetric data from within virtual environments also remain elusive, but are particularly important for supporting real science and engineering workflows.

One of the most pressing challenges in virtual reality visualization is supporting effective navigation through the environment while viewing data at multiple scales. For example, in fluid flow visualizations, a typical immersive visualization strategy is to "shrink oneself" to the size of a small particle in the flow to zoom in on local flow features. 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 bounding geometry or 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 very difficult. Thus, current approaches to visualizing and exploring high-resolution volume data sets 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 [5], the benefits of complementing 3D displays with 2D displays [22], [36]) to interactive VR applications.

Within the VR research community, the existing interfaces that are closest in spirit to desktop overview+detail

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Fig. 1. A miniature version of the 3D data appears to float in the air above the table surface. (A digital rendering is superimposed on the photograph to demonstrate the effect.) A cutting plane through the volume data is projected (like a shadow) onto the table below, where multitouch gestures are used to navigate and interrogate the data. After navigating to a useful view of these imaging data of a heart, the user is now defining a smooth 3D curve (e.g., the shape of a catheter delivery system) relative to the anatomical data set.

visualization techniques are based on the World in Miniature (WIM) metaphor [29], [35]. Although several valuable extensions to VR-based WIM techniques have been introduced recently [37], [41], these have been applied only to architectural models and cityscapes. Determining how best to utilize WIMs to navigate complex scientific volume data sets, while supporting both overview and detail views of the data, remains an open problem. To further complicate this problem, the goal of most real scientific or engineering analyses is not simply to view a data set, but rather to also interrogate the data by measuring, selecting, and querying 3D data.

This paper extends Slice WIM [14] to address these important challenges by adding the following:

1. a novel multitouch interface integrated with Slice WIM for defining and measuring 3D points, curves, and volumes within volumetric medical imaging data;
2. a hybrid 2D and 3D multiple-coordinated-view technique added to Slice WIM for performing a variety of 3D visualization operations using multiple slicing planes, including a novel multitouch interface for selecting complex volumetric features;
3. extensions to two scientific visualization applications to demonstrate the use of these new features in practical situations, including an approach for fast selection of bundles of 3D fluid flow (also relevant to other current 3D selection problems, such as selecting neural fiber tracts in DT-MRI data); and
4. an extended discussion of user feedback from application scientists and a design study conducted with novice users.

Fig. 1 provides an overview of the resulting *Interactive Slice WIM* framework, highlighting the new ability to plot smooth curves and select volumes within medical imaging data, tasks that are required by engineers designing medical devices, doctors planning patient-specific surgeries, and many other real-world scientific applications of VR.

An important enabling technology for the Interactive Slice WIM is the semi-immersive VR environment utilized (Fig. 1), which consists of a vertical head-tracked stereoscopic display positioned behind a multitouch table display. (It is now practical to construct this hardware configuration at relatively low cost [13].) The importance of the hardware for interactive techniques is that just as in a CAVE [10] or Responsive Workbench [25], 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 multitouch table, enabling a number of new interaction techniques to be explored. For example, Interactive Slice WIM utilizes the metaphor of manipulating 3D objects that float above the table by touching their "shadows" projected on the table.

The contributions of this research include:

1. A detailed description of the design and implementation of a 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 several novel multitouch interfaces, all based on an interactive-slicing metaphor, which can be used effectively to both navigate and interrogate volumetric data.
3. A demonstration of two applications of the Interactive Slice WIM framework to different types of data, including a discussion of how the interface can be extended to better support each specific application.
4. A discussion of design lessons learned and current limitations based on feedback from both casual users and domain scientists.

The remainder of the paper begins with a discussion of relevant related work. The Interactive Slice WIM framework and its use for navigation and data interrogation is then described in general terms. Following this, we describe applications of Interactive Slice WIM to 1) a high-resolution anatomical data set and 2) a computational fluid dynamics data set. The paper concludes with 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., [4], [5], [6], [12]). However, almost all of this prior work has targeted desktop and/or nonimmersive visualizations, using strategies such as multiple coordinated views arranged in separate windows (e.g., [11], [15], [31]). We aim to incorporate design lessons from this prior work while reinterpreting them to apply to virtual environments.

For example, Interactive Slice WIM presents multiple closely coordinated views of the 3D data [5] and mixes 3D visualizations with complementary 2D visualizations of the same data [22], [36], 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 multitouch table display, which supports both mixed 2D and 3D views, and multiple linked 2D views through the persistent slices feature.

2.2 World-In-Miniature Interfaces

World-In-Miniature interfaces have been used extensively in VR. Introduced by Stoakley et al. [35] and Pausch et al. [29], 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 environment—essentially 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 [41] 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 [37]. Although this recent research has focused on architectural/geospatial applications, scale and occlusion are also important considerations when working with scientific volume data sets. 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).

It is often natural to think of WIMs as resting on a surface, either a handheld prop [35], the floor of a CAVE environment [26], or as several investigators suggest, a table [35], [40]. Interactive Slice WIM uses a table, but extends previous approaches by specifically considering volumetric data, which do not include a ground plane.

Outside of VR, a desktop-based implementation of the WIM metaphor provides inspiration for our intended applications to scientific visualization. Li et al. [28], 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.

The most common use of WIM interfaces is to support navigation, however, virtual object manipulations can also be supported via miniatures [30], [35]. Our interface and applications explore the potential of WIM-based interfaces enabled by emerging technologies to support volumetric selection, path planning, and quantitative 3D measurements within scientific applications.

2.3 Touch Interfaces for 3D Visualization

Touch and tabletop interfaces have an established record of effective use in 2D applications. In addition to recent commercial popularity, researchers have documented several important advantages of 2D multitouch interfaces, including effective selection of on-screen targets [24], improved user awareness in collaborative interaction tasks [21], and improved feedback for virtual and real-world interactions [32].

It is only recently, however, that the fluid, gestural styles of interaction typically afforded by these interfaces have begun to be leveraged for exploring 3D data [7], [16], [38], [42]. A common theme in this new area of research is overcoming the perceptual problem that occurs when using a stereoscopic multitouch 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 [7], a true 3D display (this technology is still emerging) [16], or adjusting the parallax to a non-physically-realistic value as the user reaches out to touch the display [38], we utilize a solution to this problem in the form of a multisurface hardware configuration that allows for viewing an unobstructed object floating in space and touching its shadow projected onto a table [13].

This approach is motivated in part by the success of prior desktop interfaces that utilize the metaphor of manipulating 3D objects via "interactive shadows" [20]. 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 [22]. Further, combining 2D and 3D views can be particularly effective for supporting accurate spatial judgments in complex 3D environments [36].

Finally, Interactive 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., [34]). Our approach 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 [17].

3 Interactive Slice WIM Overview

We begin by describing the specific VR hardware utilized core Interactive Slice WIM concepts.

3.1 Hardware: Multisurface, Multitouch VR

Interactive Slice WIM utilizes a multisurface, semi-immersive VR environment. As shown in Fig. 1, the surfaces connect at a right angle. The horizontal surface is a multitouch display, driven by a $1{,}024 \times 768$ resolution projector. The hardware uses the FTIR-based method for detecting touches on the surface [18]. The vertical surface is a $1{,}280 \times 720$ resolution, $7' \times 4'$ rear-projected head-tracked 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.

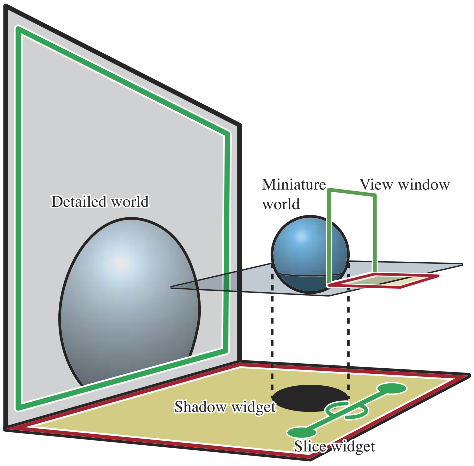

Fig. 2. Visual components of Interactive Slice WIM. In this diagram, the 3D "data set" being visualized is simply a blue sphere.

3.2 WIM Visuals and Slices

Interactive Slice WIM is composed of several visual components, each diagrammed in Fig. 2. As in traditional WIMs, a miniature 3D copy of the world serves both as a map and an interaction space. In Interactive Slice WIM, this *miniature world* is positioned so that it appears to float above the table. As in many traditional WIMs, Interactive Slice WIM also provides a visual indicator within the miniature world of the user's current location. However, rather than displaying a miniature avatar for the user, it displays a miniature rendering of the physical display hardware. A small green rectangle (the *view window*) indicates 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 4, 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 Fig. 3.

Through iterative design, we found that it is critical to establish a strong correspondence between the physical space of the display and the horizontal and vertical slicing metaphor. Thus, in both this paper and in the interface itself, a consistent color coding scheme is utilized (green=vertical slice, red=horizontal slice) for both the rectangles that define the slices and the widgets that are utilized to adjust them. Although the gestures used to control the slicing can be recognized without such explicit visual aids, we found through testing that including specific visual handles and arrows on the slice widget make the interface more readily understood by novice users and facilitates a sense of direct manipulation of the widgets.

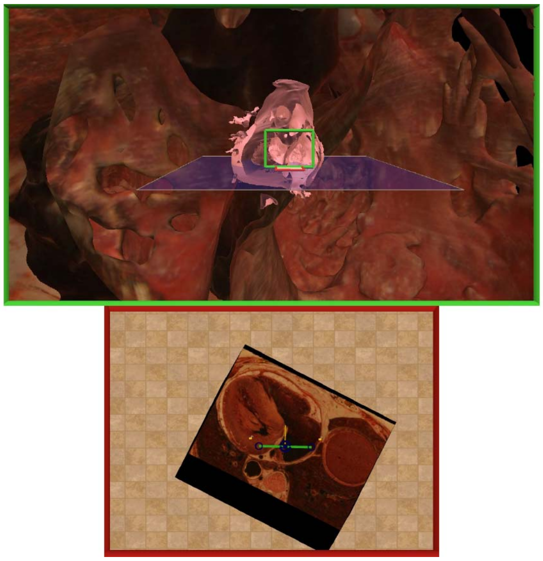

Fig. 3. The large detailed world shows the geometry of the heart. The 3D miniature world provides contextual information about the orientation of the model. The "shadow" projected onto the table (here interpreted as a slice through the volume data) provides both context and a widget for controlling the 3D interface.

4 Navigating Data Sets

Navigating through the data set to view the volume and its projection on the table from different angles is supported by a multitouch interface using 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, as in Fig. 3. (This aspect of the design is described in greater detail within the application case studies in Section 6.)

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 multitouch table. Following the multitouch gestures defined by Coffey et al. [13], these interactions are performed by touching the table with one or multiple fingers and then performing the gestures illustrated in Fig. 4. As shown in part (a) of the figure, a single point of contact provides translation in the horizontal and depth dimensions

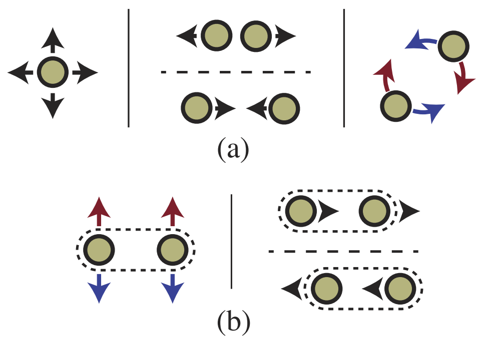

Fig. 4. (a) Gestures for translating, scaling, and rotating the WIM in the plane of the table surface. (b) Gestures for tilting and rolling.

(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 Fig. 4b are used. These gestures require a slightly different constraint than the gestures in Fig. 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.

The second important widget is the slice widget (Fig. 5). 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 data set.

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.

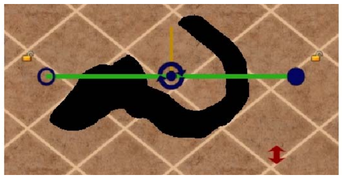

Fig. 5. The slice widget. Handles (blue circles on both ends of the line) are used to position the view window inside the miniature world. The height of the horizontal slice is adjusted up or down by dragging the thumb near the red double arrow.

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 Fig. 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, when the right index finger is touching the right handle of the widget.

Together, this combination of slicing metaphors, shadow widgets, and multitouch controls makes possible a particularly fluid style of navigating volumetric data sets.

5 Interrogating Data

This section introduces a set of extensions to the core functionality of the Slice WIM interface to support interrogating volume data. Similar to interfaces for navigating through 3D spaces described so far, a key challenge in supporting data interrogation is developing an effective mapping between the rich 2D input available via multitouch hardware and the 3D data space. As argued previously in the discussion of related work, there is a reason to believe that rich 2D input may actually be preferable to direct 3D input for some 3D data querying tasks if the right mappings between 2D input and 3D functions can be developed. To this end, Interactive Slice WIM introduces two generalizable strategies for 3D data querying. Each is described in general terms in the following sections, then additional details are provided in the application case studies in Section 6.

5.1 Specifying 3D Points, Curves, and Volumes

The first strategy extends the slice widget to support a new ability to specify 3D points, curves, and volumes relative to the current view of the data. The interaction technique utilized is inspired by the creative "balloon selection" interface introduced by Benko and Feiner [7]; we demonstrate how the bimanual balloon-style controls can be integrated with WIM interfaces and used to construct 3D curves and volumes from control points. The core interaction technique uses input from two fingers on a table to specify a 3D position. The first finger (index finger of the right hand in Figs. 1 and 6) specifies the position of the 3D point in a horizontal plane parallel to the table. The distance of the second finger (index finger of the left hand in figures) from the first specifies the height of the 3D point relative to

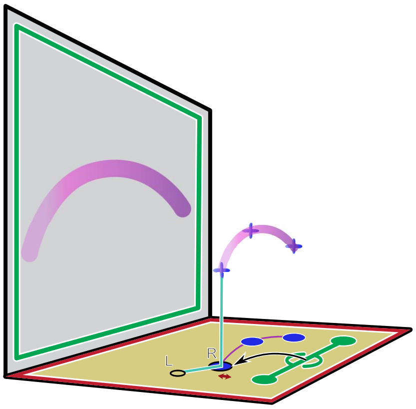

Fig. 6. Points are specified in the 3D space relative to the miniature world via a multitouch interface. Multiple points are combined to form curves, and curves may be expanded via an additional touch gesture to define a generalized cylinder of variable radius.

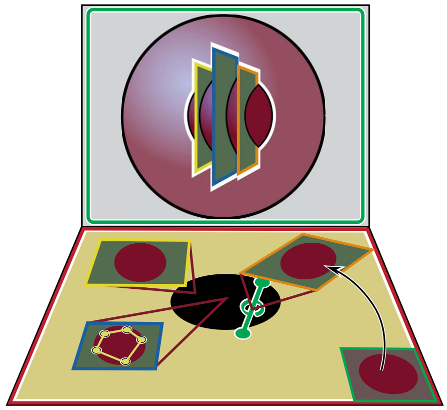

Fig. 7. Persistent slices are created by dragging a copy of the vertical slice of the data pictured in the bottom right corner of the table onto the middle of the table. These persistent slices provide a means of mapping 2D table input into multiple planes within the 3D visualization space.

the table. From the user's standpoint, a useful metaphor is to imagine the 3D point she is positioning is a balloon that floats above the table attached to a string of a fixed length that she is pinning down to the table with her two fingers; in the figures, this virtual string is depicted as a blue line.

This interface for specifying a 3D point is integrated into the slice widget as depicted in Fig. 6. The technique is activated by touching the center circle on the slice widget and dragging that finger in front of the widget. As the finger leaves the center circle the 3D point is displayed via a crosshairs icon. Placing and dragging a second finger on the display adjusts the height of the point above the table as described above. The point is displayed both within the miniature world and the detailed world. After the point is created an icon remains displayed on the table surface to indicate the original touch point. The position can be edited later by touching this icon to reengage the balloon-style interface, and the set of active points can be cleared by touching an additional icon on the table.

The ability to precisely position 3D points within a complex volumetric space as guided by WIM interface is a useful building block for many additional data querying operations. After a first point is placed in space, additional points may be constructed in the same manner. A ruler feature is activated when two points are present in the view. When three or more points are added to the view, an interpolating spline is displayed (Fig. 1). The arc length of the active curve is printed numerically on the table surface, which provides a natural display for quantitative information like this.

In addition to points and curves, volumes may be specified via an extension of the technique. Using a third point of contact, similar to the horizontal height adjustment described earlier (see the double-ended red arrow in Fig. 6), a radius can be associated with each point. (This input is similar to the balloon radius control in [7].) In the spline drawing mode, this input is tied to the radius of a tube rendered about the center of spline, turning the interface into a technique for specifying a generalized cylinder of varying radius. A useful application of this technique is described in Section 6.1.2.

5.2 Interacting with Multiple Persistent Slices

Further extending the core Slice WIM interface, we introduce a second generalizable strategy for interacting with 3D data using a WIM interface controlled via 2D input, specifically the ability to define, organize, and interact with multiple persistent vertical slices displayed on the table. Fig. 7 illustrates how this strategy integrates with the shadow widget. A new view window is introduced in the front right corner of the table. This window duplicates the view shown in the vertical wall display (hence it is outlined in green) with the exception that the view shows only a vertical slice through the data at the position of the wall display, not a full 3D rendering of the volume. After navigating to a desired location, the user turns this slice into a persistent interaction space on the table by touching it and dragging her finger to a new position on the table. This action is illustrated in Fig. 7, which contains three persistent slices.

We call the slices persistent because they stay visible on the table and remain associated with the position and orientation in which they were originally created even after the user navigates to a new view. Two complementary rendering strategies are used to indicate each slice's location within the miniature world. Within the view of the shadow on the table, each slice is rendered as a callout box that originates at a location corresponding to the 3D center of the view window at the time the slice was created. In the miniature world, the slices are rendered directly in the 3D view. Consistent color coding is used to associate the callouts on the table with the 3D rectangles rendered in the miniature world. A mathematical mapping can be easily constructed between 2D points within the bounds of each 2D frame on the table and its associated 3D frame placed in the world. Thus, a touch within any of the 2D frames on the table uniquely identifies a 3D point within the 3D visualization space. This feature enables several powerful styles of interaction, as it makes it possible to quickly define many 3D points via multiple touches. A useful application of this strategy to a 3D fluid flow selection interface is described in detail in Section 6.2.2. The user can rearrange each slice on the table to organize the workspace using the standard multitouch translate, rotate, and scale gestures that are now used in popular photo display and other applications.

It is important to note that for both these persistent vertical slices through the data and also for the horizontal slices that are central to the Slice WIM technique, it is critical for the visualizations to include sufficient out-of-plane contextual information so that users can correctly interpret the 2D data displayed on the slices. As described earlier, for horizontal slices the design goes to great lengths via color coding and the shadow metaphor to provide this contextual information. For the vertical slices described in this section, contextual information is provided by the combination of color coding, 2D graphics on the table, and 3D representation of the frames of the persistent slices in the WIM (Fig. 7).

5.3 Considerations for Highly Interactive WIM's

In the original navigation-only Slice WIM interface, the 3D portions of the WIM (miniature world and view window outline) are only displayed 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 fades back into view. With the new ability to place points, curves, and volumes in space and to interact with persistent slices, we found that in addition to having the 3D WIM fade in and out, users often wished to either focus entirely on the 3D WIM, keeping it displayed at all times, or dismiss it entirely, using only the 2D portion of the WIM on the table while focusing on the detailed 3D view. We found it interesting that this feedback about the role of the 3D WIM came to light most prominently only after users were asked to perform data interrogation tasks instead of just navigation. To address this, we have implemented a small extension to the interface (the lock icons shown in Fig. 5) to lock the 3D portion of the WIM in either a visible or hidden state.

In our design study, we received feedback suggesting that the most comfortable place to interact with the Slice WIM is in the front and center of the table (Section 8.3). Although several users mentioned this, it did not appear to slow them down when we asked them to navigate through volume data sets. In contrast, during testing of the 3D point creation interface described above, we observed that this ergonomic concern began to impact performance. Since users want to specify 3D points relative to the volume data displayed in either the miniature world or the detailed world, the interaction that specifies those points must happen in a space "beyond" the view window (because the view window clips any geometry in front of it). This means that to create these 3D points, the user must reach to a point on the table that is farther away from her body than the slice widget. Often this turns into a long reach; in fact, in preliminary versions of the interface, users tended to default to interacting in front of the slice widget as it was more comfortable and they were confused as to why the 3D point they were specifying did not show up within the detailed view.

To help users to default to a movement where their hands naturally move into the portion of volume that is displayed in the 3D view, we implemented an extension to the interface that returns the slice widget to a home

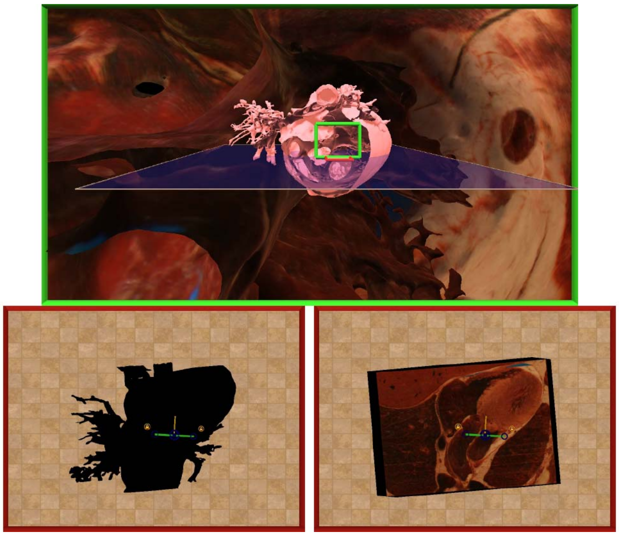

Fig. 8. Rendering the shadow widget as a true shadow (left) provides strong visual cues for the user controlling the WIM via touch gestures, but reinterpreting the "shadow" as a more sophisticated data display (right) is often preferable when positioning the view window relative to internal structures in the data is particularly useful.

position close to the front edge of the table, as in Fig. 6. Immediately after the user finishes interacting with the slice widget handles, the entire WIM reorients itself through an animated transition such that the slice widget returns to the home position. The key benefit is that as the user initiates the 3D point placement feature, the most natural motion for the user to make as she drags her finger off the center of the slice widget is to move away from her body toward the center of the table, which places the 3D point nicely within view in both the miniature and detailed worlds.

6 Applications and Specific Extensions

This section describes the use of Interactive Slice WIM in two VR scientific visualization applications. The first depicts high-resolution anatomical data and the second a high-resolution simulated fluid flow. For each application, we describe how the Interactive Slice WIM supports both navigation and data interrogation, emphasizing extensions to the core concepts introduced earlier that enhance these specific applications.

6.1 Visualizing 3D Anatomy

This application is a visualization of 3D anatomical data collected via the visible human project [2]. In this application, understanding details of the geometry, for example, the specific shape of each of the cavities of the heart is the primary focus. The application is representative of a broad range of potential medical imaging applications. In this case, the high-resolution color information available in the data set provides additional data channels to visualize beyond those available via MRI or CT modalities alone. The 3D scene displayed consists of an isosurface that describes the 3D geometry of the heart, rendered via a triangle mesh and a 3D texture that references the original color data. Figs. 1, 3, and 8 show Interactive Slice WIM applied to this data set.

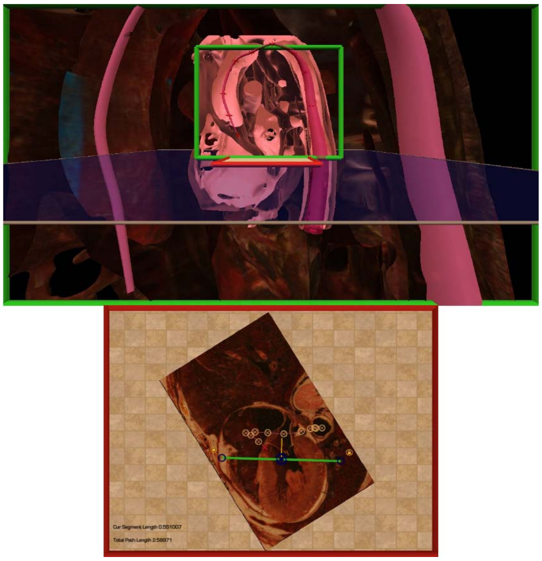

Fig. 9. A 3D generalized cylinder of varying radius has been constructed interactively to make a volumetric measurement relative to the anatomy. Here, the curve has been positioned to trace through the aorta and the user is beginning to interactively adjust the radius of the generalized cylinder to precisely match the aorta.

6.1.1 Navigating Data

A specific challenge that arises when navigating these data is maintaining a sense of context during detailed exploration. For example, consider viewing the scene in Fig. 3 without the aid of the WIM, that is, just using the textured 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 data set.

This application also explores an interesting adaptation of the basic interface. Rather than displaying a simple shadow of the miniature world on the table, the shadow is replaced here with color information taken from the current horizontal slice through the volume data. We implement this by 3D texture mapping the original volume data onto a plane. Fig. 8 illustrates the additional information that this strategy can add for this data set compared to using just a shadow.

6.1.2 Interrogating Data

Fig. 9 demonstrates a specific implementation and use of the ability to interactively specify 3D points, curves, and volumes described earlier. A series of points has been placed relative to the anatomy to capture the centerline curve of the aorta. The fact that this curve can be reliably positioned within the anatomy in this way provides some evidence for the control the user has over the interface. In the front left corner of the table, the arc length of the curve is displayed numerically, providing quantitative data to complement the immersive view. After placing the curve the user is now starting to adjust the radius of a tube centered on the curve to match the extents of the surrounding anatomy, which will generate a volume that matches the form of the aorta. The position and radius of any of the control points that define the curve can be edited by touching the corresponding control point icon displayed over the shadow widget.

From a practical standpoint, this use case is relevant to engineers because there is often a need to make quick 3D measurements relative to volumetric imaging data without requiring time consuming segmentation of the data. Using the curve construction feature, designers can perform path planning, determine a lead length needed to reach the target location, or measure curvature variations along a path. With the volume feature, designers can create approximations of anatomical objects on which FEA and CFD simulations could be run, measure clearances, and perform other operations. Since the imagery data are integrated into the visualization via slices, there is always a link back to the raw data. Thus, the interface can be used to accurately measure space even in situations where the 3D data view is only approximate (e.g., when the 3D isosurface displayed is constructed from just a quick approximate segmentation of a tissue). This has potential implications for shortening device design iterations.

6.2 Visualizing 3D Fluid Flows

The second application visualizes dense 3D fluid flow data from researchers who have developed a series of custom physiologically accurate supercomputer simulations of blood flow through a bileaflet mechanical valve positioned within realistic anatomical models of the left ventricle and aorta region of the heart [8], [9], [27]. In this application, understanding intricate details of the flow patterns formed as blood rushes past the valve and through the aorta is the primary focus, as a potential future application of the technology is virtual prototyping for surgery and medical device design.

Fig. 10 illustrates the application of Interactive Slice WIM to this problem domain. The 3D scene displayed in the miniature world is a triangle mesh capturing the bounding anatomical geometry. The detailed world view also includes this mesh and, in addition, displays many streamlines (randomly colored in this example) in order to depict the details of the flow field. In this application, the "shadow" displayed on the table has also been augmented with additional data. A color map conveys the pressure within the flow at the location of the horizontal slice through the volume data. 3D texture mapping is used to render the color map. Comparing the two applications, one important difference in the data displayed on the table surface here is that the pressure data are rendered 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. Figs. 10 and 11 depict this clearly. The shadow is needed both to provide context for interpreting the pressure data and to reinforce the correspondence with the 3D miniature world.

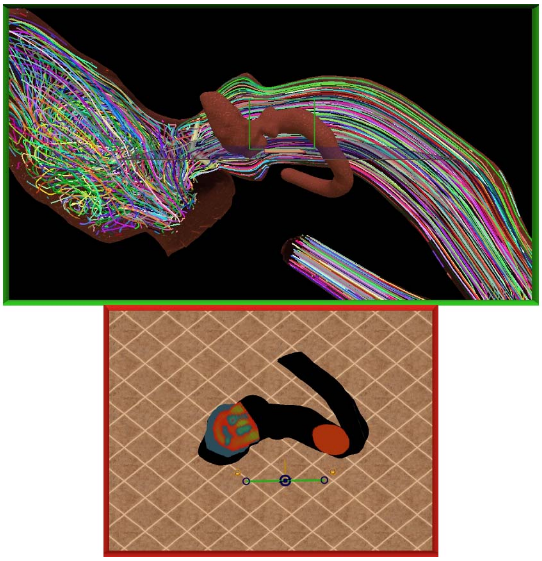

Fig. 10. Visualizing the results of a fluid flow simulation. The shadow widget is augmented with a pressure map projected down from the horizontal slice and overlaid on top of a traditional shadow.

6.2.1 Navigating Data

As seen in Fig. 10, many detailed 3D flow structures can be captured in state-of-the-art computational fluid dynamics simulation results, such as these. For scientists and engineers to interpret vortical structures and other flow features relative to the bounding anatomy and implanted devices, it is critical to be able to navigate within the data to visualize the flow at different scales. In more traditional visualizations, when the view is zoomed in enough to read small scale features in detail, the larger flow features and bounding anatomy are no longer visible. By providing multiple coordinated views of the data at different scales, Interactive Slice WIM makes it possible to maintain the global context necessary to correlate local flow features with the larger environment.

6.2.2 Interrogating Data

Fig. 12 describes a multitouch 3D flow querying interface enabled by the multiple persistent slices feature described earlier. Several slices have been positioned throughout the flow volume to capture different cross sections of the flow. Each is displayed on the table surface, and within each the

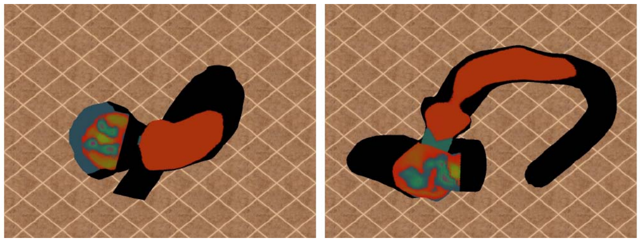

Fig. 11. Since the planer slice that produces the pressure data does not pass through the entire geometry, it is rendered on top of the shadow of the entire geometry to provide a context for interpreting the data.

cross section of the bounding geometry is rendered along with a point for each streamline that passes through this cross section. To select a region of flow, the user places three or more fingers on one of the slices. The system then computes the convex hull of the current touch points (Fig. 12b). All of the streamlines that pass through this convex hull are selected and the rest are culled from the display. Each of the persistent slices is updated to reflect the currently selected streamlines as is the 3D view of the detailed world. The selection is dynamic. The user can quickly move her fingers into a variety of shapes to select flow that passes down one side of the geometry or the other or flow that passes just by the hinging mechanism of the valve, etc.

Several alternative strategies have been proposed in the literature for facilitating this type of 3D selection, for example, lassos and other gestures have been used to select flow lines, neural fiber tracts, and the like [3], [23], [33]. However, 3D selection within fluid flows remains a very challenging task. There are several potential advantages to the strategy described here. We are not aware of any other 3D fluid flow selection techniques that provide this level of fluid, dynamic adjustment of the selection. This is facilitated specifically by the multitouch input technology. Although the input is technically 2D, the multiple points of contact make it an extremely rich 2D input. Using several fingers, a complex convex hull shape can be defined instantly, and then adjusted very fluidly simply by moving ones fingers. Thus, rather than making a single selection and then stopping, this technique is most useful as an interactive tool, dynamically exploring the 3D space through iterative culling of streamlines. Another potential advantage of this strategy is that since it works across multiple persistent slices, the user can very

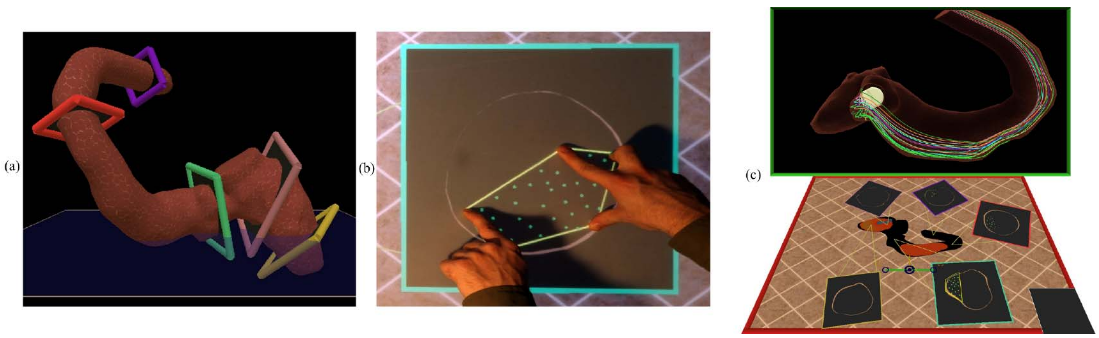

Fig. 12. A multitouch 3D selection technique using multiple persistent slices applied here to query streamlines. (a) Several persistent slices have been positioned strategically across the bounding geometry of the flow. (b) A selection is performed and quickly adjusted interactively via multiple touch points placed within one of the persistent slices on the table. (c) The selection is immediately reflected across all the persistent slices and the 3D detailed world.

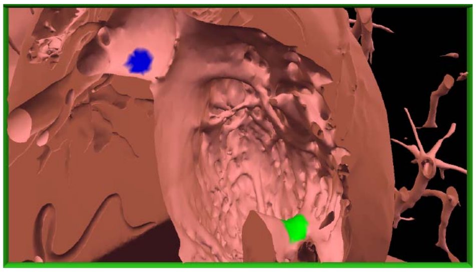

Fig. 13. The design study search and size judgment task.

quickly jump between interacting with slices that are positioned far away from each other in the 3D volume. In this way, the technique fits elegantly within a WIM-based metaphor, where the miniature environment often provides a simple interaction space for tasks that would be complex if performed directly in the detailed 3D world. For example, without the WIM, selections across multiple planes in 3D space would require the user to first navigate through the world to reach these planes.

7 User Feedback and Studies

Our framework was informed by feedback from the scientists and engineers who guided the applications described above as well as by a design study we conducted with participation from novice users.

7.1 Design Study

We developed a synthetic data analysis scenario consisting of both visual search and size judgment tasks and conducted a design study to understand how novice users were able to learn and apply the multitouch interface to perform tasks representative of scientific analyses. Eight compensated participants (seven male and one female, ages 20-27, drawn primarily from the university computer science population) took part in the study, which included time for training, use of Slice WIM, use of other multitouch visualizations, and discussion. Specific visual search and size judgment tasks were developed to add structure to the sessions. In all, each participant completed 15 search and size judgment tasks using Slice WIM. During each task, an anatomical data set similar to that described in Section 6.1 was visualized with two surface features highlighted, as in Fig. 13. Participants were asked to first locate the two features within the volume and then make a relative size judgment, reporting which feature (blue or green) was larger by touching a simple colored widget on the table. The two highlighted features were selected randomly from a set of 26 feature points. The surface area surrounding the first feature was colored green, the second blue, and the size differences were varied so that one of the features was always between 1.2 and 1.6 times as large as the other.

The quantitative results include the mean values for accuracy (96 percent) and time taken to complete each task (45 seconds). Table 1 breaks down these measures further to include the means and standard deviations across the three ratios used for the differences between the size of the feature points.

We also obtained valuable qualitative feedback from the design study. 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 points. 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. Once found, each target point was interrogated in more detail by modifying the view plane to view the target with an optimal orientation and scale. Users also rapidly jumped between the two target points multiple times to facilitate size comparison.

TABLE 1
Summary of Design Study Performance Data

Measure	Size Ratio	Mean	SD
Time Taken (seconds)	Size Ratio 1:1.6	37.41	26.26
	Size Ratio 1:1.4	44.05	29.00
	Size Ratio 1:1.2	53.49	38.39
Accuracy	Size Ratio 1:1.6	1.00	0.00
	Size Ratio 1:1.4	0.95	0.09
	Size Ratio 1:1.2	0.93	0.10

In exit questionnaires, 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. When asked what they would like to change about the interface, we received several comments related to improving the ergonomics of 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 (e.g., a clear physical widget placed on the table) 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. (Following this feedback, we implemented the WIM locking and return-to-home-position features described earlier.)

In the future, we are keen to conduct comparative studies of Slice WIM with alternative visualization methods; however, we recognize that the design of such a series of studies is a major research effort. One of the reasons is that, when compared to tools used in current practice, such as the popular Mimics software [1], Interactive Slice WIM is a new system and way of working that combines several novel strategies (multitouch input mapping 2D to 3D space, head-tracked stereoscopic viewing, and volumetric WIM techniques). As described below, our application users have found the distinction (and potential advantage) of this new approach to be obvious as compared to their current practice. Thus, our evaluations have focused primarily on qualitative comparisons with current practice. For future studies, our recommendation is that the most interesting quantitative insights regarding the interface and visualization techniques that make up Interactive Slice

WIM are likely to come from a series of studies designed to evaluate the relative importance of specific features (e.g., multitouch input mapping 2D to 3D space, head-tracked stereoscopic viewing, volumetric WIM techniques) in different contexts (e.g., single-user mode, collaborative mode). The task used in our preliminary study may provide a useful starting point for this challenging and exciting future work.

7.2 Feedback from Application Users

We have worked closely with engineers and scientists working in the area of medical device engineering to review the design of the tool as it has progressed and to better understand its potential to impact this domain. Several design decisions come as a direct result of this feedback. Most importantly, the emphasis in the new work reported in this paper on moving beyond navigation to also support interrogating data is reflective of the needs of medical device engineers. In early stages of medical device design, estimation is often used (e.g., estimating distances, estimating forces), however, it is important to relate these estimates to realistic conditions, such as anatomical data collected from medical imaging. Interactive Slice WIM facilitates this because it makes it possible to very quickly navigate through data and take precise measurements. Currently, the measurement strategies include a 3D ruler, a curve tool, and a volume tool that follows a curve, however, we believe many other extensions (e.g., fitting nurbs surfaces to anatomical features) are also possible via this framework. Moving beyond estimation, we are also excited by the potential to explore custom physiologically accurate simulations, such as in the application described earlier, which capture features at a level of complexity that is difficult or impossible to view via more traditional desktop-based visualizations. Thus, we envision that interfaces in this style can be useful not just as visualization spaces, but also as interactive design tools.

8 Discussion

This section discusses additional design decisions.

8.1 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 multitouch input to interact with a 3D WIM.

8.2 Hardware and Ergonomic Considerations

It is possible that many of the Interactive Slice WIM techniques could generalize to other hardware configurations; however, there are several aspects of the current hardware configuration that make it particularly well suited to the technique. One alternative that could be considered is to replace the large tabletop surface and move the input to a handheld tablet. This might have the advantage of enabling the user to walk around a large 3D display, such as a Cave or to sit down in a chair. A disadvantage would be a loss of screen size, limiting the effectiveness of techniques, such as the multiple persistent slices, which require room on the table to organize data views. A second likely disadvantage is that the shadow metaphor may be less effective in a mobile environment where the touch surface is not fixed in a physical horizontal orientation.

Although the current hardware is limited to a single head-tracked view, we have held numerous successful multiuser sessions and discussions with four or more participants standing around to table. As a result, we now believe these collaborative scenarios will emerge as one of the most important use cases for Interactive Slice WIM. In these scenarios, users typically stand around the table, but in other use cases, it may be preferable to sit on stools around the table.

As with any visualization technique developed for multisurface display hardware, there is potential that the user's attention may be divided between the two displays in a way that negatively impacts his workflow. Building upon the recent successes of multiple coordinated view visualization techniques in 2D environments (see Related Work), we believe similar strategies can make a major impact in improving VR workflows. The challenge in VR is determining the right interface for integrating complementary (often 2D or slice-based) information with traditional VR displays. In this regard, we consider the addition of a second table display surface as a potentially extremely valuable addition to VR hardware. As in traditional VR techniques that make use of virtual toolbelts, hand-held palettes, or menus floating in space, the table display requires users to look away from the primary 3D subject in order to access additional information; however, we have observed that users often fluidly change focus between the 2D and 3D views even as they are performing interactions, such as the fluid flow selection interface built on multiple persistent slices. Thus, we believe this multidisplay framework can fit naturally into many workflows.

8.3 Perceptual Considerations

Another result from the design study was the finding that users felt uncomfortable when the miniature world appeared too close to their eyes. This can create a problem, since when users push the miniature world away, this also moves 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.

9 Conclusion

We have presented Interactive Slice WIM, a multisurface, multitouch interface for overview+detail navigation and interrogation of scientific volume data sets in virtual reality. Interactive Slice WIM extends successful desktop-based overview+detail visualization strategies (e.g., multiple linked 2D and 3D views) and the successful VR WIM metaphor to semi-immersive interactive visualizations of scientific data. Adding an ability to specify 3D points, curves, and volumes and extending the concept of interactive slices to support multiple persistent slice interaction spaces on the table surface provides many new possibilities for querying and exploring volume data. In the future, we are excited by the potential to expand upon these techniques as well as the new VR applications presented in this paper, specifically with the goal of providing not just a views of data, but also new interactive engineering workflows.

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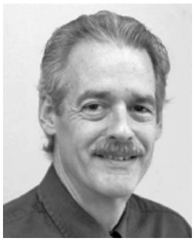

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