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HyFinBall: A Two-Handed, Hybrid 2D/3D Desktop VR Interface for Multi-Dimensional Visualization

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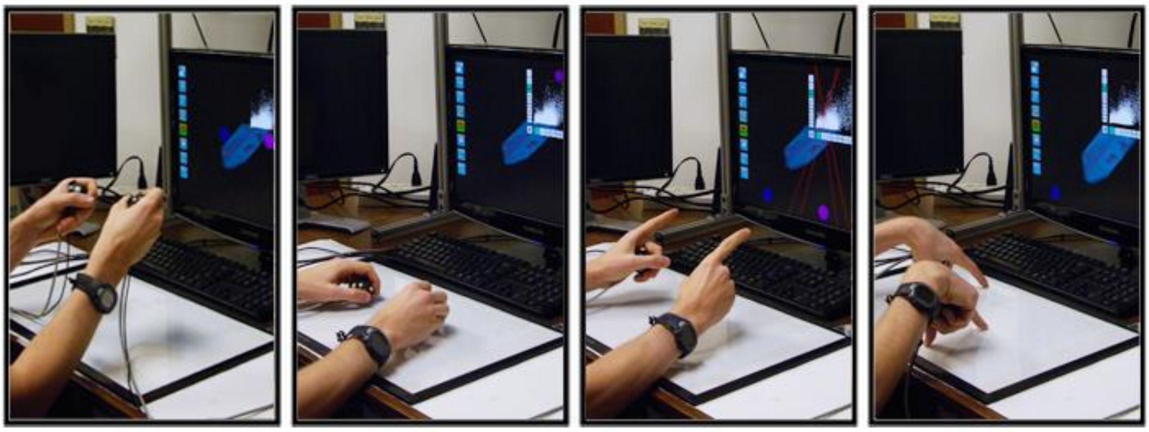
ABSTRACT

This paper presents the concept, working prototype and design space of a two-handed, hybrid spatial user interface for minimally immersive desktop VR targeted at multi-dimensional visualizations. The user interface supports dual button balls (6DOF isotonic controllers with multiple buttons) which automatically switch between 6DOF mode (xyz + yaw,pitch,roll) and planar-3DOF mode (xy + yaw) upon contacting the desktop. The mode switch automatically switches a button ball's visual representation between a 3D cursor and a mouse-like 2D cursor while also switching the available user interaction techniques (ITs) between 3D and 2D ITs. Further, the small form factor of the button ball allows the user to engage in 2D multi-touch or 3D gestures without releasing and re-acquiring the device. We call the device and hybrid interface the HyFinBall interface which is an abbreviation for 'Hybrid Finger Ball.' We describe the user interface (hardware and software), the design space, as well as preliminary results of a formal user study. This is done in the context of a rich, visual analytics interface containing coordinated views with 2D and 3D visualizations and interactions

Keywords: stereoscopic display, virtual reality, user interface, two-handed interface, hybrid user interface, multi-touch, gesture, finger-tracking

1. INTRODUCTION



(A) (B) (C) (D)

Figure 1: The HyFinBall UI supports 6DOF isotonic input (A), planar-3DOF input (B), 3D hand and finger tracking and gesture (C) and multi-touch (D). Note, the horizontal, multi-touch display is projected and disabled in this image, but see Figure 2.

The ubiquitous Windows-Icon-Menu-Pointer (WIMP) user interface and its 2D mouse user interface techniques began with Xerox Parc's and other's seminal work. Similar to 2D interaction techniques (ITs [1]), 3D ITs often require physical devices (e.g. ChordGloves or pinch gloves [2], a bat [3], Cubic Mouse [4]) to provide a full six degrees of freedom (DOF) interaction. Furthermore, HCI research has explored direct inputs by human modalities, such as voice, gaze, and gestures, for more natural ITs than those offered by physical input devices. Researchers have placed a particular emphasis on the study of natural human hand modalities like multi-touch direct input, and 3D hand gestures. These techniques allow direct user interactions with minimal learning.

In this paper we present a minimally immersive, desktop VR [5] interface for a visual analytic application that provides two-handed bat (3D mouse) input, two-handed 2D mouse input, multi-touch and 3D gesture. The primary devices are two 6DOF button balls. We used these previously [6], borrowing from the bat, the FingerBall [7], and the button-enhanced bat [8]. This paper presents the HyFinBall ("hybrid-finger-ball") user interface described below:

- **HyFinBall**: The HyFinBall interface starts with a pair 6DOF tracked balls with multiple buttons. Each ball is 4.5 cm in diameter roughly the size of a ping-pong ball. The software user interface has the following properties. When a button ball is held in the air (Figure 1A), a 3D cursor is displayed and 6DOF (xyz+yaw,pitch,roll) interactions are active. When a button ball is placed on the desktop, the UI automatically switches from treating button ball as 6DOF isotonic device to treating it as a planar-3DOF input device (xy-position + yaw) and the 3D cursor is replaced by a 2D cursor in the plane of the screen. Each button ball independently switches between a 6DOF and planar-3DOF mode. During this switch, the user interface techniques available for the button ball switch from 3D ITs to 2D ITs. There is a translational offset between the physical location of the HyFinBall and its displayed 2D and 3D cursors. 6DOF mode uses an elbow-resting posture [8] while planar-3DOF mode uses a palm-resting posture. Strong consideration is given to stereoscopic display issues in the desktop VR environment when displaying the cursors. In particular, certain planar-3DOF ITs use projected 3D cursors.
- **HyFinBall + Finger-Tracking**: The HyFinBall is small enough to hold in a precision grasp [7] and small enough to be held with only the pinky, ring finger and palm in an average adult hand. This leaves the thumb, forefinger and (possibly) middle finger free. The free fingers can either:

  interact on a horizontal 2D, multi-touch desktop display

  OR

  perform three finger 3D interaction and gestures when in 6DOF mode.

  By design, these 2D and 3D finger-tracking modes can be engaged without incurring an acquisition time penalty, i.e. the user does not drop and pick-up the button ball to engage and disengage these finger interaction modes.

The concept of using a single device that switches automatically between 6DOF mode and planar 3DOF mode, while not new (such the VideoMouse [9], and Logitech 2D/6D Mouse [10]) has not, to our knowledge, been integrated into any rich application that requires both 3D interaction and 2D interaction across coordinated views. The design space implied by the HyFinBall interface has not been explored with respect to desktop VR environments (in particular its stereoscopic 3D component) and this type of interface been not been studied for one-handed UIs, let alone two-handed UIs. To our knowledge, there has been no demonstration of a hybrid user interface (HUI) where the user uses a small form factor 6DOF held-device with a precision grip that can be continuously held while allowing the free fingers can engage in 2D multi-touch and/or 3D gesture interaction.

A user study is in progress focusing on the core HyFinBall concept comparing it to a mouse, the planar-3DOF-only mode and 6DOF-only mode across a variety of 2D and 3D combination tasks. In this paper, we present the HyFinBall and HyFinBall+Finger-Tracking concept and prototype (hardware and software). We present our anecdotal observations and describe the design space of the resulting hybrid interaction techniques. Finally, we present some preliminary findings of the aforementioned user study. This is done in the context of a rich, visual analytics interface containing coordinated views with 2D and 3D visualizations and with strong consideration of stereoscopic display issues in desktop VR.

2. BACKGROUND AND RELATED WORK

Many researchers have introduced 3D UI techniques for VEs. Bowman et al. [1] conducted many of the most recent, broad reviews of 3D UIs and ITs and have reviewed and evaluated a number of 2D and 3D ITs. They also have identified specifications of ITs that will improve the usability of 3D interactions in real-world applications and have proposed guidelines for future ITs [11]. Liu et al. explored modern ITs for 3D desktop personal computers (PCs) [12]. A number of other articles also include review of physical input devices for 3D UIs [13,14], and ITs for large displays [15].

Bimanual interaction enriches interaction because humans often use two hands to accomplish tasks in the real world. A significant amount of research shows the advantages of bimanual interactions [16,17,18] based on Guiard's Kinetic Chain theory that classifies different categories of bimanual actions [19].

Several taxonomy's of spatial input technologies (hardware) [20] have been created as well as taxonomies of 3D spatial user interaction techniques (software) [21]. Here, we use the following coarse categorization of spatial input hardware:

- 2D vs. 3D input
- held-devices vs. body-tracking

Our operational definitions are as follows. A 2D input device only tracks within a physical plane. 3D input tracks motion in 3-dimensions (at least 3DOF position and up to 6DOF). Held-devices are spatial input devices held by the user, while body-tracking tracks the body (such as hands and fingers). Body-tracking never requires the user to grasp a prop, but it may require some encumbering mechanism (gloves, fiducial markers, etc.).

A traditional mouse is a 2D held-device with 2 position DOFs. A 2D mouse with the ability to yaw perpendicular to the motion plane [21] is referred to here as a planar-3DOF device. Multi-touch is a body-tracking, 2D input with roughly 20 DOFs (10 fingers $\times$ 2 position DOFs). VIDEOPLACE was an early body-tracked 2D interface [22]. Notably the user was completely unencumbered (i.e. requiring no worn apparatus of any kind, not even fiducial markers).

3D input interacts in a 3D space. The bat [3] is an isotonic, 3D held-device with 6DOF pose (position and orientation). A bending-sensing data glove with a 6DOF tracker attached is categorized as 3D body-tracking , not a held-device. The ideal implementation of body-tracking, of course, is a completely unencumbered system. Wang et al [23]demonstrate unencumbered hand plus finger-tracking. Our operational definition of body-tracking treats encumbered and unencumbered implementations as sub-categories.

Various researchers have demonstrated [7,24,25] that having a 3D held-device grasped in the hand is beneficial due to the tactile feedback (passive haptics) it provides for 3D manipulation. Such feedback does not exist in hand or finger-tracked 3D UIs, but does exist in 2D multi-touch UI's or 3D systems augmented with haptics.

When considering a held input device, a device is held in either a precision grasp or power grasp. For some applications, such as a VR system for training a user to use a real-world tool, a power grasped prop is ideal—assuming the real-world tool requires a power-grasp. However, a precision grip allows finer control due the larger "bandwidth of the fingers". Physically the HyFinBall device follows Zhai et al.'s FingerBall which had a single button activated by squeezing [7]. Our HyFinBall interface uses multiple buttons and is two-handed following Shaw and Green [8]. (We use these button balls in Ulinski et al. [6] but that system does not contain any of the HyFinBall hybrid UI concepts). As a general purpose input device for desktop VR applications, we follow the above authors and promote using a pair of generic shaped devices that remain in the user's hands for relatively long durations to minimize device acquisition time penalties. This is opposed to using multiple, specially shaped 3D held-devices that must be put down and picked up repeatedly. We suggest that for data visualization applications (as opposed to VR training applications) a pair of generic devices (or perhaps a few devices of different but generic shapes [26]) will be superior.

Early tangible user interfaces [27] were 2D held-devices that were planar-3DOF. Tangible interfaces were unique in that the user had a multitude of different held-devices available on a horizontal display surface and the held-devices were untethered and required no power (an external camera tracks their 2D pose).

Most user interface devices and corresponding user interface techniques that provide spatial manipulation use either held-devices or body-tracking, but not both. There are some exceptions. For example, the touch mouse contains a multi-touch surface on the top of the mouse [28]. However, to our knowledge, there has been relatively little development and experimentation with user interfaces that support 2D and 3D held-devices while simultaneously enabling 2D/3D hand plus finger-tracking. The goal of the HyFinBall+Finger-Tracking interface is to explore this design space

Ideally the HyFinBall button ball would be untethered allowing full 360 degree rotations without an encumbering, entangling cord. Bradley and Roth demonstrate untethered computer vision tracking of a fist-sized ball [29], but occlusion remains a problem, especially for a two-handed scenario. Current battery and sensor technology still precludes constructing an accurate, small-form factor wireless 6DOF ball, but this area of engineering is very active [30]. Finally, non-isomorphic rotation techniques [1] can ameliorate cord entanglement during rotation operations.

Mapes and Moshel [2] use an HMD with 6DOF tracked pinch gloves and a physical surface at a 45 degree angle. A pair of 3D cursors is positioned roughly corresponding to the position of the user's hands. When the hands rest on the surface they are supported and the pair of pinch-gloves essentially acts like a pair of 3 button mice. However, the display of the 3D cursors remains the same regardless of hand position. In contrast, in the HyFinBall planar-3DOF mode, if the user rests the button ball on the desk it changes both the cursor display and the interaction techniques available. This difference is motivated in part, due to the display system difference, i.e. HMD in Mapes and Moshel vs. desktop VR here. In the HyFinBall planar-3DOF mode, the 2D cursors are within the plane of the vertical display screen while the button balls remain on the desktop surface. This is designed specifically to mimic mouse usage and to place the 2D cursors at zero-screen parallax to simplify stereo viewing issues when interacting with the 2D GUI elements.

The term hybrid user interface (HUI) refers to a UI with multiple methods for spatial input, frequently supporting both bimanual or unimanual interaction and 2D and 3D interaction. Benko et al. [31] combine a multi-touch 2D surface with hand and finger 3D gestures and 3D interaction in an augmented reality system. They coin the terms HUI and cross-dimensional gestures.

Some earlier devices support a similar notion of cross-dimensional interaction. The VideoMouse [9] and the Logitech 2D/6D Mouse [10] are a single device that support both 6DOF mode and planar-3DOF mode. However, in neither system was this concept extensively developed into a hybrid 2D/3D UI nor was two-handed interaction supported. The utility of confining the motion of 6DOF device to a physical plane, such as a held tablet, to reduce the physically manipulated DOF's has been demonstrated [1]. However, these prior works do not use a significant displacement between the physical device and its representative 2D or 3D cursor (as in [8]) and neither of these works' UI's implement the 6DOF to planar-3DOF mode switching found in the HyFinBall interface.

Massink et al. introduced HyNet, an HUI system for desktop-based navigation [32]. This work uses a traditional mouse for navigating the 3D world with a conventional desktop system. However, the system only uses 2D GUIs with 2D UIs and does not provide a solution for 3D visualizations and VE systems. The authors also introduce a programming abstraction for the HUI, with traditional desktop-based systems that used conventional mouse and keyboard inputs. The HUI addresses both theoretical abstraction and 3D input modalities.

Alencar et al. present HybridDesk that combines 2D and 3D interactions with a tracked Wiimote and WIMP interface for an oil platform visualization [33]. There are three UIs in HybridDesk used to evaluate their HUI techniques: VR-Nav for navigation and selection, VR-Manip for manipulation, and the traditional WIMP UI. More recently, Magic Desk [28] utilizes multi-touch input, a mouse, and a keyboard within a traditional desktop environment for unimanual and bimanual interactions. The authors explore suitable physical positions of multi-touch input relative to the user during the experiment. Althoff et al. present a multimodal interface for navigation in arbitrary virtual VRML worlds [34], which uses a mouse, keyboard, joystick, and multi-touch input. However, their environment was limited to 2D visualizations and 2D interactions. The Slice WIM interface, which uses a multi-touch table with a head-tracked, stereoscopic wall screen display for a medical imaging volumetric dataset [35], allows multi-touch interaction on the table to control 3D data using two widgets.

Multimodal user interfaces (MUI) generally use more than just spatial input; for instance they combine voice and gesture [36,37]. Bolt introduces a system called "put-that-there," which uses voice and gaze inputs [38]. Within GIS systems, voice and gaze inputs also are popular interaction methods in MUIs [39,40]. The main advantage of natural human input modes is that they do not require any held-device and users need less training.

HUIs and MUIs can be combined with augmented reality as well. ICARE is an example of such a mixed environment [41]. Bianchi et al. developed a hybrid AR system, which used a hybrid external optical tracker for the user's head pose and a subsequent visual landmark-based refinement of the pose estimation [42] that uses AR's overlaying of virtual objects on the user's real environment [43]. Other previous works include medical volumetric datasets designed for use by surgeons [44,45].

Many HUI and MUI systems incorporate hand-held, mobile devices. Song et al. introduce an application called what-you-see-is-what-you-feel that uses a mobile device for input and a wall-mounted display for medical imaging volumetric data visualization [46]. Users employ 2D multi-touch input on the handheld device to manipulate the 3D medical volume data on the large wall-mounted display through the wireless network.

Researchers also can use HUIs and MUIs in collaborative systems. Each user can handle a different system employing heterogeneous displays with various techniques to share the visualization or data with other colleagues. Schmalstieg et al. introduced a mixed reality environment that combines AR, ubiquitous computing, and a desktop metaphor for a collaborative system used with medical volume data [45].

3. THE HYFINBALL INTERFACE OVERVIEW

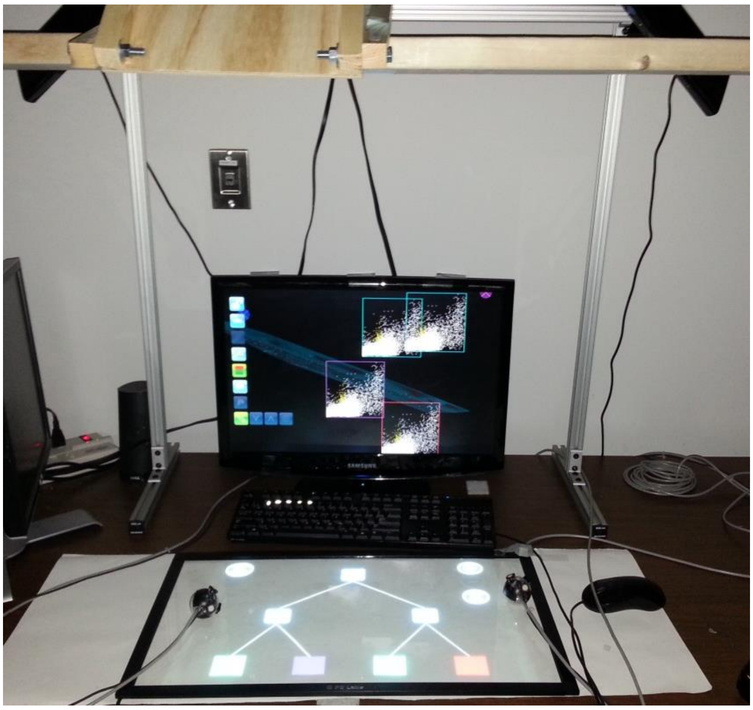
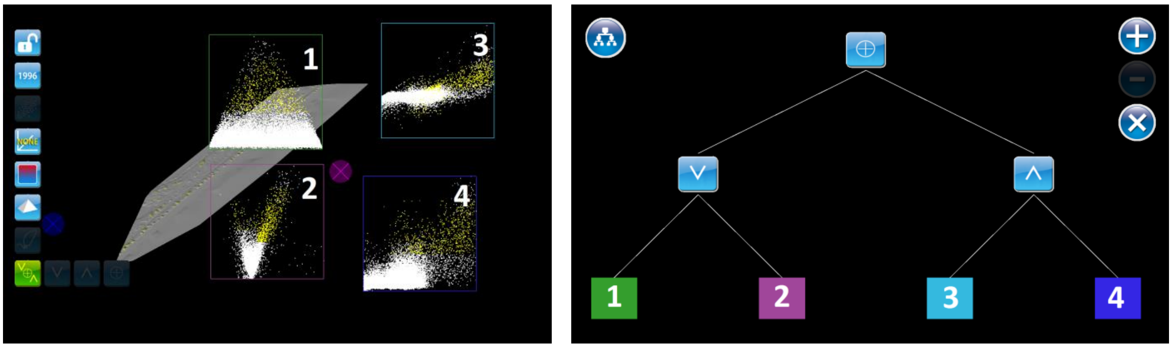


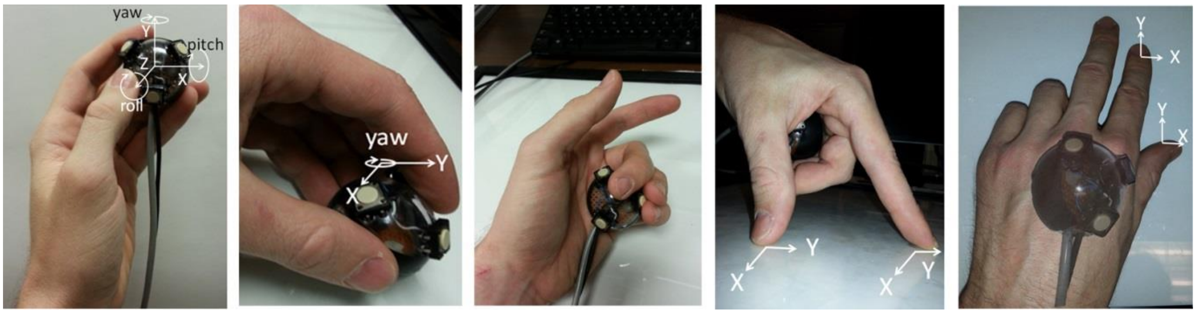
Figure 2: HyFinBall UI: Head-tracked stereoscopic vertical display, projected multi-touch table using PQLab's frame, dual button balls, and dual Kinects for 3D hand and finger-tracking.



(A) (B)

Figure 3: Scatter-plots with selected regions and interactive (A), and Boolean expression tree (B).

We present the HyFinBall UI in the context of a rich multi-dimensional application called DIEM-VR. DIEM-VR is a tool for analyzing terrain meshes from 10 years of LIDAR scans of the North Carolina Coast from the NOAA Digital Coast database. We extend a linked feature space interface from our prior work [47] that integrates multi-dimensional, feature space 2D views with 3D terrain views. In the HyFinBall system, the user sits at dual screen, desktop VR system. It uses Nvidia 3D vision glasses and a Polhemus Fastak for head-tracking and for tracking the HyFinBall devices. Two Windows Kinects view the desk space running 3Gear's finger-tracking software [48]. A PQ Labs multi-touch screen [49] is placed on the horizontal desktop with an overhead projector (Figure 2). A pure 2D display and direct 2D manipulation is performed on the multi-touch horizontal display while 3D content as well as limited 2D content appears on the vertical display. For the DIEM-VR application, the images in the vertical and horizontal screens in Figure 2 are reproduced as a screen captures Figure 3A and B. The vertical screen displays a 3D terrain patch as well as feature space 2D scatter plots. The horizontal display shows a interactive boolean expression tree that controls selection of terrain mesh points using a boolean combination of the highlighted selections in the 2D scatter plots.



(A) (B) (C) (D) (E)

Figure 4: Hand off table, 6DOF mode (A). Hand on table, planar-3DOF mode (B). Dual fingers 3D gesture (C). Fingers on table, multi-touch (side view) (D). Fingers on table, multi-touch (top x-ray view showing held and hidden button ball) (E).

As discussed in the introduction, the HyFinBall user-interface takes particular advantage of the small formfactor of the button ball to enable a number of 3D and 2D interactions paradigms without having to drop and reacquire the input device. In the DIEM-VR application 3D navigation and volumetric selection of the 3D terrain occurs using one or both of the button balls held in the air, but with the elbows resting. This 6DOF button ball interaction mode is shown in Figure 1A and Figure 4A. Next, interaction with 2D objects on the vertical screen, such as the scatter plots in DIEM-VR, occurs with one or both of the button balls placed on the desk surface (Figure 1B and Figure 4B) in which case planar-3DOF interaction mode is enabled. Third, when the user tucks the button ball in his palm (Figure 1D and Figure 4D and E), the free fingers such as the thumb and pointer finger interact with the 2D graphics on the horizontal display using multi-touch. In DIEM-VR, this multi-touch mode controls the Boolean expression tree mentioned earlier and elaborated upon in Section 4.4. Finally, although only experimentally implemented in our DIEM-VR application (due to tracking limitations), when the user tucks a button ball in his palm and makes 3D pointing gestures (Figure 1C and Figure 4C), 3D hand and finger tracking enables a ray-based 3D selection within DIEM-VR.

Before delving further into the how DIEM-VR leverages the HyFinBall interface, we mentioned a few caveats about the hardware setup. The PQLab's touch detection is robust and we integrate into the DIEM-VR Boolean expression display. We, however, anecdotally found the 3Gear 3D finger tracking and gesture recognition less robust in its current iteration. In particular, we find a relatively high-number of false negatives during gesture recognition and find it's tracking range more limited than that of the Fastrak used for the HyFinBalls. However, the 3Gear system is relatively new and these issues vary with the variety of ways the Kinect's can be physically arranged. Therefore, we have only loosely integrated a ray-based 3D selection in DIEM-VR using 3D pointing gestures.

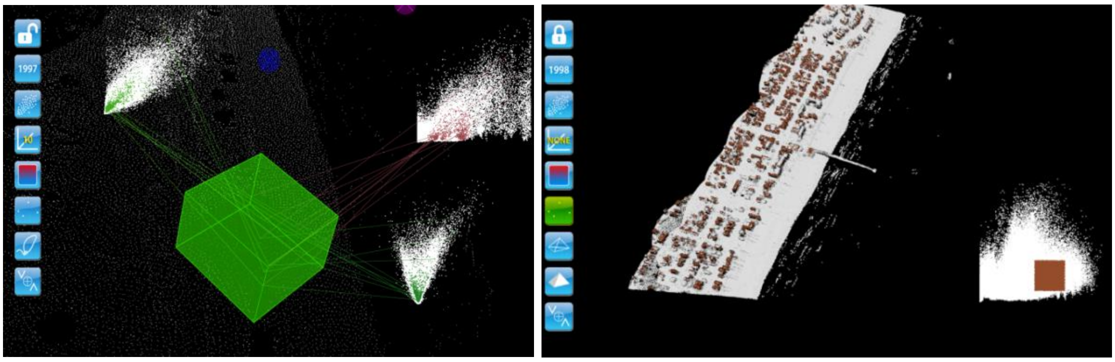
The touch surface is a PQLab 24" multi-touch frame lying horizontally on the desk. A projector projects an image down onto the surface. A projector is needed instead of a flat panel display because when the button balls are used in planar-3DOF mode a horizontal LCD panel would ruin the EM tracking. Ideally a rear projected horizontal display would be used to avoid shadows, but in practice in this top-down configuration, the hands tend to cast projector shadows over nearly the same areas that are occluded from the user's viewpoint.

4. HYFINBALL AND DIEM-VR DETAILS

This section discusses the details of the 6DOF, planar-3DOF, and finger-tracking interactions within DIEM-VR and how DIEM-VR demonstrates the 6DOF/3DOF auto-mode switch.

Shaw and Green [8] advocate adding a user adjusted translational offset between the 6DOF button device and the 3D cursor in their two-handed system. This allows the user to keep her elbows resting in her lap, or on the desk or chair arm to combat the common arm fatigue problems in VR interfaces. This offset is part of the 6DOF mode in our system. However, in our prior experimental work with two-handed 6DOF input [6] and in our formative evaluation of the presented HyFinBall interface, we found that while keeping elbows resting on a surface reduces fatigue compared to the naïve 'arm's outstretched' approach of early VR systems, this interface is still more fatiguing than using a mouse. With a mouse, the hand and palm--not just the elbow--rests on a surface. Rich data visualizations involve coordinated views of both 2D and 3D components such as in DIEM-VR. Therefore we developed the HyFinBall UI with auto-mode switching between 6DOF and planar-3DOF mode to allow the user to perform one (or two-handed) 3D interactions as well as 2D interactions with the vertical screen while keeping her palm(s) resting on the desk. As we shall explain, in DIEM-VR the 2D scatter plots are intimately tied to the 3D terrain therefore we present these 2D elements on the vertical screen with the 3D terrain while the purely 2D Boolean expression tree remains on the horizontal multi-touch surface. This is a general concept of the HyFinBall UI: pure 2D interactions occur on the horizontal display while 3D interactive graphics and, any 2D interactive graphics intimately tied to the 3D graphics appear on the vertical display.

On the vertical screen, DIEM-VR displays a single patch of terrain which can be optionally color-coded by height or displayed as a wireframe mesh or point-cloud. A series of 2D menu buttons appears on the left of the primary screen. These implement a horizontal, pull-“right” menu. All 2D menu items are displayed at zero screen parallax. The user can add and delete multiple scatter-plots whose plot points each correspond to a terrain point. Each plot point's x-y location is determined by a geometric characteristic of the associated terrain point such as the terrain point's average local slope, local degree of roughness, etc. In other words, each original terrain point has several additional geometric characteristics associated with it and by creating scatter-plots along these dimensions, the user can view the terrain in a different feature space such as plotting local roughness versus elevation. The scatter-plots are constrained to the zero-parallax plane.



(A) (B)

Figure 5: Points selection (A) 3D selection box of terrain as point cloud (B) Selection of LIDAR points in scatter-plot highlights house roofs.

4.1 6DOF 3D Cursors

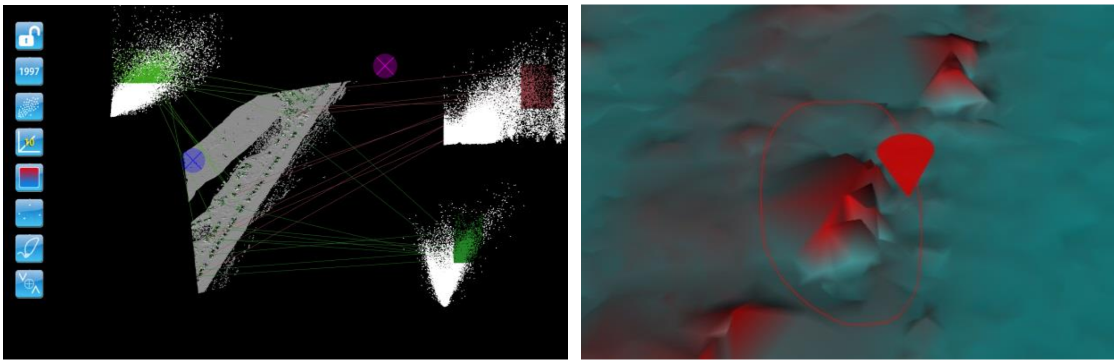
In its 6DOF mode, the left HyFinBall implements a scene-in-hand metaphor [3] for camera pose manipulation plus separate 3D cursor centered view scaling [50]. In 6DOF mode the left HyFinBall’s virtual representation is a transparent, blue sphere with a user adjustable translational offset [8]. When the left HyFinBall is placed on the desk, planar-3DOF mode is enabled. Now, the HyFinBall’s cursor is replaced by a transparent, 2D blue disc that always remains at zero screen parallax. This cursor interacts like a standard 2D mouse cursor for selecting the menu bar on the left. From our anecdotal observation and several pilot study participants, in the stereo display the switch from the 3D sphere cursor to the 2D disc cursor is immediately apparent.

The right HyFinBall’s 6DOF mode’s 3D cursor is a transparent, orange sphere with a user adjustable translational offset. This 3D cursor implements and initiates 3D selection box creation (Figure 5A). The selection box is used to select points on the 3D terrain. LIDAR scans have multiple returns and are hence multi-planar (not strict height-fields). There are situations where one may want to select points not only within a certain foot-print but also within a limited height range. For example, the user might want to select tree top returns and not the lower layer returns from the underlying ground. While selection in these situations is not as complicated as selection within true volumetric data [51], we provide a general 3D selection box interface. Further, this general capability for volume selection will be necessary when integrating true volumetric data into the terrain systems as we did in [51]. The 3D selection box can be created, moved, rotated and resized using a technique that is a combination of the two-handed technique of Ulinski et al. [6] and a 3D widget [11].

4.2 Planar-3DOF 2D Cursors

When the right HyFinBall is placed on the desk, the 3D cursor is replaced by a transparent, 2D orange disc that remains at zero screen parallax. In this mode, the orange disc acts like a 2D mouse cursor for interacting with any created scatter-plots. When a 2D cursor hovers over a scatter-plot boundary, icons along the x or y axes appear allowing selection of the statistic that will be plotted on the given axis. Various statistics such as average gradient, maximum gradient, local standard deviation can be selected. The user can move the plot or switch the plot data axis using a button, Button A. The user can select a rectangular region of scatter plot points with Button B. With the 2D cursor, the user can brush points in the scatter-plot. Brushing occurs by creating a rectangular selection region. The selected points are highlighted on the terrain surface using a color pre-assigned to the scatter-plot. In Figure 5B, the scatter-plot in the lower-left plots elevation versus local gradient. The brown selection region is selecting for relatively low elevations with minimal gradient. This causes mostly house roofs to be highlighted in the terrain view.

The user can optionally enable the display of lines connecting the scatter-plot points and the terrain points. This gives a strong visual impression of how the brushed scatter-plot points are spatially distributed on the terrain. (For performance, only a randomly chosen subset of the connecting lines is drawn). Understanding the spatial structure of this “line net” is greatly enhanced by the stereoscopic display. It has some conceptual similarities with traditional 2D parallel coordinates. Figure 6A shows three scatter-plots with line nets connecting their brushed regions to the terrain points. These line nets intimately visually tie the 2D scatter-plots to the 3D terrain and hence keeping these 2D graphics on the same vertical display as the 3D terrain is important.



(A) (B)

Figure 6: Point-cloud rendering of terrain patch and interactive, coordinated scatter-plot representations of LIDAR points (A), and 2D Lasso Selection (B)

We assume that during above described 2D interactions with the 2D menu or scatter plots that the user’s eyes fixate on geometry with zero parallax and that the user is not attempting to fixate on geometry with non-zero parallax. (The latter is the condition under which the naïve display of desktop 2D cursor in a stereo 3D system creates problems). Our anecdotal experience indicates this is the case, but future experimentation using an eye tracker is needed. We render the 2D cursors as slightly transparent discs so the user can see through them to any farther 3D geometry. In Figure 6A the left buttonball disc is transparent blue and the right is purple.

When displaying these 2D cursors, we automatically reduce the eye separation. If one HyFinBall is in planar-3DOF mode and is performing 2D interaction, then the modeled eye separation is cut in half. If both HyFinBalls are in planar-3DOF mode and performing 2D interactions, eye separation is set to zero. The eye separation changes are animated over a 2s time period recommended by Ware et al [52]. This reduction is again predicated on the assumption that if the user enters planar-3DOF mode they are interacting with the 2D zero-parallax objects and hence fixating at the zero-parallax depth.

We also experimented with enabling a simulation of depth-of-field image blur of the 3D geometry during planar-3DOF 2D interactions. The design space includes the presence/absence of the enabling of depth-of-field simulation and the tradeoff between the fidelity of the depth-of-field rendering and its reduction on frame-rate.

Overall design space issues include presence/absence of the eye separation adjustment, the degree of adjustment, the rate of adjustment, the conditions of adjustment and interaction with depth-of-field implementation. In general, our anecdotal results indicate eye separation reduction is useful when the user is performing planar-3DOF 2D interactions.

4.3 Planar-3DOF Projected Cursors

In its planar-3DOF mode, the right HyFinBall can also be used for 2D lasso selection of the terrain points. In this mode, the orange disc is replaced by a different 3D cursor whose 3D position is the intersection of a ray cast from the cyclopean eye through the 2D cursor's computed position on the frustum projection window. In prior work, we used a similar technique where we replaced the display of the desktop 2D mouse cursor with projected 3D cursor. This enabled a mouse controlled travel technique option in our exo-centric, travel technique on stereoscopic virtual workbench [53]. The projected 3D cursor can appear at any screen parallax depending on the location of the intersected terrain under the GUI cursor position. This approach is sometimes referred as geometry-sliding [54].

We chose for the planar-3DOF mode to perform the lasso operation rather than using a 6DOF mode image-plane technique based on the hypothesis the latter would induce greater arm fatigue. During 2D lasso selection we assume the user is fixating on the terrain surface location under the 3D cursor so the eye separation is set to its default setting. Our anecdotal experience indicates this assumed fixation point is correct. An experimental evaluation with an eye tracker could confirm this. If the user needs to select a restricted height range, a 3D selection box can be created as described in Section 4.1.

Finally, there is an individual terrain triangle selection mode. In this mode the terrain triangle underneath the projected 2D cursor is selected and all other terrain triangles within a range of similar height values are also selected. As the 2D cursor is dragged this selection is continuously highlighted. (Other criteria for selecting 'similar' terrain polygons are, of course, possible).

All these terrain region selections and scatter-plot selections use brushing-and-linking across these coordinated views that are updated in real-time.

4.4 Multi-Touch and Finger-tracking

As discussed earlier, when the user tucks the button ball in his palm (Figure 1D and Figure 4D and E), the free fingers such as the thumb and pointer finger can interact with the horizontal multi-touch surface or trigger 3D gestures.

DIEM-VR uses the multi-touch display for the Boolean expression tree once the user creates multiple scatter plots and brushes different regions in each scatter plot. The Boolean expression combines the different selections in various ways to make a final selection where only the terrain points that satisfy the Boolean expression are highlighted in the terrain view. The horizontal multi-touch display shows the tree structure of the Boolean expression (visible in Figure 2 and reproduced in Figure 3B). For example, in Figure 3B, the Boolean expression shows a logical expression of (1 OR 2) XOR (3 AND 4). Numeric labels map elements of the expression to the scatter plot. The user can save the current expression by the (+) menu icon on the right top and an icon is added on the left top. Users can delete, select or modify prior saved expressions. All changes are immediately reflected in the terrain vertex highlighting, the line net display and the scatter plot highlighting.

We specifically chose to touch enable the horizontal display rather than the vertical one, to maintain a palms-resting posture during the multi-touch interaction rather than requiring an outstretched-arm posture that is known in VR to generate user complaints of shoulder fatigue. Further, within the DIEM-VR application the Boolean expression UI is a separate, purely 2D interface unlike the scatter-plots whose line-nets are visually tied to the 3D terrain. Therefore, the Boolean expression UI is highly suited to 2D interaction afforded by the horizontal multi-touch surface.

Again, we can demonstrate hand+finger-tracking while still holding the buttonball using 3Gears Kinect based tracking and we integrated a ray-based 3D selection in DIEM-VR using 3D pointing gestures. However, we found the current tracking range and error rate of the hand+finger-tracking to be prohibitively restrictive when trying to pilot test a user study that integrates them with the rest of the HyFinBall UI. For instance, the Polhemus's EM tracking of the HyFinBall's never drops out the way it can with the Kinect based tracking and the "error rate" of detecting mechanical button presses is essentially zero. This discrepancy led pilot test participants to want to use the buttonballs instead of 3D finger-tracking for any practical 3D user task such as object selection or manipulation. Nonetheless, because the concept of enabling 3D hand+finger tracking while still holding the buttonballs is at least demonstrable, we present it as part of the overall HyFinBall UI.

5. DESIGN MOTIVATIONS AND EMPIRCAL QUESTIONS

This section discusses several of the key design considerations and motivations for the HyFinBall interface and as well a number of interesting questions that will require empirical study. In an in-progress user study we are testing several of our design motivations as experimental hypothesis. It helps our discussion of these motivations and hypothesis if we briefly describe the conditions in our experiment. The study focuses only on the 6DOF and planar-3DOF combination. The four devices device conditions are:

I. the auto-switching HyFinBall UI
II. dual planar-3DOF mode only UI
III. dual 6DOF mode only UI

This comparison is done across a variety of 2D and 3D tasks in different sequential combinations. This study does not use the horizontal multi-touch display and the tasks involve 3D terrain manipulation and selection and 2D menu and scatter plot manipulation. The goal is to determine to what degree each of the four device conditions is better suited to pure 2D tasks, pure 3D tasks and to combination 2D and 3D tasks.

5.1 Fatigue – Elbows-Resting vs. Palms-Resting

As stated earlier, using the planar-3DOF mode for 2D interactions on the vertical display is motivated by the desire to avoid arm fatigue issues that would arise if the user had to instead use image-plane techniques with the 6DOF mode. Image-plane techniques would require hovering the 3D cursor over the image of the 2D menus or scatter plots to manipulate them. Our experiment tests this hypothesis by comparing user subjective reports of fatigue when doing purely 2D tasks using condition III, 6DOF image-plane techniques, and condition II, planar-3DOF mode. When the user task is a mix of 2D and 3D tasks, we also expect condition III to be more fatiguing than condition I, the auto-switching HyFinBall mode, because the auto-switching mode allows the 2D operations to be performed with resting palms. Of course, there is a trade-off with condition I, since the user must switch between a palm-resting posture and an elbow-only resting posture in order to switch between 2D and 3D operations.

The overall effectiveness of the 6DOF/planar-3DOF auto-switching will undoubtedly ultimately depend on the balance between the 2D and 3D interaction operations used in a given application and the temporal sequencing and durations of planar-3DOF interactions and 6DOF interactions. Our in-progress experiment is a first step in exploring this. Our anecdotal observations, indicate that users perform better and very much prefer condition I or III over II or IV when the task includes 3D navigation and 3D manipulation of a 3D selection box.

5.2 Auto-switching 2D and 3D cursors

Section 4 described how the HyFinBall UI uses 3D cursors and several types of 2D cursors within a stereoscopic environment. There has been a fair amount of prior work in desktop 2D GUI's regarding having the 2D image of the cursors change to indicate different application states or interaction modes. There has been interesting work in cursors for 3D selection such as Ware and Lowther's One-Eyed cursor [55]. Teather and Stuerzlinger compared 4 cursor selection techniques in a [56], and more recently Bruder et al [57] explore different offset techniques on a virtual workbench. The HyFinBall raises additional questions because the cursor automatically switches between a 6DOF 3D cursor, a 2D zero-parallax cursor, and a projected 3D cursor (as in HyFinBall 2D lasso mode).

5.3 Multi-Touch and Finger-Tracking

Our current implementation of the HyFinBall UI demonstrates the possibility of leveraging the buttonball form factor to allow multi-touch and hand+finger tracking interaction without dropping the device. The multi-touch UI is robust enough to consider formal user studies, but the tracking range limitations and 3D gesture error rates of the Kinect-based tracking still need improvement.

At the moment we can only speculate about design issues and questions that could be investigated with more robust 3D hand+finger tracking. If the 3D finger tracking and gesture recognition were as robust as the simpler EM tracking and buttons, it would be interesting to explore what interactions 3D are best performed with hand+finger tracking and what are best performed with the 6DOF buttonballs. Moehring and Froehlich performed a study using very robust and accurate hand and finger tracking (with Vicon [58] marked gloves) and compared this with a 6DOF held-device (a Flystick) for a series of 3D manipulation tasks [26]. Users preferred the naturalness of finger tracking. However, users of the Flystick performed significantly faster than "bare" finger tracking. Adding pinch-sensitive finger tracking improved task performance times to be within 10-20% of the Flystick condition. This suggests that manipulating a physical object (such as a buttonball) may prove advantageous for some 3D object manipulation tasks over 3D hand+finger tracking within our demonstrated HyFinBall interface. From a practical standpoint it is a bit challenging to test this because the systems that provide robust hand+finger tracking require wearing gloves or thimbles with fiducial markers which may make simultaneously handling a buttonball cumbersome.

6. CONCLUSION AND FUTURE WORK

This paper presents our two-handed hybrid user interface, HyFinBall, for interaction with rich, multi-dimensional visualizations that require coordinated 3D and 2D views in a semi-immersive VE. The HyFinBall concept is implemented within a specific visualization tool called DIEM-VR for analyzing terrain meshes. These interaction techniques can be used with not only geospatial data but also with other scientific or medical datasets such as volume datasets with 2D interactive transfer functions or feature spaces representations. Potentially more abstract, less physically based 5-dimensional datasets could be explored by separating the dimensions to into various linked 3D and 2D visualizations. We suggest the HyFinBall user interface could be a useful UI approach for multi-dimensional visualizations whose component data dimensions are each best visualized using a different display plus input hardware combination suggesting a cross-dimensional approach.

As described in the earlier section, a study is underway that compares the following: auto-switching HyFinBall UI, dual planar-3DOF mode, dual 6DOF mode and a single mouse. A participant performs a variety of 2D tasks, 3D tasks, and combination 2D followed by 3D tasks using DIEM-VR. The mouse mode uses projected 3D cursors for all 3D interactions and is our base-line condition. Our hypothesis is that after a training period, the auto-switching UI will perform better (faster) at the combined 2D+3D tasks than all other UIs and equal to the planar-3DOF only mode and mouse for 2D only tasks and equal to the 6DOF mode for 3D only tasks. We expect the 6DOF-only mode to be generally worse for 2D tasks and more fatiguing.

HyFinBall with multi-touch works robustly, but we have yet to formulate user studies. HyFinBall with 3D hand/finger tracking is not yet robust enough to formally evaluate. Future multi-Kinect configurations may solve the problems with gesture recognition error rate and limited tracking range. Alternatively robust marker based hand and finger tracking could be employed. We are currently adding a dual camera Vicon system to our hardware ensemble. We believe there is an interesting design space to be explored when combining the HyFinBall button balls with robust 3D finger tracking. Finally, based on the ALCOVE [59] and our work in [53], we are in the process of configuring our system into a more seamless L-shaped display that also displays stereo 3D on the horizontal surface. Several of the prior works mentioned in Section 2 have begun exploring stereo plus multi-touch, but to our knowledge prior work is limited.

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