

WYSIWYF: Exploring and Annotating Volume Data with a Tangible Handheld Device

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ABSTRACT

Visual exploration of volume data often requires the user to manipulate the orientation and position of a slicing plane in order to observe, annotate or measure its internal structures. Such operations, with its many degrees of freedom in 3D space, map poorly into interaction modalities afforded by mouse-keyboard interfaces or flat multi-touch displays alone. We addressed this problem using a *what-you-see-is-what-you-feel* (WYSIWYF) approach, which integrates the natural user interface of a multi-touch wall display with the untethered physical dexterity provided by a handheld device with multi-touch and 3D-tilt sensing capabilities. A slicing plane can be directly and intuitively manipulated at any desired position within the displayed volume data using a commonly available mobile device such as the iPod touch. 2D image slices can be transferred wirelessly to this small touch screen device, where a novel fast fat finger annotation technique (F³AT) is proposed to perform accurate and speedy contour drawings. Our user studies support the efficacy of our proposed visual exploration and annotation interaction designs.

Author Keywords

User interaction, volume data, data exploration, visual annotation, multi-touch, accelerometer, handheld devices.

ACM Classification Keywords

H.5.2 User Interfaces: [Interaction Styles]; I.3.6 Methodology and Techniques: [Interaction techniques].

INTRODUCTION

Technological advances in data acquisition and computational simulation have made the visualization of 3D volume data a common and integral part of many scientific disciplines. Examples include quantum chemistry

simulations [23], medical volume data [19], volumetric flow data [34], as well as large-scale galaxy structure simulations [13]. Since volume data has internal structures that could be highly complex, visualization and interaction methods are needed to accentuate occluded structures and their relationships.

Despite the immense research effort and progress in volume visualization techniques, interactions with such applications are still very much through mouse-keyboard controls, or relatively large and expensive virtual-reality apparatus such as the virtual workbench and haptic devices. In this paper, we describe our efforts in developing an affordable volume data visualization and interaction system that uses interaction devices that are widely available in the consumer market. Our system employs a standard upright multi-touch display, which can be a custom-made multi-touch display (as in our case, see Figure 1) or a multi-touch LCD display, together with a handheld device with multi-touch and 3D-tilt sensing capabilities, like the iPhone or iPod touch, for example. By combining the strengths of both devices into a seamless integrated system, we are able to provide direct and tangible manipulation of volume data in ways that are intuitive, efficient and easy to use.

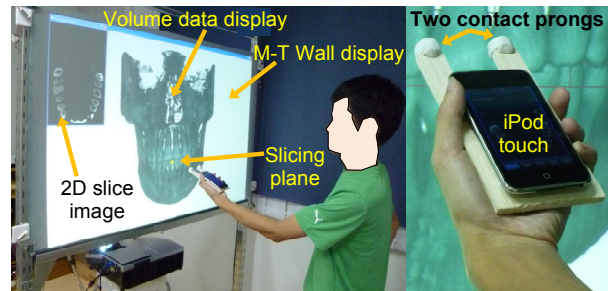


Figure 1. The WYSIWYF approach: the iPod touch in the user's hand provides natural control of a slicing plane against a reference 3D volume display on the multi-touch wall display.

To our knowledge, this is the first visualization system that fully integrates a commodity handheld device (with multi-touch and 3D-tilt sensing) and an upright multi-touch display to support direct and tangible exploration and annotation of volume data. We present several novel interaction methods that provide efficient exploration and annotation of volume data on this WYSIWYF system [37]. They are summarized as follows:

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- **Direct Tangible Volume Slicing.** Firstly, we propose using a tangible handheld device such as an iPod touch to slice the volume data displayed on the upright multi-touch screen. By directly touching the wall display with the handheld device, we can initialize a 3D slicing plane at the very locality of the touch. Using the tilt sensing capability of the iPod touch, we can also synchronize the slicing plane's orientation to that of the handheld device during the contact. In the same way, the slicing plane can be translated by directly sliding the device over the wall display, with the visible volume data acting as a useful reference image. Such direct manipulation provides an intuitive and efficient means to walk through various cross-sections in the volume data.
- **Remote Tangible Volume Slicing.** We extended the WYSIWYF design principle further to allow the user to remotely manipulate the slicing plane on the wall display. A combination of local fingers and tilt gestures on the handheld device allows near full 3D control of the slicing plane. Being able to move a distance away from the large multi-touch wall display helps alleviate the problems of limited viewing angle, hand occlusion and annoying pixilation artifacts (due to projector resolution).
- **Constrained Rotation of the Slicing Plane.** A unique feature implemented in our system is the ability to use the multi-touch capability of the handheld device to anchor carefully chosen point and line constraints about which the slicing plane can be rotated in 3D space. Such constrained rotation is helpful in simplifying the complex manipulation of a plane with many degrees of freedom.
- **Efficient Visual Annotation on Small Touch Screen.** Lastly, with the ability to transfer 2D sliced images to the small screen on the handheld device, users can draw simple visual annotations on these images and have these annotations transferred immediately back to the volume data visualization on the wall display. To support this feature, we proposed a novel technique for fast and accurate finger tracing of smooth continuous contours in a 2D image that is displayed on a small touch screen.

RELATED WORK

Interaction with Volume Data

According to Ratti et al. [24], interaction approaches for exploring 3D data sets can be classified as graphical interfaces, virtual reality interfaces, augmented reality interfaces, and tangible interfaces. Since this work relates more to the virtual reality and tangible aspects in this scheme, we review mainly these two categories:

Virtual reality approach. This approach focuses on immersing users in a virtual environment with the 3D volume data and optionally some 3D user interface elements and virtual simulation tools. To support the user

interaction, various virtual reality devices such as position or head tracking and stereoscopic viewing are required. Avila and Sobierajski [2] proposed a haptic interaction approach for volume visualization; they simulated a virtual tool by using the position and orientation provided by a haptic device. Szalavári and Gervautz [32] introduced the Personal Interaction Panel system consisting of a tracked simple clipboard and pen; this setup enables a natural two-handed interface for assorted applications. Aliakseyeu et al. [1] developed the Visual Interaction Platform (VIP) for navigation and manipulation of 2D and 3D data; it is an augmented reality platform for different natural interaction techniques. Subramanian et al. [31] employed this platform to show that hybrid 2D and 3D interfaces can offer better performance than 3D or 2D interfaces alone. Their work supports constrained rotation on 3D objects by inserting a virtual pin on the 2D workspace via a digital pen.

Unlike [1], we do not require a passive prop and its associated tracking system. Instead, we integrated various functionalities available on off-the-shelf handheld devices, such as the multi-touch screen and tilt-sensing, to perform volume data annotation and manipulation. Similar to [31], we also support constrained rotation of a slicing plane by direct specification of up to two rotation points, but we use touch inputs on handheld device's multi-touch display.

Tangible approach. Tangible interfaces seek to interact with virtual objects by manipulating tracked props in physical space. Hinckley et al. [15] proposed one of the first tangible 3D interfaces to support continuous clipping interaction in 3D space; it allows surgeons to use passive interface props to explore a patient's anatomy data by interactively generating cross-section views of the data.

Fröhlich et al. [10] built the Cubic Mouse system that embeds a six-degree-of-freedom tracker in a cube-shaped box; users can manipulate this tangible device to transform and slice 3D objects. Qi and Martens [22] investigated the problem of positioning a slicing plane within a volume data set by using a wooden cube and a pen/frame in physical space; tracked by a vision-based system, the wooden cube controls the volume data orientation and zoom factor while the pen/frame controls the orientation and position of the clipping plane. Bonanni et al. [5] proposed the Handsaw system to explore cross-sectional cuts in a volume data set, either by projecting a luminous line or by holding an outstretched hand at the desired cut location; related sectional information can be shown on an adjacent display. Couture et al. [7] designed the GeoTUI system, a tangible user interface specifically for geophysicists; it employed a tabletop vision-projection setup for the selection of cutting planes on the geographical data. Spindler et al. [29] developed the PaperLens system that tracks and projects on a sheet of paper in physical space over a tabletop surface; we can move the paper to navigate and slide a virtual 3D

data volume, and freely move and orientate the paper in a tangible manner.

The use of tracked props in existing works of this approach requires users to switch visual foci between the hand-manipulated tangible interface and the computer screen. Our use of a large interactive surface for both image display and user interaction with a tangible interface provides a single visual focus for both visualization and interaction, thus removing the stressful time-shared visual foveation. Moreover, the use of a computation-capable tangible device with a built-in multi-touch surface enables instantaneous transfer of desired 2D slice images for volume data annotation and portable take-away storage.

Tangible approach with handheld devices. Today, many consumer handheld devices come with built-in accelerometers to sense 3D tilting. These devices enable us to develop a low-cost system for volume data exploration. Gallo et al. [12] employed the Wiimote controller to manipulate and select 3D medical data with two system states: pointing state to use the Wiimote like a laser pointer, and manipulation state to use the Wiimote to rotate, translate and scale a 3D object. Zsaki [38] made use of a two-axis accelerometer as a tangible input to slice a given volume data set in a natural manner. Besides using the tangible device to slice volume data, the tangible interface in our system is able to receive and display the 2D sliced images. These reference images displayed on the handheld device are useful for supporting visual annotation as well as allowing users to locate and specify anchor point(s) for constrained point and line rotation of the slicing plane.

Handheld Devices and Large Displays

There are numerous works that involve interaction between handheld devices and an assortment of display systems.

Handheld devices as remote controllers. Similar to TV and VCR remote controllers, handheld devices equipped with multi-touch and 3D-tilt sensing capabilities can also serve as remote controllers for supporting user interaction with a co-located display system. Kela et al. [17] explored gesture commands with accelerometers in design studio setting to control devices such as TV and VCR, while Ballagas et al. [3] presented a structure of taxonomy to examine the interaction paradigm of using smart phones to control contents on a digital display. Later, Boring et al. [6] proposed and compared three different interaction methods, called scroll, tilt, and move, for using a mobile phone to continuously control a pointer on a large display. Dachsel and Buchholz [8] proposed the throw and tilt gestures on handheld devices to interact with a large display. Kim et al. [18] controlled the virtual navigation in a CAVE™ setup by using multi-touch on an iPhone/iPod touch. More recently, Katzakis and Hori [16] applied the accelerometer and magnetometer on smart phones to manipulate the rotation on 3D virtual objects.

Applications with handheld device interaction. Wilson and Sarin [36] developed an interactive surface called BlueTable; it can automatically connect to mobile devices, allowing us to conveniently transfer photos and show them on the table. Since mobile devices have higher visual and input resolution than local regions on large displays, Olwal and Feiner [20] suggested tracking mobile devices over large displays to take advantage of mobile devices to support better graphics and user interaction. Similarly, Volda et al. [33] proposed using an iPod to perform interactive lensing in focus+context visualization on a tabletop surface. Another application class that often integrates handheld/mobile devices and large displays is multi-player games. Shirazi et al. [28] designed and implemented the Poker Surface, which combines a multi-touch table and mobile phones for an interactive card game. Various natural interactions such as throwing, touching the table, tilting and shaking are explored in this work. Echter et al. [9] studied a new paradigm of multi-player game (using the Sudoku game) with public display on a tabletop and private display on one's own mobile phone.

Contacting handheld devices on upright displays. Directly touching a display with a mobile device as a form of interaction is a relatively new concept. Hardy and Rukzio [14] proposed using such a touch action to perform position selection, data picking or dropping over a large display. Schöning et al. [25] studied the authentication issue for this interaction scenario when using handheld devices to interact with a public multi-touch surface and proposed using the camera flash with an infra-red camera to identify the touch action. Steinicke et al. [30] explored the potential of using a multi-touch mobile device with stereoscopic displays.

Compared to these works, the main novelty of our work is the use of a direct touch contact between the handheld device and upright multi-touch display to enhance the control of the slicing plane during the exploration of the volume data. The convergence of these two types of interactive devices allows the design of useful interactive features such as the ability to initiate constrained slice plane rotation and fast visual annotation from a remote multi-touch display on the tangible interface.

SYSTEM SETUP

Our system setup consists of an iPod touch (tangible interface), a large vertical multi-touch wall display, a wireless router and a server PC (see Figure 2). Wireless connection with low-latency UDP is used to transmit sensor data and files between the iPod touch and server. The multi-touch wall display transmits touch information to the server through UDP over wired Ethernet link.

Multi-touch Wall Display and Tangible Device

This work employs a vision-based whiteboard-style multi-touch display system (see Figure 1). The interactive surface

uses the infrared laser light plane (LLP) emitters to detect the multiple finger contact points. For the tangible device, we used an iPod touch for rapid prototyping, and employed many of its built-in features, which include a 3-axis accelerometer, multi-touch screen, wireless network, and 3D graphics capability.

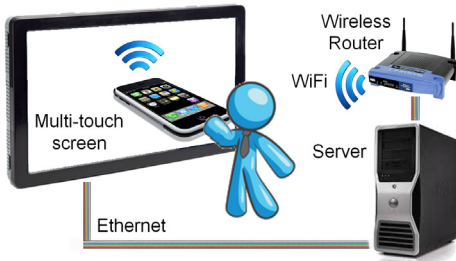


Figure 2. The system setup.

Server Program on Server PC

Our volumetric data visualization application uses the Visualization Toolkit (VTK) [26] to render the volume data. A small pop-up window on top-left of the screen shows sliced image as we manipulate the slicing plane, see Figure 1. An integrated interaction module receives and processes input data both from the multi-touch wall display and the remote handheld device. Wall display interaction-sensing is implemented as a thread, which records all multi-touch events and stores them in a linked-list data structure shared with the application thread. The iPod touch interaction-sensing is implemented as another thread that receives and processes user input from the mobile device, as well as sends 2D sliced image data to the device upon request.

Client Program on Handheld Device

The iPhone SDK is used to build a client program to sense the touch and tilt events, and transmit them to the server PC. At the same time, the client program also receives and displays the small-sized 2D sliced image received from the server program. Since the iPod touch is used for slicing plane manipulation and also visual annotation, the client program on the mobile device operates under three modes: *remote control*, *image manipulation* and *annotation*. In remote control mode, the device sends both accelerometer and multi-touch signals to the server for controlling the slicing plane. Moving-window low pass filtering is used on the device to reduce the jitter inherent in the accelerometer signal. 2D sliced images can be automatically loaded to the device when the tilt activation button (see Figure 4) is released. The image manipulation mode allows the 2D sliced image to be translated, rotated and scaled using simple finger gestures on the device's multi-touch screen. Finally, the annotation mode allows users to quickly draw outlines or contours on the 2D sliced image and to send their sketches back to the server PC for visualization.

VOLUME DATA EXPLORATION AND ANNOTATION

Our volume data exploration and annotation system integrates the natural user interface of a 2D interactive

multi-touch wall display with the physical 3D manipulative dexterity afforded by a handheld device with multi-touch and tilt sensing capabilities. In our usage configuration, the large multi-touch wall display is employed for general volume data visualization purposes. Its large screen format is amenable to group viewing, such as when a doctor is teaching human anatomy to a small group of medical students. Basic 3D data manipulation operations can be done on this display using finger gestures. The handheld device, e.g., an iPod touch, is used as a tangible interface that allows the user to interactively position a slicing plane, control its orientation, and perform visual annotations. The next section details the different groups of interaction designs involved in realizing this integrated system.

Volume Data Manipulation on Multi-touch Wall Display

For completeness, we briefly describe how the volume data is manipulated on the multi-touch wall display. These wall-display-based operations help set the reference of the volume data image to a convenient 3D orientation so that the user can begin to use the tangible handheld device to specify the desired slicing plane. Since the interactive surface is essentially 2D, a combination of single finger, two-finger and multiple-finger gestures are required to perform object-centered rotation, scaling, and translation operations, respectively, as summarized in Figures 3(a-c).

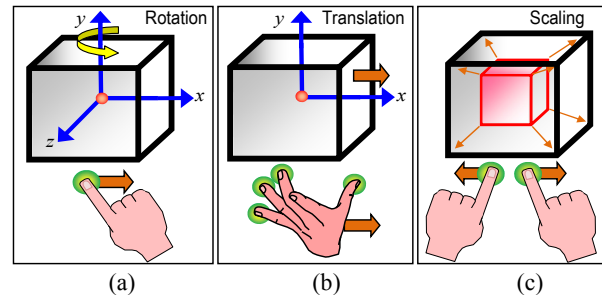


Figure 3. Basic volume data manipulation on the wall display. (a) Rotation about the data-centered origin using a one finger swipe gesture, (b) translation in the x and y directions using a 4-5 finger panning gesture, and (c) scaling using two-finger drag-in, drag-out or pinch (two fingers of one hand) gestures.

Volume Data Slicing

Visual exploration of volume data often requires a user to manipulate the position and orientation of a slicing plane in order to observe, annotate or measure internal structures within the 3D volume data. The flexible and direct manner by which this slicing plane can be manipulated would greatly enhance the exploratory power of the visualization system. The primary strength and novelty of our system is the combined use of a multi-touch wall display and a tangible tilt-aware interface. We describe novel and intuitive interaction design afforded by this system.

Positioning and rotating the slicing plane

Imagine being able to specify the slicing plane's position and orientation (on the x and y plane) by just drawing a line

over a volumetric display in front of you. This is exactly the type of direct manipulation afforded by our system. The physical contact between the mobile device and the volume data that is being visualized on the multi-touch display provides an intuitive way for a user to specify the initial position and orientation of a slicing plane within the 3D data. In order to enable a standard multi-touch wall display to detect the contact of the tangible device, we attached a simple wooden base to the iPod touch, thus providing it with two rounded protruding prongs (see Figures 1 and 4). These prongs allow the mobile device to contact the multi-touch display with a simulated two-finger touch gesture of fixed Euclidean spacing d , which the application has been calibrated to detect. The slicing plane's new position on the x - y plane can be specified by directly touching the wall display at any desired location with the mobile device (the z -axis position remains unchanged).

Once in contact with the wall display, the user can press the tilt activation button (see Figure 4) on the mobile device to inform the client program to continuously transmit tilt sensor data to the server. The orientation of the slicing plane can now be computed, and will follow the iPod touch as the device is rotated against the wall display. This way of controlling the slicing plane is intuitive and gives the user the sense that he is holding a physical slicer in his hand.

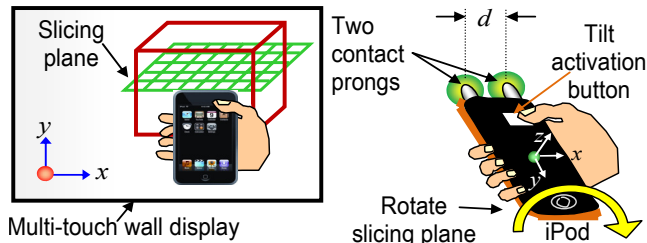


Figure 4. Position a slicing plane by touching the wall display with a modified two-prong contact (attached to the handheld device) and controlling x - y orientation of plane by pressing the tilt activation button and rotating iPod touch.

Translating the slicing plane

The slicing plane is a virtual window with boundary in the 3D space, corresponding to what is shown on the handheld device screen. The slicing plane can be translated either along its own coordinate axes (x' , y' , z') or the wall display coordinate axes (x , y , z). Incremental translation about the slicing plane coordinate system is more intuitive and has proven useful when there is a need to move the slicer to a precise position to acquire a 2D image slice for geometric measurements. Figure 5a shows how the multi-touch capability of the mobile device is used as a convenient remote interface for controlling the slicing plane translation. One finger gesture on the mobile device's multi-touch screen translates the slicer in x' - z' plane while two fingers moving gesture translates the slicer along the y' -axis. However, a more intuitive and speedy way to move the

slicer is by using direct manipulation of the iPod touch on the multi-touch wall display. Making two-pronged touch contact and moving the iPod touch along the wall display's x - y plane will translate the slicer on its x' - y' plane (see Figure 5b). The flexibility of our integrated system also provides users the option of positioning the slicing plane by translating the 3D volume data on the wall display using the panning gesture (see Figure 5c).

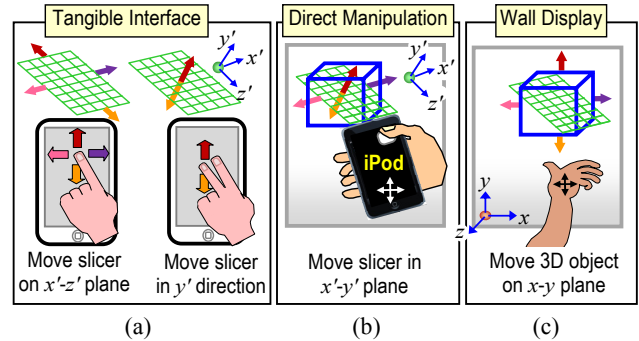


Figure 5. The translation of the slicing plane about its coordinate system can be done by (a) remotely using various finger gestures on the iPod touch and/or (b) sliding the iPod touch against the wall display. (c) Multi-touch manipulation of the wall display can be used to move the 3D volume data relative to the slicing plane.

Constrained rotation about slicing plane normal

The handheld device's 3-axis accelerometer is unable to detect rotation about the z -axis (see Figure 4) since no gravitational force change is experienced by the device's inertial sensor when it is held horizontally and facing up. In order to perform constrained rotation about the slicing plane normal, manipulation of the reference volume data on the wall display is needed. This is achieved when one finger is held stationary on the multi-touch surface while another finger moves. The direction of the moving finger determines clockwise or counterclockwise rotation.

Tangible constrained 3D rotation of slicing plane

The slicing plane's 3D orientation can be manipulated by performing corresponding tilt gestures on the handheld device, while the tilt activation button is being touched. The slicing plane in the virtual space will rotate in unison with the tangible interface, matching angle for angle, axis for axis. Unfortunately, a horizontally held iPod touch cannot detect rotations about its z -axis (see Figure 4) since no gravity changes occur. Thus, the slicing plane can only be rotated along the x and y axes. The constrained rotation of the 3D object about the slicing plane normal, which can be performed using finger gestures on the wall display (described earlier) can compensate for this limitation.

By default, the slicing plane will rotate around an anchor point located at the mid-point of the slicing plane's edge that is the closest to the iPod touch when contact was made with the wall display. A novel and powerful feature provided by our interaction design is highlighted in Figure

6, which shows a user trying to orientate the slicing plane such that it flushes and touches the sloping cut surface of a 3D cylindrical object. Due to the many axes of freedom in controlling the 3D orientation of a plane in free space, this is not an easy feat to achieve for a novice. By providing the ability to interactively shift the anchor point about which the constrained plane rotation can occur, this greatly simplifies the exploratory process required to tilt the slicer to the desired 3D orientation. Once the slicer has intersected a strategic position in the 3D object, the user merely needs to use the multi-touch screen on the iPod touch to visually move an anchor ball on the slicing plane to any desired 2D location on the plane. As far as we are aware, this is the first interactive volume visualization system that uses a single tangible device to provide tangible slicing plane manipulation and the ability to interactively shift the point of constrained rotation.

An additional feature of our interaction design is the ability to sequentially place (two) anchor points on the slicing plane, thereby allowing constrained rotation about a line. This is especially useful in the visualization of fabricated 3D machine parts where line geometry is prevalent. Once the slicing plane is in position and the relevant 2D slice image data is acquired, the next task that may be performed is visual annotation.

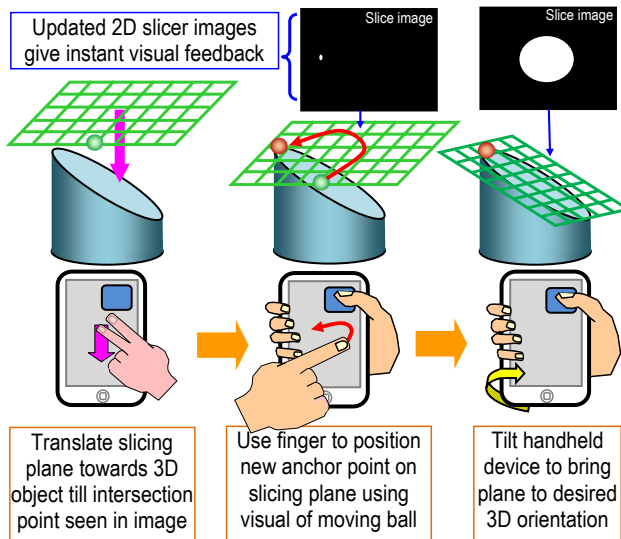


Figure 6. Easy manipulation of slicer to desired 3D orientation using a novel multi-touch technique for specifying an arbitrary point on the slicing plane, about which the constrained plane rotation can be performed. With one finger touching the tilt activate button, another finger from the other hand can be used to slide the anchor ball to a new location (orange ball) from its initial default location (green ball).

Volume Data Visual Annotation

The ability to visually annotate 3D volume data provides the user with a powerful tool to visualize and communicate structural relationships between embedded objects. Figure 7 illustrates an example where simple planar outlines

drawn on two teeth, one on the upper jaw and one on the lower jaw, can allow a dentist to quickly communicate to the patient why dental braces are needed to correct the teeth misalignment caused by malocclusion.

Releasing the tilt activation button on the iPod touch after manipulating the slicing plane will wirelessly transfer the 2D sliced image data. With the 2D image conveniently in the hand of the user, he can now perform the visual annotation operation remotely while seated comfortably away from the wall display. Tracing annotation outline over the slice image on a small multi-touch screen can be inaccurate and tedious. We next discuss the issues related to this problem and propose a novel technique to perform fast visual annotation on a small multi-touch screen.

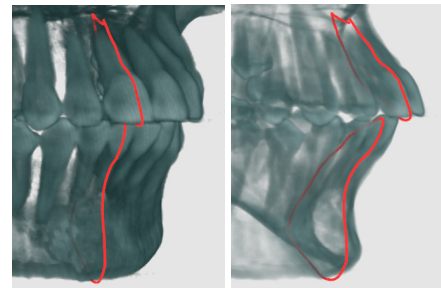


Figure 7. Examples of planar outline annotations showing the extent of malocclusions in a dental patient.

The fat finger problem

The fat finger problem [4, 21, 27, 35] is a well-known problem related to the difficulty to accurately locate a desired point on a touch display by using one's finger. Unlike a pen or stylus that has a sharp tip, the human finger is soft and compresses to a large blob-like contact point when pressed against a multi-touch surface. The centroid of this detected blob may not coincide with the point on the image where the user wishes to draw the desired outline. Using cross-hair visual feedback does not help because of the occlusion of the human finger over the visual area of interest. The two finger technique of Benko et al. [4] is not appropriate here since a single finger is needed to do boundary tracing. An interesting solution to the fat finger problem is *LucidTouch* by Wigdor et al. [35]. By sensing finger touches from behind the display and augmenting the screen visuals with point cursors and pseudo translucent shadow fingers, users can select accurate screen locations without finger occlusions. Unfortunately, this is not currently a solution on the ubiquitous iPhone or iPod touch.

In fact, the simplest way to alleviate this problem is to zoom up the visual region of interest so that the object boundary region where the outline is to be drawn is now of size commensurate to that of the human finger tip (see Figure 8a). However, this image zooming gives rise to another problem. In order to complete the outline drawing of the entire shape, the user has to go through many individual zoom-up sections of the image (see Figure 8b).

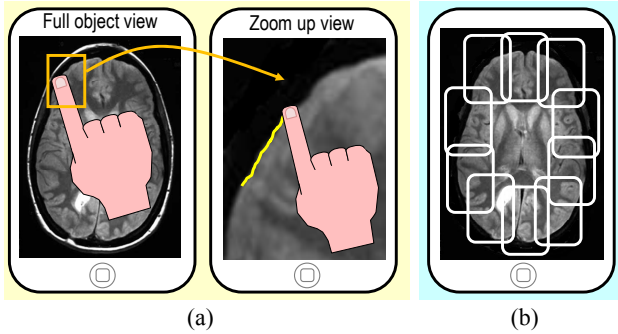


Figure 8. The fat finger problem. (a) Image zooming helps alleviate this problem. (b) But the object boundary is now spread over many overlapping image zoom-up segments.

Single finger down drawing

There are basically two interaction modes during visual annotation (see Figure 9a). The PAN mode allows the user to pan the image to reveal out-of-view regions that may require visual annotation. A thick green boundary around the image is used to indicate PAN mode. The DRAW mode allows the user to annotate by tracing an outline along the desired object boundary in the image. In this mode, the image remains stationary and a yellow line is drawn under the sliding finger. The DRAW mode is indicated by a thick red boundary around the image. The users can switch between the two modes by touching the thick red or green border with the same tracing finger (one-handed) or with the non-gripping thumb of the hand that is holding the handheld device (two-handed). Our user performance evaluation on the visual annotation task shown in Figure 12 revealed that the two-handed switching technique is on average about 28% less accurate and 15% slower than the one-handed technique. Moreover, some users complained that coordinating repeated PAN-DRAW switching using two hands was confusing and their finger that performs the mode switching sometimes occlude relevant image regions.

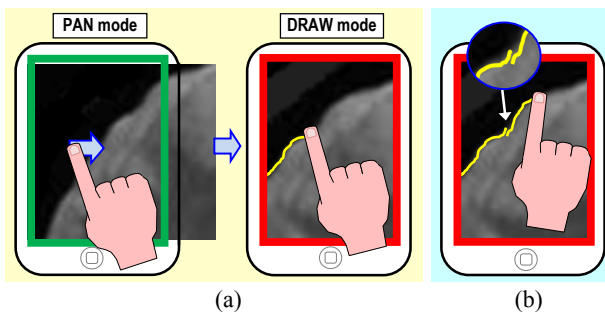


Figure 9. (a) The basic PAN and DRAW annotation modes. (b) Overlap and discontinuity in the outline when the finger is lifted up and placed down again to resume the drawing.

To address the fat finger problem, the complete outline to be drawn is now spread over many zoomed-up image sections. This requires the user to perform countless image panning and drawing actions thus switching between PAN and DRAW modes repeatedly. If the superior one-handed

technique is adopted, this requires the drawing finger to be lifted up to perform the switch between the PAN and DRAW modes. When the user removes his finger to switch mode and then places it back to continue the drawing from where he last stopped, overlaps and small discontinuities in the outline can result due to the inaccurate placement of the user's finger over the last drawn point (see Figure 9b).

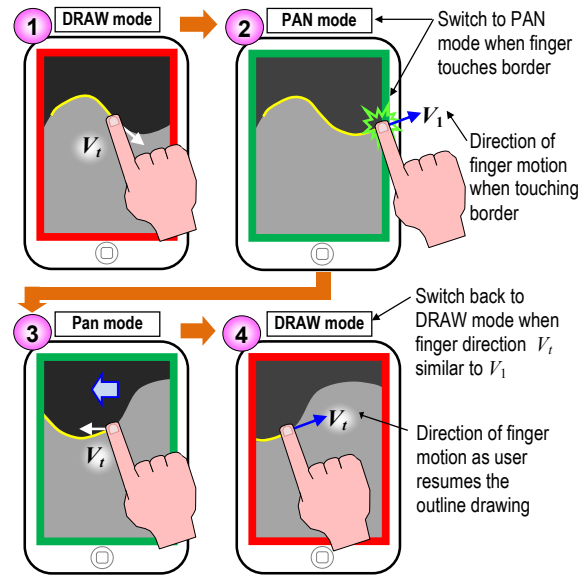


Figure 10. The basic steps in the Fast Fat Finger Annotation Technique (F³AT). Steps 1-4 are repeated until the entire contour along the boundary of the object is drawn or whenever the user decides the outlining is done.

The Fast Fat Finger Annotation Technique

We propose a novel technique called the Fast Fat Finger Annotation Technique (F³AT) to address this problem. The user normally starts annotation with an image view that displays the complete object boundary. When he touches the boundary area where he wishes to start the drawing, the image can automatically zoom up (to a resolution preset by the user) so that enough visual resolution is now available to avoid the fat finger inaccuracy when drawing. The image is now in DRAW mode. Figure 10 illustrates the various steps in using F³AT. One finger is used to trace the desired outline along the boundary (step 1) until it reaches the red border (step 2), where no more drawing can be done since the remaining boundary in the image is out of view. At this instant (when finger touches red border), the annotation mode automatically switches to PAN mode (step 2). The border changes its color to green, indicating to the user that he can freely pan the image in the opposite direction to the drawing direction to reveal more image boundary region to draw (step 3).

The main novelty in the proposed F³AT is the constant monitoring of the direction of finger movement during the image pan. As soon as the panning direction of the user's finger returns to the general drawing direction, given by the

vector V_1 in (step 2), DRAW mode resumes (step 4). The trigger for automatically switching back to DRAW mode determined by the dot product of two vectors given by

$$V_1 \cdot V_t > 0$$

where V_1 is the motion vector of the finger when it last touched the red border and V_t is the current motion vector of the finger in PAN mode. Essentially, any motion vector with an angular difference of $\pm 90^\circ$ from V_1 is sufficient to trigger a switch back to DRAW mode.

The main advantage of using the F³AT to trace lines on a small touch screen is the fact that the user can complete the contour drawing along the boundary of a large image region without lifting up the drawing finger even once. This avoids overlaps and discontinuities in the outline (see Figure 9b). Additionally, since the F³AT automatically switches between PAN and DRAW mode based on the context of the user's finger position (touching red border) and motion direction (last drawing direction), this allows the user to perform annotation more speedily than the traditional approach of manual toggling between PAN and DRAW mode as is evident from our user study results.

USER STUDY

Two series of user studies were conducted. A total of 10 participants (6 males, 4 females) aged between 22 and 30 were involved. Prior to the trial, none of the participants have used the systems in our study. To remove biases arising from task familiarization, equal numbers of participants used one technique first to complete the required task and then the other and vice-versa.

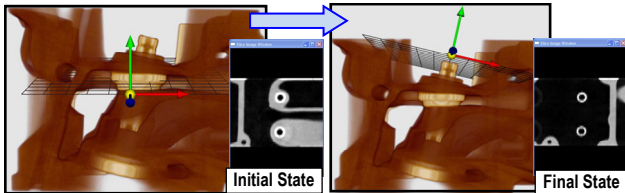


Figure 11. Task 1 requires the user to manipulate the position and orientation of the slicing plane from the initial state shown on the left to the final state shown on the right.

Manipulating the Slicing Plane

The goals of this study are to observe how well users of the proposed interface are able to transfer their practice skills on one task to another new task and the variability in the acquired competency level among a small population of naive users. A traditional mouse-and-keyboard interface was used to obtain a set of baseline timing measures that allows us to gauge the quantum of improvement afforded by our proposed WYSIWYF approach.

The study compares the speed performance in manipulating the position and orientation of the slicing plane from an initial state to a new one. The 2D slicer image is shown pictorially to the user (see Figure 11, right side) to allow

him to judge if the plane is in the required position and orientation. The task completion time using the WYSIWYF system is compared to a traditional keyboard-mouse system, which uses a combination of mouse (to manipulate the volume data) and keyboard control (to translate and rotate slicer about its various axes). A graphical depiction of the keyboard and mouse functions was made available for user reference. Users could practice performing task 1 with the interface currently under trial for up to 5 minutes. After the practice, the slicing plane was reset to its initial state and the time taken to perform task 1 was recorded. The user was then given another task 2 without the possibility of practice to see if they can transfer their newly acquired slicer manipulation skills to a novel situation.

Table 1 summarizes the mean timing results μ and their respective variances δ . As expected, the direct and tangible 3D manipulation of the slicing plane afforded by our system allowed the user to perform the tasks much more speedily. For the familiar task 1, it was 97% faster and for unfamiliar task 2, it was 142% faster. The increase of about 15s when moving from task 1 to task 2 using the proposed system compared to a much longer 42s using the mouse-keyboard approach suggests that users are better at transferring the practice skills to another new task using the WYSIWYF approach. The intuitive and direct manner in which the slicing plane can be positioned (by touching the screen with the device) and orientated (by tilting the device) makes it easier for the users to figure out how to perform the necessary operations to manipulate the slicing plane to the target. The comparatively lower variances in timing for our proposed system also suggest that the more intuitive integrated WYSIWYF mode of interaction allows a larger cross-section of users to acquire similar level of competency with limited usage exposure on the system.

Method	Complete Task 1		Complete Task 2	
	μ (sec)	δ (sec ²)	μ (sec)	δ (sec ²)
Keyboard + Mouse	26.4	112	68.6	960
Wall display + iPod touch	13.4	27	28.3	187

Table 1. Comparative results of the slice plane manipulation study between the proposed and a keyboard-mouse system.

Visual Annotation

The second user study compares the timing performance in doing contour tracing on a small touch screen device (iPod touch) using the manual approach of toggling between PAN and DRAW modes with one hand and the novel F³AT.

Table 2 shows that the proposed F³AT method is 49% faster than the manual method. Every single user drew the required contour faster using F³AT. In fact, the significantly lower variance in average task completion

time for F³AT suggests that this method of visual annotation is probably more intuitive and easily adopted. User comments on F³AT were all positive, praising its speed and convenience. The F³AT accuracy in following the required trace path is also slightly better than the manual mode.

Method	Average timing (sec)	Variance of timing (sec ²)	Average tracing accuracy (pixel)
Manual	111.8	0.16	0.88
F ³ AT	75.1	0.09	0.78

Table 2. Comparative results of the visual annotation user study between the one-handed manual and F³AT method.

In fact, our observations were that for faster drawing speed, which F³AT affords, the more likely it is that the user gets negligent in keeping to within the stipulated line trace width. However, the greatest advantage of F³AT is its ability to draw an entire outline without lifting one's finger. The benefits are clearly illustrated in comparison of the visual quality of drawings produced by the two techniques (see Figure 12b-c). The contour drawn using F³AT is smooth and continuous while that drawn using the manual method has many overlaps and discontinuities.

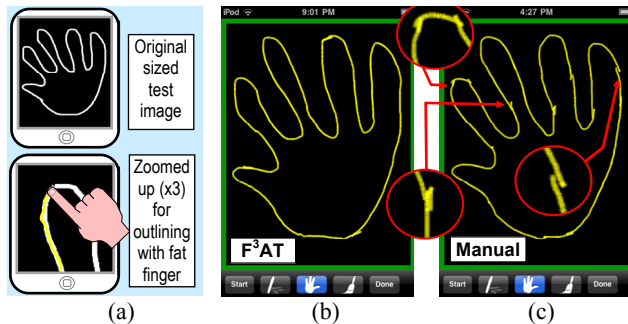


Figure 12. Visual annotation user study. (a) Test image used was zoomed up by 3 times for user to outline. (b) A user's sample result for the F³AT and (c) one-handed manual trials.

CONCLUSIONS

We have described a novel interactive visual exploration and annotation system that combines the strengths of a standard upright multi-touch display and a commonly available handheld device that acted as an intuitive tangible interface. We described how the WYSIWYF concept was realized using the 3D-tilt sensing and multi-touch capability on the handheld device. A novel feature of this concept is the ability to directly and efficiently manipulate a slicing plane on the multi-touch wall display by making direct contact with the handheld device. We can also use this same handheld device to remotely manipulate the slicing plane while activating the constrained rotation capability to selectively reduce the degree of freedom of the slice plane. Finally, we also proposed a fast and accurate contour drawing technique so that small touch

screen devices can be efficiently used to perform remote visual annotations. User studies conducted support the efficacy of our proposed visual exploration and annotation interaction designs. In future, we also would like to explore our interaction techniques in astrophysical visualization settings [11].

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