A MOVABLE TOMOGRAPHIC DISPLAY FOR 3D MEDICAL IMAGES

Gaurav Shukla[1], Bo Wang[1], John Galeotti[2], Roberta Klatzky[3], Bing Wu[3], Bert Unger[1,2], Damion Shelton[2], Brian Chapman[1], and George Stetten[1,2]

[1] Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, 15261
[2] Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, 15213
[3] Department of Psychology, Carnegie Mellon University, Pittsburgh, PA, 15213 ⋆

Abstract. We describe here the first working prototype of a novel display for viewing 3D medical images. The position and orientation of a freely movable touch-screen display are optically tracked and used to continuously determine which slice to display within a 3D data set. The slice is registered "in situ" relative to a fixed coordinate system, through which the display is moved. We have coined the term "grab-a-slice" for the new display, to connote the intuitive nature of the interaction it provides with volumetric data, potentially more so than that provided by traditional fixed displays. With grab-a-slice, the user experiences the illusion of slicing through an invisible patient. The touch-screen allows the user to directly identify the location of any point of interest within the 3D image data. Grab-a-slice has a number of possible clinical and scientific applications. In particular, we are exploring its utility for improved vascular tracing to identify pulmonary embolus in contrast-enhanced computed tomography (CT). In addition, we are planning psychophysical studies of how users explore and navigate through medical image data with this new display. We are also developing methods of graphical augmentation for grab-a-slice using stereo display, to improve the ability of users to understand the raw content of a tomographic slice in the context of the surrounding 3D anatomy and to improve their ability to navigate through a 3D dataset. Finally, we are exploring the use of grab-a-slice to supervise semi-automated image analysis routines.

1 Introduction

Three-dimensional medical images, such as those acquired by magnetic resonance (MR), computed tomography (CT), or other volumetric imaging modalities have been a great boon to physicians seeking to learn non-invasively about a patient's condition. In clinical practice, 3D images are generally still viewed one slice at a time on a 2D display, using a mouse or keyboard to sequence through a stack of such slices. The slices are usually oriented orthogonal to the cardinal axes (sagittal, coronal, axial) representing samplings from the original 3D data, or

⋆ We acknowledge NIH grants 1R01HL087119, RO1HL089750, and R21EB007721, which supported this work.

the slices may be arbitrarily oriented, computed by interpolating values from the original 3D data. In the current clinical reading room, the display screen remains motionless before the observer as the slice is moved through the patient. While this method of display has been sufficient for many applications, it creates a disconnect between the 3D anatomic relationships in the patient and the stationary sequence of 2D images, especially when the slices represented are not parallel, i.e., the view path is curved. Planning a procedure (e.g., image-guided needle biopsy) in the 3D coordinates of the patient may be less than intuitive when the images are displayed on such an immobile 2D screen.

To address this problem, we have constructed a special type of medical image display that is free to move about in a 3D space representing the coordinate system of the data. At any given time, the display shows a slice that corresponds to the current location and orientation of the display. We hypothesize that manipulating such a display through what amounts to an "invisible patient" will preserve the perception of 3D anatomic relationships in a way not possible with current immobile displays. We use the term "grab-a-slice" to describe this new type of display. We report here the first working prototype.

2 Related Work

Various methods have been developed for rendering 3D data onto a stationary 2D display, with or without special hardware for stereovision (e.g., Levoy's classic paper [1]), but these are not widely used by clinicians. Navigation through a 3D environment has also inspired several approaches. Ware and Osborne [2] provide a user interface for exploring virtual graphics environments they call "scene-in-hand," a virtual camera control that changes the perspective of 3D environment in response to the manipulation of a tracked tool. Hinckley et al. use passive interface props, [3] tracked objects that are simple and hand-held, to generate tomographic slices of medical image data. The cubic mouse, [4] developed for specification of 3D coordinates in graphics applications, consists of a tracked in-hand device coupled with rods and buttons to specify motion of virtual objects along various axes. Other approaches, including the SpaceBall line of products (3DConnexion, Silicon Valley, CA) implement a non-tracked 3D navigation tool. All of the above still used a stationary display, as opposed to the movable display described here.

Tracked movable boom-mounted displays [5][6] that are counterbalanced so that the operator can manipulate them by hand have been used as immersive displays into 3D virtual environments. However, to our knowledge, they have not been used for tomographic slicing of a volume.

Augmented reality systems in which head-mounted displays are coupled with algorithms for 3D perspective rendering have been studied extensively. [7][8]This approach has also been applied to viewing tomographic slices. [9][10]

The grab-a-slice display has evolved out of an effort in our laboratory and elsewhere to develop image guidance systems that merge ultrasound (US) images with a direct view of the patient. [11][12] Our device, called the Sonic Flashlight (SF), consists of a small display and a half-silvered mirror mounted on a conventional US transducer. Looking through the mirror, the operator sees the reflection of the real-time US image floating *in situ* within the patient, precisely where the scan is currently being obtained. The SF merges the US image, US probe, operator's hands, surgical instrument, and patient into the same field of view, enabling perceptually guided action. Similar approaches have been taken by others for displaying slices of CT and MR data *in situ*. [13–15]

We have conducted extensive research into the underlying psychophysical properties of *in situ* image guidance. This research has demonstrated advantages as compared to conventional displays in the accuracy of perceived target depth, immunity to errors due to surface deformation, and the interpretation of shape and pose of 3D targets. [16–20] We use the term "tomographic aperture" to denote the manner in which 3D data is sampled by slicing, analogous to that of a conventional aperture through which the world is sampled by projection. We have found that the *in situ* image display provides a perceptual link between in-plane and through-plane distance as well as a spatial buffer for memory to combine sequential 2D information into a 3D context.

This avenue of research led us to conceive of the tracked grab-a-slice display, which produces an *in situ* image with larger size and greater clarity than possible with the SF. As opposed to the SF's virtual image, which is limited by the intervening mirror, grab-a-slice represents an easily manipulable tomographic aperture based on a real image that can be touched with a finger to identify individual points in 3D space.

3 Methods

We constructed a wooden frame for a 15" touch-screen display (Microtouch M150, 3M, Inc.) that allows the display to be manipulated in 4 degrees of freedom (DOF) with respect to a stationary tabletop. A user may move the display with a single hand using one of two handles (see Figure 1). The apparatus is free to translate across the tabletop in two directions (A and B), and to rotate about the "yaw" axis (C), facilitated by Teflon pads under the platform, which provide low dynamic friction and allow for comfortable one-handed manipulation. A hinged mount with ball-bearing tracks permits the display to rotate about the "pitch" axis (D). Sufficient static friction in the hinge and between the platform and the tabletop, along with proper balance of the hinged assembly, guarantees that the screen remains immobile when released. Rigid bodies have a total of 6 DOF, but we deemed it unnecessary to physically implement the remaining 2 DOF: translation in height normal to the tabletop and rotation in the "roll" direction within the image plane. Both can be readily implemented in software, and a footswitch can control, in effect, raising and lowering the invisible patient or rolling the patient around the long axis from prone to supine. A seventh DOF, isotropic scale, can also be manipulated in software, effectively magnifying or shrinking the entire patient.

Fig. 1. The current grab-a-slice display can be manipulated in four degrees of freedom (see text).

We mounted 10 infrared light-emitting diode (IRED) markers on the grab-a-slice display for detection by an optical tracking system (Optotrak Certus, Northern Digital Inc.). The Optotrak can localize each IRED marker with an accuracy of approximately 0.1mm and a sampling frequency of at least 100 Hz, using a rigid array of three cameras fixed with respect to the tabletop. All the markers are mounted on the portion of the grab-a-slice apparatus that is rigidly attached to the display itself. Thus the markers can be treated as a rigid body by the Optotrak software to compute orientation and position for the display as a whole relative to the camera array.

For our system to function, each point in the 3D image must correspond uniquely to a point in physical space. This is achieved by placing the image data at a fixed location relative to the camera origin. We adapted software originally designed in our laboratory for displaying simulated and pre-acquired 3D data with the SF. [21] The software takes measurements from the optical cameras and performs the image slicing and rendering, all in real time.

Calibration of the grab-a-slice consists of the following procedure. An optically tracked stylus is used to find the 4 corners of the touch-screen display in camera coordinates, and the scale of the displayed data is adjusted accordingly so that the data is displayed as life-size (the scale may also be changed intentionally). The grab-a-slice display is assigned to be at the mid-axial slice across the thorax when placed at the center of the table with zero pitch and zero yaw. The long-axis of the patient is assigned to the "range" or z axis of the camera coordinate system.

As the apparatus is moved to other locations and orientations, the Optotrak software continually reports the locations of the 4 corners of the display based on their relationships to the IRED markers. To display the appropriate slice

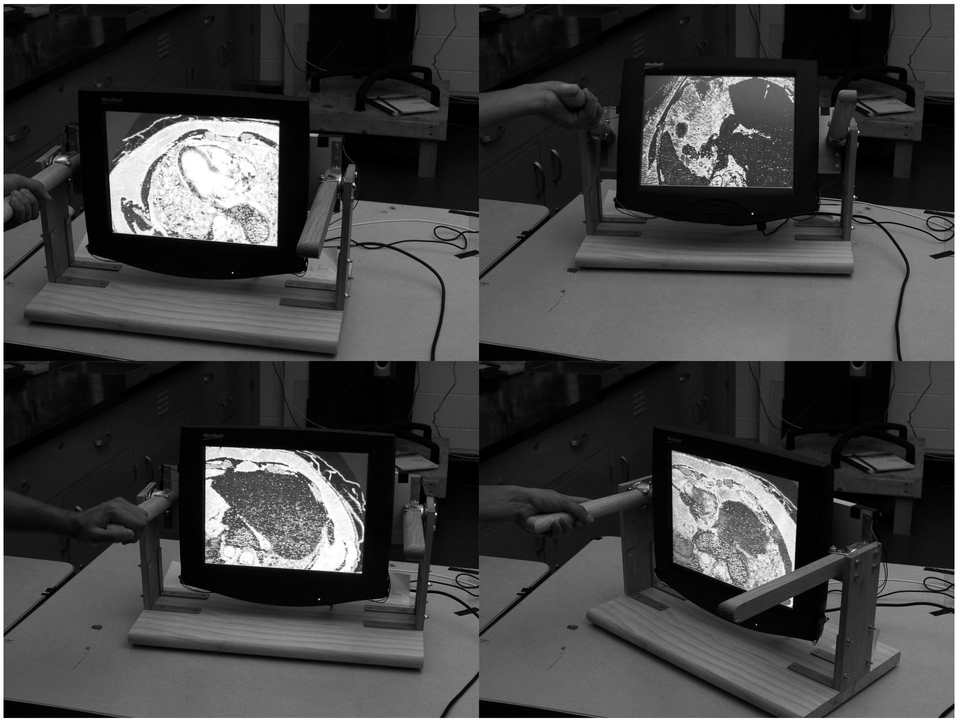

Fig. 2. The grab-a-slice display showing CT images of the lung. Various locations and orientations of the display result in corresponding slices through the invisible patient being displayed. Degrees of freedom consist of 2 translations and 2 rotations.

from the 3D data on the display, the locations of the 4 corners of the display are used to extract the appropriate slice from the 3D data set, by means of a 3D texture mapping board (GeForce 8800, NVIDIA, Inc.). The method of 3D texture mapping interpolates voxels from a 3D data set onto polygons in arbitrary planes for 2D display, in this case a single rectangle occupying the surface of the touch-screen. [22]

A 3D dataset consisting of a (de-identified) CT scan of a human thorax was used for our initial demonstration. The results are shown in Figure 2. As can be seen, the displayed image content responds to movement of the apparatus through the coordinate system of the CT image data.

Since the display is also a touch-screen, the operator can easily and unambiguously identify locations in the image coordinate system. This feature serves as an intuitive 3D mouse. A separate immobile display (not shown) operates as a control panel to activate the system, select the particular 3D data set to load, as well as adjust brightness, contrast, and the additional transform parameters discussed above.

4 Discussion

Grab-a-slice represents a potentially useful tool in medicine. We envision the device to have at least three areas for clinical application.

One area is preoperative planning. Surgeons often examine medical images before performing a procedure. For example, a surgeon attempting to extract a bullet from a patient's abdomen may look at an abdominal CT scan to identify the bullet's location, possible obstacles, and to determine an optimal path of approach. At present, the surgeon must cognitively relate this information, displayed as 2D slices on a stationary screen, to the subsequent 3D interaction with the patient in the operating room. Being able to examine the CT data with grab-a-slice may provide the surgeon with a more intuitive sense of 3D anatomical relationships, analogous to what is termed in the military as, "situational awareness." The surgeon can preoperatively plan and record a surgical path and demonstrate it to the surgical team. The screen may be located on a table directly adjoining the patient, with the "invisible patient" oriented parallel to the real one, thus making corresponding orientations and distances directly comparable.

A second clinical application involves using grab-a-slice as a training tool. Medical students, nurses, residents, and other health professionals often have difficulty learning to interpret 3D medical images; the orientation of the patient and the relationship between slices is not always readily apparent. Medical students in the anatomy laboratory could dissect a liver in the cadaver while examining a grab-a-slice rendering of a CT scan of the same liver on an adjacent table, gaining expertise with medical images at an early stage in their training.

A third clinical realm for grab-a-slice is diagnostic radiology. The particular application we are studying is the diagnosis of pulmonary embolism (PE), an acute, life-threatening, and treatable condition with over 650,000 incident cases in the USA annually. PE is diagnosed by a combination of clinical symptoms, laboratory results, and medical imaging to determine the presence, location, and size of potential emboli. Radiological evaluation of CT data for evidence of PE involves tracing branches of the pulmonary vessels containing suspected emboli back to the heart, to determine whether the vessel in question is an artery or a vein (pathologic emboli are always in the arteries). Tracing these vessels along their course is a non-trivial task using a stack of 2D slices, and we are evaluating whether it may be made easier and more reliable with grab-a-slice.

In addition to offering potentially useful clinical applications, grab-a-slice represents a new platform for at least two areas of fundamental psychophysical research: 3D visualization and 3D navigation. The processes that humans use to build up mental representations of 3D structures are of great interest to the psychophysical community. Grab-a-slice could be used to study how humans perceive curvature in 3D and to evaluate the ability to define a path through a 3D maze structure. Navigation through a maze is analogous to a surgeon's preoperative and intra-operative route planning, avoiding obstacles to reach targets. The *in situ* nature of grab-a-slice provides a novel way in which to study these human perceptual and cognitive processes, and compare them to those used with conventional displays.

Potential pitfalls of the device include the added space required and the ergonomics limitations on the extent of rotation and translation. The current device is also quite expensive, due to the optical tracking system, but this can be solved by substituting any of a number of cheaper technologies including other optical, RF, or inertial tracking systems, as well as mechanical encoders.

5 Conclusion

We report here the first prototype of a tracked movable display in which tomographic slices through 3D data are viewed by moving the display through the data space to show the slices *in situ*. Previously, with the SF, we employed a virtual image to produce the illusion that the surface of the patient was transparent. Here, with grab-a-slice, we use a real image to slice through what amounts to an invisible patient. Future iterations could be boom-mounted, similar to displays already used in surgical suites, or light handheld wireless devices freely manipulated in all 6 DOF. The approach holds promise for methods of graphical augmentation using stereo to improve the ability of users to understand the raw tomographic data in the context of the surrounding 3D anatomy and to improve their ability to navigate through a the 3D dataset. Finally, we are exploring the use of grab-a-slice to supervise semi-automated image analysis routines.

References

1. Levoy, M. Display of surfaces from volume data. IEEE Computer Graphics and Applications, 8, 3, 29-37 (May 1988)
2. Ware, C. and Osborne, S. Exploration and virtual camera control in virtual three dimensional environments. In Proceedings of the 1990 Symposium on interactive 3D Graphics (Snowbird, Utah, United States). ACM, New York, NY, 175-183. (1990)
3. Hinckley, K., Pausch, R., Goble, J. C., and Kassell, N. F. Passive real-world interface props for neurosurgical visualization. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Celebrating Interdependence (Boston, Massachusetts, United States, April 24 - 28, 1994). ACM, New York, NY, 452-458.
4. Fröhlich, B. and Plate, J. The cubic mouse: a new device for three-dimensional input. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (The Hague, The Netherlands, April 01 - 06, 2000). CHI '00. ACM, New York, NY, 526-531.
5. Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., Kenyon, R., and Hart, J.C. The CAVE, Audio-Visual Experience Automatic Virtual Environment. Communications of the ACM, 67-72 (June 1992)
6. Browning, D.R., Cruz-Neira, C., Sandin, D.J., DeFanti T.A. Projection-Based Virtual Environments and Disability. Virtual Reality Conference, 1994.
7. Looser, J., Billinghurst, M., and Cockburn, A. Through the looking glass: the use of lenses as an interface tool for Augmented Reality interfaces. In Proceedings of the 2nd international Conference on Computer Graphics and interactive Techniques in Australasia and South East Asia (Singapore, June 15 - 18, 2004). S. N. Spencer, Ed. GRAPHITE '04. ACM, New York, NY, 204-211.

8. Kalkofen D., Mendez E., Schmalstieg D. Interactive Focus and Context Visualization for Augmented Reality. In Proceedings of 6th IEEE and ACM International Symposium on Mixed and Augmented Reality, Nara, Japan, 191-200 (Nov 2007)
9. State, A., Livingston, M. A., Garrett, W. F., Hirota, G., Whitton, M. C., Pisano, E. D., and Fuchs, H. Technologies for augmented reality systems: realizing ultrasound-guided needle biopsies. In Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques SIGGRAPH '96. New York, NY, 439-446.
10. Sauer F., Khamene A., Bascle B., Schimmang L., Wenzel F., Vogt S. Augmented Reality Visualization of Ultrasound Images: System Description, Calibration, and Features. IEEE and ACM International Symposium on Augmented Reality. (2001)
11. Stetten, G. , Chib, V. Overlaying Ultrasound Images on Direct Vision. Journal of Ultrasound in Medicine, 20, 3, 235-240 (2001)
12. Hofstein, S. Ultrasonic Scope. US Patent no. 4,200,885, Apr. 1980.
13. Masamune, K., Masutani, Y., Nakajima, S., Sakuma, I., Dohi, T., Iseki, H., and Takakura, K. Three-Dimensional Slice Image Overlay System with Accurate Depth Perception for Surgery. In Proceedings of the Third international Conference on Medical Image Computing and Computer-Assisted intervention (October 11 - 14, 2000). S. L. Delp, A. M. DiGioia, and B. Jaramaz, Eds. Lecture Notes In Computer Science, vol. 1935. Springer-Verlag, London, 395-402.
14. Masamune, K., Fichtinger, G., Deguet, A., Matsuka, D., and Taylor, R. 2002. An Image Overlay System with Enhanced Reality for Percutaneous Therapy Performed Inside CT Scanner. In Proceedings of the 5th international Conference on Medical Image Computing and Computer-Assisted intervention-Part II (September 25 - 28, 2002). T. Dohi and R. Kikins, Eds. Lecture Notes In Computer Science, vol. 2489. Springer-Verlag, London, 77-84.
15. Masamune, K., Sato, I., Liao, H., and Dohi, T. 2008. Non-metal Slice Image Overlay Display System Used Inside the Open Type MRI. In Proceedings of the 4th international Workshop on Medical Imaging and Augmented Reality (Tokyo, Japan, August 01 - 02, 2008). T. Dohi, I. Sakuma, and H. Liao, Eds. Lecture Notes In Computer Science, vol. 5128. Springer-Verlag, Berlin, Heidelberg, 385-392.
16. Chang, W., Amesur, N., Klatzky, R., Zajko, A. , and Stetten, G. Vascular Access: Comparison of US Guidance with the Sonic Flashlight and Conventional US in Phantoms. Radiology, 241, 771-779 (Dec 2006)
17. Wu, B., Klatzky, R., Shelton, D., Stetten, G., Psychophysical Evaluation of In situ Ultrasound Visualization IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on Haptics, Virtual and Augmented Reality, 11, 6, 684-693 (Nov/Dec 2005)
18. Klatzky, R., Wu, B., Shelton, D., Stetten, G. Learning to perform actions in near space under perceptual vs. cognitive control. ACM Transactions on Applied Perception. Vol. 5, No. 1 (Jan 2008)
19. Wu, B., Klatzky, R., Shelton, D., Stetten, G. Mental concatenation of perceptually and cognitively specified depth to represent locations in near space. Experimental Brain Research, 184, 3, 295-305 (2008)
20. Klatzky, R., Wu, B., Stetten, G. Spatial representations from perception and cognitive mediation: The case of ultrasound. Current Directions in Psychological Science (in press).
21. Shelton, D. Virtual Tomographic Reflection for Psychophysical Analysis of the Sonic Flashlight. Ph.D. Dissertation, Robotics Institute, Carnegie Mellon University, advisor G. Stetten, March 2007.
22. Watt, A. Fundamentals of Three-Dimensional Computer Graphics. Reading, MA: Addison-Wesley (1990)