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Short Paper

A Prototype Holographic Augmented Reality Interface for Image-Guided Prostate Cancer Interventions

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Abstract

Motivated by the potential of holographic augmented reality (AR) to offer an immersive 3D appreciation of morphology and anatomy, the purpose of this work is to develop and assess an interface for image-based planning of prostate interventions with a head-mounted display (HMD). The computational system is a data and command pipeline that links a magnetic resonance imaging (MRI) scanner/data and the operator, that includes modules dedicated to image processing and segmentation, structure rendering, trajectory planning and spatial co-registration. The interface was developed with the Unity3D Engine (C#) and deployed and tested on a HoloLens HMD. For ergonomics in the surgical suite, the system was endowed with hands-free interactive manipulation of images and the holographic scene via hand gestures and voice commands. The system was tested in silico using MRI and ultrasound datasets of prostate phantoms. The holographic AR scene rendered by the HoloLens HMD was subjectively found superior to desktop-based volume or 3D rendering with regard to structure detection and appreciation of spatial relationships, planning access paths and manual co-registration of MRI and Ultrasound. By inspecting the virtual trajectory superimposed to rendered structures and MR images, the operator observes collisions of the needle path with vital structures (e.g. urethra) and adjusts accordingly. Holographic AR interfacing with wireless HMD endowed with hands-free gesture and voice control is a promising technology. Studies need to systematically assess the clinical merit of such systems and needed functionalities.

CCS Concepts

• ***Human-centered computing*** → *Human computer interaction (HCI);* • ***Graphics systems and interfaces*** → *Mixed / augmented reality;*

1. Introduction

While image-guidance in interventional and surgical procedures offers critically needed three-dimensional (3D) information, the cornerstone clinical practice is two-dimensional (2D) visualization (i.e., on 2D displays) of those 3D data. In practice, this requires the interventionist to perform mental extraction of 3D features and their spatial relationships by viewing numerous 2D MRI slices from the 3D or multislice sets [GPZT98], a challenging and time-consuming task. Augmented reality (AR) visualization has been hailed as a potential solution to the above challenges. By fusing and co-registering images, rendered anatomical structures, and other spatiotemporal patient information into a combined model, information is contextualized. Most recently, this concept of immersing the operator in the information was further enhanced with the introduction of head-mounted displays (HMD) [KOGD*16, CFM*16, KKJ*17, MMNT*17].

Magnetic resonance imaging (MRI) and Ultrasound (US) fusion provides the operator with intraoperative US real-time guidance and detailed anatomical information from the preoperative MRI. In practice, the required hand-eye coordination is challenging. These systems require the operator to: (i) manually perform the interventions on an orientation (including the intrarectal manipulation of the US probe), while (ii) visualizing the intervention on a screen in a different orientation. Moreover, the view of the area of procedure is in 2D (i.e., fused real-time US image and corresponding MRI slice). There is a clinical need to interact, spatially merge, and visualize information from MR, US, and tracking needle trajectories, and align this information onto the patient's position during the interventions. Recent advancement in holographic

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technology may overcome these challenges by rendering an augmented/mixed reality environment to provide true 3D perception of the anatomy. Indeed, a growing number of studies demonstrates the potential of AR in urology [HKC*16, HHMM*14, BPPW99, TGS*09, MAS*13, SVA*09, MMNB*18].

In this work, we describe an AR holographic interface for performing image-guided prostate interventions, that establishes a data and command pipeline that links the sensor (MRI scanner or US machine) and the operator. For the presented work, we customized the output for use with the Microsoft HoloLens HMD [Mic17]. Specific architectural and computational features were selected based on operational aspects set forth with the collaborating physicians: (i) speed, (ii) interactive manipulation of images and virtual object rendering, and (iii) as hands-free as possible interaction with the system's front-end. In response, this work expands upon the concept that the HMD acts as an interface, while a separate processor (the Host PC) performs the vast majority of processing to eliminate latencies and enable efficient computation. In preparation for future on-site studies, the platform is endowed with the needed transformations to maintain a direct matching of the holographic and MRI (real) spaces; this enables the operator to control the US biopsy probe on-the-fly and select on the holographic scenery a specific anatomical area, locus, or trajectory. We further included the use of gestures and voice commands for virtually all needed processing (image and rendered structures visualization, stereotactic planning, and human-in-the-loop probe maneuvering). The platform was tested in silico with MRI datasets from a prostate phantom.

2. Methods

2.1. Overview of the Framework

Figure 1(a) shows an illustration of the setup of the entities in the holographic scene that includes the operator, hologram structures, and a 2D virtual display. The virtual 2D display mimics a conventional visualization of individual slices and was added in response to the input of the operating physicians to perform tasks, such as setting trajectories or marking boundaries. The 2D virtual display embedded into the holographic scene enabled the operator to use HoloLens exclusively and not split effort between the hologram and a conventional 2D display. Since all entities in the hologram and the virtual 2D display are scaled and registered to the MRI scanner coordinate system, any graphical action performed is automatically replicated on both the 2D and holographic sites. The operator can inspect the hologram by moving freely around it. Fig 2 shows the architecture of the computational core showing its modules and the flow of data and commands.

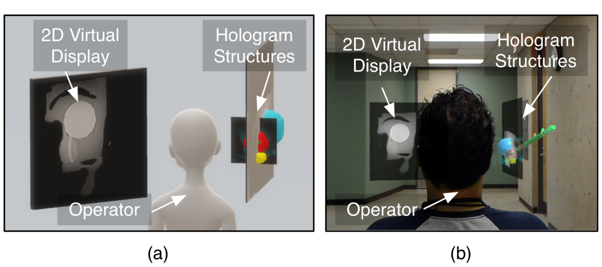


Figure 1: *(a) Topology and (b) a photograph of the holographic AR interface, showing the operator immersed into a scene that includes the 3D holographic structures and an embedded 2D virtual display window.*

Table 1: *Voice command words and their function*

Manipulation of Transrectal Probe	
Command	*Function*
Probe	Enable movement of probe
Rotate	Activate rotational joint (DoF 1)
Translate	Activate prismatic joint (DoF 2), i.e., translation of the needle carriage
Prostate Intervention Planning	
Command	*Function*
Stereo	Activate stereotactic view
Target	Select target point (both stereotactic and free-hand)
Trajectory	Adjust trajectory anchored on target point (only stereotactic)
HoloScene & Image Manipulation	
Command	*Function*
Sagittal	Enable navigation of the MRI set on the Sagittal plane
Transverse	Enable navigation of the MRI set on the Transverse plane
Coronal	Enable navigation of the MRI set on the Coronal plane
Level	Change the window-level value
Width	Change the window-width value

To enable the holographic AR interface to be used for advanced processing, including interactive segmentation and human-in-the-loop input to classification or expert systems, we needed to address the limited computational power and memory of the HoloLens. In response, we implemented a version of the system where the computational core runs on an external PC. In this configuration, the Host PC performs processing of the MRI and US datasets, and then sends the data to the HoloLens via a dedicated TCP/IP connection. We use the lightweight data-interchange JSON format, wherein the messages specify the MRI image plane (Sagittal, Coronal or Transversal), the number of the slices, contrast values, and an array with the intensity values of each pixel.

The Holographic Module was developed in Unity 3D and tested on the HoloLens. The input for the Host PC comes from a file that contains the pixel intensity values for every slice. We have developed a script that reads the file, stores the data in RAM, and generates 2D textures as requested by the operator. On the HoloLens side, there is a mesh in the form of a plane rendered corresponding to the slice location were we apply the texture generated.

2.2. Hands-free Control of the Holographic AR Scene

An objective in the design of the system was a hands-free interface for the holographic scene for the manipulation of the following options: select and adjust slices and contrast, load datasets and orientations, and manipulate the probe. This feature was deemed necessary to streamline operations without the need of sterilizing computer devices or equipment, operator repositioning to access them or an assistant. In this implementation, we used the native hand gestures and voice recognition features of HoloLens to perform the above procedures [Mic17]. Table 1 reviews the voice commands and the corresponding functions performed upon their call. Other voice commands could be implemented depending on operational needs and the kinematic structure of the manipulator. No

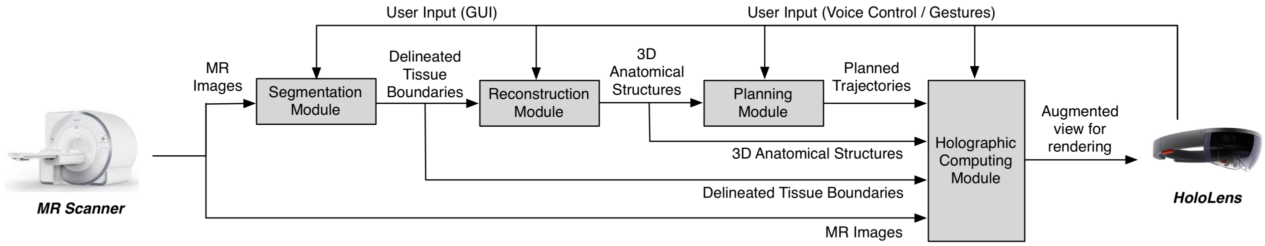


Figure 2: *Architecture of the computational core showing its modules and the flow of data and commands*

other form of human-machine interfacing was used or deemed necessary at any point of the particular studies and manipulations.

Figure 3: *Images from the HoloLens showing the operator selecting one, two and three slices from the MRI set that are then refreshed in both the 3D rendering window (right side) and the 2D virtual window (left side).*

Figure 3 shows the operator's view as he adjusts the objects in the holographic AR scene. The orientation is selected by voice commands (e.g. Sagittal, Coronal, Transverse), while a hand gesture swiping from left to right enables the operator to go through all the slices of the set. The 3D rendering window shows the structures with the slice mapped to the location in relation to the structure, this slice will move through the structure as the operator swipes through the set. Concurrently, the 2D virtual window shows the current slice and updates as the hand of the operator moves.

2.3. Planning and Control

During planning, the software continuously performs two tasks. First, as the operator adjusts the trajectory, the collision module checks whether any point of the intended trajectory collides on a vital structure (determined by forbidden zones). In either case the operator is warned with a pop-up window and the module resolves the collision. Second, the software concurrently updates all virtual structures in the hologram, as well as on the embedded 2D virtual display. As an example, as the trajectory is updated it is shown in the hologram in 3D and if it intersects the slice presented, the point is shown on the 2D virtual display.

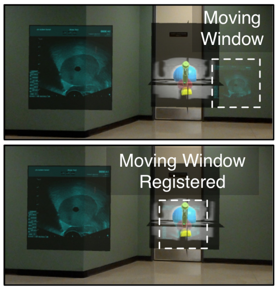
3. Results

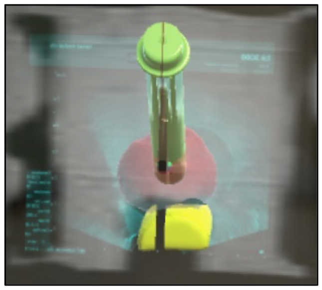
In all studies, the holographic AR visualization was subjectively identified by all operators (2 urologists performing transrectal prostate biopsies, 1 radiologist specialized in acquisition and delineation of prostate MR images, and 5 engineering/scientific researchers) to be superior to desktop-based volume rendering in regards to (i) 3D appreciation of the spatial relationship of multiple rendered structures, (ii) detection and collision avoidance of critical structures (such as the urethra or bladder), (iii) ergonomics and ease in selecting a trajectory, and (iv) readjusting the US biopsy probe. Throughout our studies, such as those presented in Figures 4-6, we noticed that while the operators were running the system, they would move their bodies and heads relative to the scene to better view structures or trajectories. This was a clear indication of the value of AR holographic interface: the operators were intuitively moving in 3D space, immersing themselves into the surgical scene. What was even more intriguing was how little time it took to feel confident operating the system in its current form: less than 45 minutes. The clinical personnel underscored the benefit of intuitive ergonomics and speed of interactively setting the trajectory while viewing the forbidden zones superimposed to the ensemble of rendered structures (i.e. the virtual entities in the AR) and/or MRI slices. Overall, holographic interfacing for planning and gesture interfacing was preferred over desktop visualization.

In view of future planned in situ work in guiding prostate interventions, we are pursuing multimodal MRI and US co-registration. Herein, we present the holograph-assisted manual MRI and US co-registration. Figure 4 shows images from the HoloLens illustrating this functionality. The operator calls the US image set with the voice command "Ultrasound" that is then displayed in the 2D virtual window. The operator can then activate manual registration and US-to-MRI superposition with the voice command "Register". At this state, the operator can interactively move the ultrasound window along all 3-axes using gestures. Current work is directed toward providing the operator with measures of US-to-MRI feature and landmark matching to enhance manual registration.

Another application of the holographic AR interface for manipulating a realistic model of the trans-rectal US biopsy probe using voice and gesture control is shown in Figure 5. The operator has complete control over the movement of the probe while it is shown in 3D, and can see actuated projections of the movements. To enable the projections, the operator can either voice the command "translate" or "rotate". In 5(a) we can see the probe in green and the projection of the probe in yellow. The operator can use the voice command "probe" to manipulate the location of the probe in 3D space using their hand. The tip of the probe will always point to the center of the structure to reduce the need of manual rotation, as seen in 5(b).

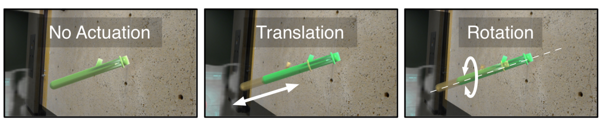
Figure 6 illustrates voice-controlled adjustment of the contrast



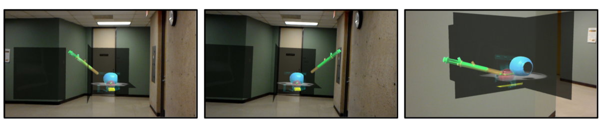


(a) (b)

Figure 4: *(a) Illustration of the interactive manual feature of the software for co-registration of images acquired from two modalities, MRI and US. (b) View presenting the US image registered with 3D anatomical strucutres generated from MR images.*



(a)



(b)

Figure 5: *Perspective of the operator manipulating the realistic rendering of the trans-rectal US biopsy probe using (a) the probe projection feature where the projection is yellow, and (b) manipulating the location of the probe in 3D space.*

Figure 6: *Example of multiple contrast configurations from the operator perspective to visualize anatomical structures of interest while planning the position of the probe.*

of an image. In this figure, the contrast of an MRI slice is adjusted while the operator views those changes on the HoloLens, using the voice command "Level" or "Width" to adjust the window-level or window-width values. These new values are applied to all MRI slices and any other orientation or slice invoked by voice commands or hand gestures will retain the same contrast configuration. Similarly, the ultrasound slice has separate contrast features that can be adjusted while manipulating the ultrasound slice.

4. Discussion

The rapid evolution of low-cost wireless HMD offers the opportunity to bring holographics to daily practice beyond academic sites and may facilitate a paradigm shift in the clinical realm: from the visualization of 2D images or 3D structures on 2D flat screens, to immersion into the imaging data and imaging-based 3D or 4D renderings [KKJ*17, CL17, TRL*17, QBJ*17, MMNT*17]. This work was motivated by the potential of merging imaging, holographic, and hands-free human-machine interfacing to achieve more ergonomic and intuitive planning of urologic procedures. The design of our system was based on addressing challenges related to clinical deployment such as: MR data presentation, and performing fast and efficient planning in 3D that is safe by avoiding vital structures. While this is an early work, it soon became apparent that streamlining the workflow, reducing the workload, and achieving the smallest possible learning curve are critical features.

In response to early testing, we introduced new architectural and functional features. First, the dual Host PC/HMD provides the computational resources for current and future tasks: maintaining 60 fps even during demanding image manipulation, integrating with real-time MRI reconstruction, and multi-modal co-registration (e.g. for ultrasound and MRI fused guidance). Second, the AR holographic interface offers both (a) superior visualization of complex 3D structures and (b) effective negotiation of vital structures for interactive planning. Though the field of view was limited, it did not affect the visualization during planning as it was compensated by moving the head around. Third, hands-free interfacing of the physician to the system with hand-gesture and voice recognition were praised and desired by all study subjects. The system enabled us to identify preliminary workflow protocols for performing image-guided interventions with holographic immersion. While the platform was only assessed in silico for MRI-guided trans-rectal access to the prostate, it is adaptable to include other modalities and procedures.

While the described implementation provided the needed proof-of-concept and a roadmap for future efforts, the presented work here has certain limitations. First, only three clinical personnel contributed in assessing the functionality of the platform, while MRI studies were performed on a prostate phantom. Second, these preliminary studies were subjective and included only qualitative assessment of the functionality and ergonomics of the platform. We are designing quantitative studies that incorporate metrics for comparing functionality and ergonomics, and multi-site studies are planned with the next update of the software. The comparative studies will be perfomed with real-time MRI-to-ultrasound fusion prostate biopsy systems. Currently, we are extending the image processing functionalities with appropriate libraries (such as ITK) and optimizing it with a multi-thread implementation [NZDST13] and GPU acceleration [RNNTZ14]. We would also include capabilities to optically track the transrectal ultrasound probe (which is fixed to a passive arm of the MRI-to-ultrasound fusion prostate biopsy system) and project the visualization information on it. The preoperative MR images will be registered with US images using non-rigid deformation algorithms [KLHZ*12, FKS*15] thus accounting for the deformations in prostate caused due to changes in patient position, differences in bladder filling, placement of surgical tools (MR coils or probes) inside rectum, and intra-procedural tissue distortion.

5. Conclusion

Holographic augmented reality interfacing, especially considering the current trends in wireless HMD and hands-free interactive manipulation, appears to be a promising venue toward immersion of the urologist into the plethora of 3D and multimodal image-extracted, clinically relevant information for planning and eventually performing procedures. The merit of immersive technologies will eventually be determined in the clinical realm and especially with regard to patient outcome and cost-effectiveness. Aiming toward integration in the daily workflow of the clinical site, in this work we focused on ergonomics and intuitiveness based on the input of the end-user. In response we incorporated voice and gesture activated image and holographic-object manipulation for planning. The experience from developing this platform underscored the need for extensive studies to assess merit in clinical practice and, secondary to the inclusion of a new computational layer in patient management, to establish appropriate legal regulations.

Acknowledgements

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