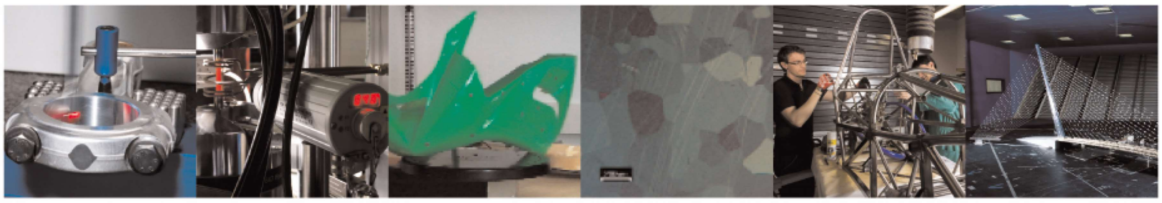

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Evaluation of How Users Interface with Holographic Augmented Reality Surgical Scenes: Interactive Planning MR-Guided Prostate Biopsies

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CONFLICT OF INTEREST
The authors of this submission have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

ETHICS
The ethical committee (Medical Research Center, Qatar) at the Hamad Medical Corporation approved the study.

Data Availability Statement
Research data are not shared.

ABSTRACT

Background: User interfaces play a vital role in the planning and execution of an interventional procedure. The objective of this study is to investigate the effect of using different user interfaces for planning transrectal robot-assisted MR-guided prostate biopsy (MRgPBx) in an AR environment.

Method: End-user studies were conducted by simulating an MRgPBx system with end-firing and side-firing modes. The information from the system to the operator was rendered on HoloLens as an output interface. Joystick, mouse/keyboard, and holographic menus were used as input interfaces to the system.

Results: The studies indicated that using a joystick improved the interactive capacity and enabled operator to plan MRgPBx in less time. It efficiently captures the operator's commands to manipulate the augmented environment representing the state of MRgPBx system.

Conclusions: The study demonstrates an alternative to conventional input interfaces to interact and manipulate an AR environment within the context of MRgPBx planning.

Keywords: User Interfaces for planning interventions, Augmented reality (AR), MR-guided transrectal prostate biopsy

INTRODUCTION

Prostate cancer is the second most common malignancy affecting men globally[1] and diagnosed cancer in terms of incidence in men worldwide.[2] Histological evaluation of the prostate through biopsy sampling of its tissue serves as the gold standard for risk stratification as well as directing therapeutic care.[3,4] The advent of multi-parametric MRI and MR-guided prostate biopsy (MRgPBx) has significantly changed the diagnostic pathway for prostate cancer. It has improved the pathological and oncological outcomes for prostate cancer patients with better optimization for pre-treatment risk assessment.[5] For intraoperative real-time image guidance, MRgPBx may use either: (a) ultrasound, in which case an MRI-ultrasound fusion system registers preoperative annotated MR images with intraoperative transrectal ultrasound or (b) real-time MRI, in which case the patient resides inside the MR scanner bore.[6] While in both cases the operator uses a range of information, the plethora of information pertaining to the area-of-intervention is usually displayed on a two-dimensional (2D) screen and used by the operator to plan the biopsy.

Prostate biopsy procedures involve sampling of the suspected lesion and multiple random cores; as a consequence, the accuracy and repeatability of the sampling directly impact cancer detection rates.[7,8] Thus, robotic assistance systems hold great promise to improve accuracy, repeatability, and overall optimization of the procedure.[9] They lower procedure time by facilitating accurate alignment of the biopsy needle to access the lesion.[10] As a result, multiple robotic manipulators have been developed over the last decade to actuate transrectal probes and assist the operator during prostate interventions.[11–17] In these systems, the position and orientation of the probe are registered with respect to the scanner and visualized in conjunction with MRI or MRI-fused-US images on a 2D display. Based on the information perceived, the operator plans the biopsy and sends actuation commands to the robotic manipulator. In the case of in-bore biopsies, the interaction of the operator with the MR scanner and robotic manipulator is performed via a planning workstation situated outside the scanner room. The operator interacts with the workstation using standard input and output devices such as keyboard/mouse and 2D screens, respectively.

The interfaces are the tools for the two-way flow of information, i.e., for the operator, about the area-of-intervention via the system, and from the operator to the system operating on the area-of-intervention. During the biopsy planning, the quality of the visual information rendered for the operator and the interactive capacity to efficiently capture the operator's commands depend upon the used human-computer interfaces. These interfaces can greatly influence the planning and execution of an interventional procedure.[18,19]

For such intervention scenarios, many studies have shown the advantages of using virtual or augmented reality (AR) interfaces to improve surgical procedure's accuracy and efficiency.[20–26] These output interfaces enables the surgeon to visualize and focus on critical anatomy in an immersive and intuitive setting, while also increasing insight on anatomy/pathology of the disease.[18] Moreover, such a computational facility enables "relevance-based visualization" by enabling the display of virtual data for different phases of the procedure.[27,28] Recently, the HoloLens has been applied for soft tissue biopsies and needle placements. Bettati el al. conducted studies on phantoms to demonstrate increase in accuracy and decrease in the turn-around-time for lung biopsies.[29] Another study by Amacker et al. used the HoloLens for ultrasound guided needle placement on the leg and vessel phantoms.[30] These preliminary studies demonstrated the potential use of improving the operator's spatial orientation. Similar studies have shown the usage of the HoloLens in lumbar facet joint injections,[31] CT-guided lesion targeting,[32] and radiofrequency ablations for liver tumors.[33]

On the other hand, flow of information from the operator to the system usually involves control of a robotic manipulator during an intervention, interfaces similar to gaming joysticks have been used and deployed on commercial systems (such as Monarch® Platform, Auris, USA; CorPath, Corindus Vascular Robotics, USA; and Soloassist II - AKTORmed GmbH, Germany).

The objective of this study is to investigate the interaction of the operator with a transrectal robot assisted MRgPBx system using different input interfaces and its effects on the flow of information between the operator and the system. An AR planning environment using the HoloLens device is implemented to render the information to the operator and the interaction of the operator with the environment is performed using commonly used interfaces: mouse/keyboard, joystick, and holographic menus interacted using hand gestures. The study analyzes a plurality of parameters, such as urologist professional experience, duration and accuracy of biopsy planning, count of visualization adjustments, and count of robotic manipulator actuations to assess its impact on the flow of information and the potential benefits of using these interfaces for planning MRgPBx under different modes of operation.

MATERIALS AND METHODS

User studies were performed with six subjects (S_i ; $i = 1$ to 6) to investigate effect of using different user-interfaces for interaction of the operator with a transrectal robot-assisted MRgPBx system. The subjects were categorized based on their professional background and prior experience working with computer-generated 3D environments. In regard to professional background, there were three groups of subjects: engineers (S_1 and S_2), general physicians (S_3 and S_4), and urologists (S_5 and S_6). In regard to prior experience with 3D environments, they were classified in two groups: S_1, S_2, and S_3 with prior 3D experience and S_4, S_5, and S_6 without prior 3D experience. In the context of this work, the prior 3D experience refers to manipulation (via pan, zoom, and/or rotation) of computer-rendered 3D environments on two-dimensional screens. The ethical committee (Medical Research Center, Qatar) at the Hamad Medical Corporation approved the study.

All user studies were performed on an AR environment, that acted as an interface for rendering the information to the operator. The AR environment simulated the planning and performance of the transrectal MRgPBx intervention planning system (Fig. 1a). In the AR environment, virtual representations of physical entities were rendered as holograms (Fig. 1b and 1c), which includes: (a) MR images corresponding to the area-of intervention along with 3D mesh models of the urethra and prostate, (b) a generic design of an actuated manipulator (based on previous works)[11,13–15,34] with a transrectal probe connected to its distal end, (c) the probe's workspace represented as a span of biopsy needle trajectories, and (d) a proxy of the probe (initially aligned with the probe's pose). An MR compatible prostate phantom (Model 048A; CIRS Inc., Norfolk, USA) was used to generate the area-of-intervention. MR images of the phantom were collected on a Siemens 3T Skyra scanner with a T2 Turbo-Spin-Echo

(TR: 3600; TE: 101; FS: 3; Slice Spacing: 3.3mm; Slice Thickness: 3mm; FOV: 200x200mm; 320x320). The images were processed to generate 3D mesh models of the prostate and urethra (as shown in Fig. 1c). The software was implemented as a distributed system comprising of two elements: a computational unit running on an intervention planning workstation and an interfacing unit running on a HoloLens device. The two-device approach was selected to overcome the computational limitations of the HoloLens head-mounted display (HMD) to compute the probe's workspace and calculations of the manipulator's kinematics without hindering the device's visualization mechanism. The computational unit is in charge of generating the AR environment by loading the data, computing the probe's workspace, and calculating the robot's kinematics. Additionally, it provides the user with a GUI which is rendered on a 2D screen and is used to interface with the 3D environment parameters as well. The HoloLens device serves as an IO device where hand gestures and voice commands are used as an input mechanism, and its AR projector serves as visualization output. Furthermore, it communicates with the computational unit through a TCP connection to exchange data, visual properties (such as visual positioning, visual transparency, etc.), and the user input.

The application was developed in C++ as a module built on top of the Framework for Interactive Immersion into Imaging Data (FI3D).[35] The framework enabled the described system with the AR visualization capabilities and communication protocol for the two entities to exchange visual data and user input. The framework allowed us to focus in the development of the studies without needing to manage the technical details of the application, i.e., rendering of images and 3D models, data management, and communication between the workstation and the HoloLens device. These features are offered natively by the framework, and we built the prostate biopsy AR environment on top of the framework which facilitated with the technical requirements. To do so, we defined all the visuals shown in Fig. 1b and the controls to manipulate the AR environment using the framework's API, resulting in the automatic generation of the AR environment in the HoloLens device.

The AR planning environment (as shown in Fig. 2a and in the video uploaded as supporting document) was evaluated under two operational modes: Mode-I with side-firing and Mode-II with end-firing of the biopsy needle, as it is being done with current transrectal probes.[36,37] In Mode-I, the motion of the probe was constrained to translation and rotation along a virtual axis inside the rectum (Fig. 2b and Fig. 3), whereas Mode-II provides additional upward/downward, sideways (in/out), and angulated movements of the probe with the anal aperture used as a fulcrum (Fig. 2c and Fig. 4). A generic design of the robotic manipulator with four degrees-of-freedom (DoF) was used, based on the manipulator design previously presented and used in other studies.[34,38,39] Mode-I required actuation of only DoF-3 and DoF-4 for rotating and translating the probe, whereas Mode-II required actuating of all four DoF for the needed motions. Under each mode, the subject's interaction with the AR environment was performed using three input devices: mouse/keyboard, holographic AR menus, and a joystick. The lesions to be targeted while planning biopsies were rendered in the form of spherical objects in the environment. These targets ($n = 5$) were pre-positioned inside the prostate and their positions varied for the two modes. As the user-studies focused on the interaction of the user with the AR environment, the studies were conducted offline (i.e., in absence of a connected manipulator and MR scanner) and suitable assumptions were made related to registration and actuation of the manipulator/probe. The first assumption included that the manipulator base is affixed on the MR scanner bed and the manipulator is registered with respect to the MR scanner co-ordinate system. This will enable registration of MR images acquired via the scanner with the manipulator/probe in the virtual space. Secondly, the pose of the probe after actuation of the manipulator can be computed with respect to MR scanner coordinate system by acquiring and analyzing MR images depicting fiducials on the probe.

Before conducting the studies, subjects were familiarized with the holographic views and manipulations available with the various input interfaces (in particular, familiarization with the different interactions available to conduct the biopsy planning). The sliders on the holograms (Fig. 5a) and screen (Fig. 5c) were used to modify the DoF of the robotic manipulator, which in turn move the needle into an appropriate location that can penetrate the targeted lesion. Additionally, the same interactions were made available through a PlayStation 4 DualShock 4 controller (as shown in Fig. 5b).[40] The left set of buttons (arrows) and thumb sticks on the controller were assigned to ease the manipulation of the proxy. The configuration on the controller was set such that if a button (or bending of the stick) causes motion of the proxy in a desired direction, the opposite button (or bending of the stick in the other direction) causes motion in the reverse direction. This natural configuration was intuitive for usage. As it is easy to perform manipulation using the arrows on the controller, the proxy's movements common to both Mode-I and Mode-II (i.e., translation and rotation of the proxy) were assigned to them. The motions required for Mode-II were assigned to the left and right thumb sticks. The left thumb stick motions (i.e., up/down and right/left) were mapped to the proxy's up/down and in/out translations, respectively. The right thumb stick motion (i.e., rotational) was mapped to the angulation of the proxy. These two thumb sticks enabled multi-directional control of the probe. The least used functionalities, such as visual toggles and traversing the slices, were assigned to the right set of buttons (shapes) and the trigger buttons located on the back of the controller. After familiarizing with the various forms of input, the user was also given time to familiarize with a control used to transform (rotate, translate, and scale) the holographic scene using an anchor object. This allows the user to scale the scene to a size deemed necessary by the user to observe the needle collision with the targeted lesion, as well as move the scene to avoid walking around it if preferred by the user.

During the user-studies, subjects were asked to plan the intervention by visually analyzing the probe's workspace with respect to the MR images and manually adjust the pose of the probe's proxy using the interactions given to adjust the manipulator, such that the biopsy needle reaches the targeted lesion. When the needle trajectory was finalized for a target, the subject concluded the planning by clicking on the "Check Target" button. If the biopsy was successful, a new target was generated, otherwise, the subject was asked to continue planning with the existing target. A biopsy was considered successful if the distance between the biopsy needle and the center of the spherical target was less than the sum of the spherical target's and needle's radii (target's radius + 0.3 mm).[41]

For every targeted lesion during the simulated biopsy planning, the duration required to complete the biopsy task and its accuracy were recorded. The accuracy of the simulated biopsy was measured as the distance between the center of the targeted lesion and the closest point to the needle's center line (using the point-to-line distance formula). The number of actuations made (actuation count) through the different interfaces for manipulating the probe's proxy pose under the two modes were recorded as well. Additionally, the number of times the holograms were transformed (either rotated, scaled, or translated) around the real space was recorded. For the Mode-II trials, due to the need of actuating DoF-1 and DoF-2, it was possible for the proxy to be positioned out of a possible configuration (i.e., violating the

DoF value constraints). Thus, the duration for which the proxy's pose remains valid was also recorded.

RESULTS

The explanatory variables of the study consisted of 'Professional Experience', 'Prior 3D Experience', 'Targets', 'Modes', and 'Interfaces', and the remaining recorded values constituted as the response variables: 'Accuracy'; 'Duration'; actuation counts for 'Translate Proxy', 'Rotate Proxy', Proxy Angle', 'Proxy Out / In', and 'Proxy Down / Up' as well as their total sum; binarized interaction counts for 'Rotation', 'Translation', and 'Scaling' as well for total transformations; and 'Duration for valid proxy pose' in case of Mode-II. The response variables were used to describe the interaction of the operator with the MR scanner and robotic manipulator via the interfaces and characterize the information flow. In this study, we focus only on objectively determined response variables, and we did not consider any subjective measures that could provide information about the perceived workload at each trial of the experiment.

From the explanatory variables in the study, we considered the factorial of the variables 'Targets' with 5 levels, 'Modes' with 2 levels, and 'Interfaces' with 3 levels, resulting a total of 5×2×3=30 possible combinations. All thirty combinations applied to each of the six participating subjects (i.e., we had 30 measurements per subject) providing six replications of the design and giving rise at the end on 30×6=180 data points for the statistical analysis. The factors 'Professional Experience' with 3 levels and 'Prior 3D Experience' with 2 levels are considered as nuisance factors that were available and used in the statistical models to further reduce the experimental error. The subjects were considered as random blocks in the statistical models, considering the possibility of significant subject-to-subject variation. In each of the 180 trials, all aforementioned (objective) response variables were recorded and then each one was analyzed using a mixed effects model, with the fixed main effects being the explanatory variables under study and with the participating subjects considered as random blocks. In addition, for each of the response variables, an appropriate transformation was used so that the statistical assumptions (based on diagnostics) are not violated. For each transformed response, the p-values of each of the explanatory variables in the full mixed effects model (Anova) were computed and assisted in indicating the significance. Furthermore, post-hoc analysis (Tukey) was performed to determine statistical difference between all possible pairs. The followings results were observed:

Accuracy & duration for biopsy planning

All the subjects were able to successfully perform virtual biopsies during the studies within the range of required accuracy (Fig. 6). No statistically significant difference was observed among subjects based on their professional experience (researchers, general physicians, and urologists) or prior experience working in 3D environments. Irrespective of the input interface, subjects were able to hit the targets with higher accuracy in Mode-I as compared to Mode-II ($p < 0.0001$). The duration required for Mode-I was also less as compared to Mode-II ($p < 0.0001$). The interfaces played a significant role in determining the duration. The joystick took the least duration for planning biopsies as compared to AR menu ($p < 0.0001$) and mouse/keyboard ($p = 0.0015$). The average durations required for the joystick, AR Menu, and mouse/keyboard were 99 s, 166 s, 125 s, respectively. It was also observed that the duration was significantly affected by the target (P=0.0001). Though the size of subsequent targeted lesions (T3, T4, T5) decreased as compared to the first target (T1), the accuracy improved (as the operator was forced to hit smaller radius targets) with less duration required (average duration for T1, T3, T4, and T5 were 213 s, 130 s, 115 s, and 106 s, respectively). The target T2 was the largest, hence the accuracy was lower; it had a lower average duration (85 s) for planning.

Actuation of probe's proxy

It was observed that the three interfaces (AR menu, joystick, mouse/keyboard) used during the studies significantly affected the actuation counts required to pose the probe's proxy during biopsy planning (Fig. 7). In particular, for the explanatory variable 'input interface type', the *p*-values were $p < 0.0001$ and $p = 0.0001$ for response variables representing individual actuation counts ‘Translate Proxy’, 'Rotate Proxy'. Whereas *p*-values for Mode-II only were $p = 0.0039$, $p = 0.0215$, and $p = 0.0044$ for response variables representing individual actuation ‘Proxy Angle', ‘Proxy Out / In’, and ‘Proxy Down / Up’, respectively. The *p*-values for total actuation counts for both Mode-I and Mode-II individually were $p < 0.0001$. In general, based on the mean and average value, the AR menu required a higher actuation count as compared to the joystick and the mouse/keyboard interfaces. Whereas within the two, the joystick required a higher actuation count as compared to the mouse/keyboard.

Interaction with holograms

The interaction counts (i.e., if the operator has interacted by either rotating, translating, or scaling the hologram) showed statistical significance for input interface type ($p = 0.0293$). As shown in Fig. 8a, the total binarized interaction counts (i.e., counted as 1 if the operator has interacted with the hologram or 0 if not) for AR menu, joystick, mouse/keyboard were and 39, 33, and 43, respectively, and were not statistically different.

Duration for valid proxy pose

The type of interface significantly affected the duration for which the proxy pose was valid in Mode-II ($p = 0.002$). As shown in Fig. 8b, the joystick took the least average duration as compared to the AR menu ($p = 0.0001$) and mouse/keyboard ($p = 0.0380$). The average durations spent in a valid configuration for the joystick, AR menu, and mouse/keyboard input interfaces were 95 s, 153 s, and 114 s, respectively.

DISCUSSION

The user-studies demonstrated that the generated AR planning environment was perceived alike by the subjects, irrespective of their professional or prior experience working in 3D environments. The interaction counts with the holograms rendered in the AR planning environment were also similar, irrespective of the input interfaces used during planning.

It was observed that targets were planned with higher accuracy and less duration in case of Mode-I as compared to Mode-II, irrespective of the interface used, most probably reflecting the simplicity of Mode-I as it requires manipulation of only two DoFs: translation and rotation of the probe. Among the interfaces for the two modes, joystick as an input interface took the least duration for planning a biopsy. Additionally, in the case of Mode-II, the proxy remained in a valid pose for a shorter duration while using the joystick. This could mean that the subjects were able to easily manipulate the pose of the probe's proxy to evaluate different possible proxy configurations for a biopsy and select the most suitable one with less duration.

It was noted that the joystick input as compared to mouse/keyboard required a higher actuation count whereas the duration for biopsy planning was less. This observation supports the notion that with the joystick the operator can provide more information in less time. One may then assume that the joystick improved the interactive capacity to efficiently capture the operator's actuation commands. The actuation count was highest for the AR menu and also the duration to plan the biopsy. This showed that the AR menu was difficult to operate and send information for planning.

A goal in these studies was to investigate the use of an AR device, i.e., the HoloLens, as an output interface for visualization of biopsy planning. Although visualization of the 3D interventional environment on a 2D screen is enough to plan a biopsy,[42] the additional visual properties of holograms have the potential to make biopsy planning easier to learn and execute. This is because visualization through holographic AR provides true 3D visualization, giving depth to the renderings. One thing that may be of interest is that a HoloLens cannot be brought into the biopsy room, due to the magnetic field of the MRI. As a result, the biopsy planning environment being rendered by the HoloLens must be interacted with prior to entering the MRI room. As a result, one may wonder why use AR over virtual reality. Although the current system can be adjusted to work with virtual reality, AR is more practical as it can be used hands-free and gives the physician the ability to see the surroundings. The operator may scale the holograms to match dimensions of the anatomy, place physical entities such as the biopsy needle or probes onto the holograms and assess the size and poses of these physical entities with respect to the area-of-intervention before performing the biopsy. Another important observation that may be made is that the proxy maneuvering was applied through a set of sliders, rather than grabbing the proxy itself and moving it around with one's hand. Preliminary tests demonstrated that the sensitivity of the movement with one's hand made it difficult to make small adjustments in one dimension without affecting the other dimension. This would require further development and studies to improve the ergonomic and intuitive interaction using hand gestures.

The motion of the transrectal probe is constrained by the anatomical structures during biopsy. In case of transrectal MRgPBx biopsy, the patient's position is prone and elevated from the hips (by placing a pillow underneath the pelvic). When the probe after lubrication is inserted into the rectum, the main resistance and constrain in terms of probe motion is provided by the anal sphincter at the rear end. In case of Mode-I of operation (side firing), the axis of the probe (along which the probe rotates and translates) passes through the anal sphincter which provides the resistance. The rectal wall doesn't impose any further constrains on the robot kinematics.[43] However, in Mode-II of operation (end-firing), the operator has to ensure axis of the probe doesn't displaces from the region of anal aperture. In the current study, the operator manually plans the motion of the probe's proxy and uses anal aperture as a fulcrum. To automate this, virtual fixtures can be integrated based on the anatomical boundaries acquired through MR imaging to constrain the motion of proxy within acceptable anatomic thresholds while planning.[44,45]

During biopsy, the morphology of the prostate changes as it deforms under the pressure exerted by the transrectal ultrasound probe. The deformation caused by probe actuation can be addressed by acquiring a new set of real-time MR images to confirm the pose of the probe with respect to prostate and refreshing the visual information on the HMD before inserting the biopsy needle.[42] It should be noted that insertion of biopsy needle, in either Mode-I or Mode-II, also causes tissue deformation. Though the detection rate is similar for both modes[46,47] except for certain regions,[36,48] the biopsy targets initially identified on the MR image need to be readjusted to account for this morphological change in prostate. This would require integration of non-rigid registration algorithms based on computational approaches (such as finite element models,[49,50] b-spline mapping,[51] non-linear warping,[52] and mutual information registration[53,54]) into the software to account for elasticity of the prostate.

The studies were conducted taking into consideration the clinical scenario of real-time in-bore MRgPBx. While currently such systems are not routinely used in clinical practice, in-bore MR prostate systems are further developed and investigated.[9,10,55] In a hospital, conducting these prostate biopsies may be difficult due to logistic issues related to availability of dedicated MR scanners and an intervention team comprising of MRI technicians, radiologist, and urologists. As a result, MRI-Ultrasound fusion systems are preferred in a clinical setting, where MRgPBx is performed using preoperative MRI fused with real-time intraoperative transrectal ultrasound.[56] The proposed AR environment will be in particularly beneficial for such setup where dynamic holograms of real-time ultrasound image fused with prostate/lesion boundaries (extracted from preoperative MR images[57]) is displayed along with the transrectal probe in true 3D. The information projected on to the patient during biopsy will improve the hand-eye coordination for transrectal probe manipulation. The implementation would require integration of an external tracking system[58] to continuously register the poses of transrectal probe and the HMD, fed it to the computational unit to compute the poses of holograms in real-time, and dynamically render it using the HMD. This will open doors for integration of proposed AR planning environment in existing planning software / platforms for MRI-Ultrasound fusion systems (such as UroNav – In Vivo/Philips, Artemis – Eigen, Urostation – Koelis, Virtual Navigator – Esaote, HI RVS – Hitachi)[59] as well as real-time MR guided systems (such as DynaTrim In Vivo/Philips[60] and RCM – Soteria Medical[61]).

With joysticks or trackballs in surgical or image-guided interventions, it's intuitive to align the visualization of the intervention area with the workspace of the interventional tool motion as if the operator is using a first-person point of view. This alignment is observed in Monarch® Platform by Auris or Ion Endoluminal system by Intuitive Surgical, where a flexible robotic endoscope controlled by a joystick/trackball is used to navigate the lung periphery for a biopsy. However, in the current implementation, this alignment is not possible because the intervention area was rendered as a hologram using the HMD and observed by the operator from different viewpoints depending upon the position of the operator. This non-alignment of visual and proprioceptive fields causes a limitation on the intuitive use of joysticks. An alternate method would be to first align the holograms with respect to the operator and then to use an interface that replicates the operator's motions for moving a TRUS probe during prostate biopsy. An interface in the form of a stylus can be used to replicate the TRUS probe, and its motions can be one-to-one mapped to the virtual probe motions in the AR view.[62–64] This would require conducting further studies to evaluate effectiveness of the stylus as compared to the joystick, especially in respect to an AR environment.

The emergence of immersive visualization with HMD is often combined with the adjective "holographic" to describe the viewed computer generated augmented or mixed reality scenery. With such devices, the 3D entity is present and exists only inside the HMD, rather than formed in the actual 3D space. These HMD do not use the physics principles of generating a hologram as a 3D object in real space (e.g., with multiple modulated laser beams). These devices generate a 3D perception, i.e., using the literal translation of the Greek word ολόγραμμα (writing or recording of the entire "whole" object), and the operator perception of the scenery is ολογραφική (holographic, as an adjective, i.e., describing the entity that generates or contains holograms). It should also be noted that in this work, the presented scene is an augmented reality one because the rendered scene is co-registered to the real space using the native capabilities of the used HMD. The employed HMD (HoloLens) is used as an Input/Output (IO) device that enables the users to (i) view a 3D scene in the 3D space and (ii) interact with it.

Looking into translation to the clinical realm, we should be aware that until different HMDs are available, new computational methods may emerge that offer improved tools in processing, characterizing, and rendering image-based information, and new clinical paradigms. This, as well as a plurality of prior and current groundbreaking efforts of developers and investigators worldwide, are part of the effort to enable such transitions. The observations on the performance of those three interfaces for interacting with holograms may guide investigators through this endeavor. Secondary to these observations, our team's plan is to embark on the pursuit of more ergonomic interfaces (including incorporating advanced voice control) and other handless and non-interfering human-machine interfaces.

CONCLUSION

The study evaluates various input interfaces, including the conventional mouse/keyboard, built-in hand gestures in the AR device, and an external joystick peripheral for manipulation of the interventional environment visualized with AR. The results show that other forms of input aside from the conventional ways and the built-in mechanisms of the AR device, such as the joystick, can significantly improve the amount of information that the physician may enter into the planning environment at a given time. The results from these studies also showed the potential use of AR visualization to enhance robot-assisted prostate biopsy procedures by immersing the physician into the AR environment.

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Figures

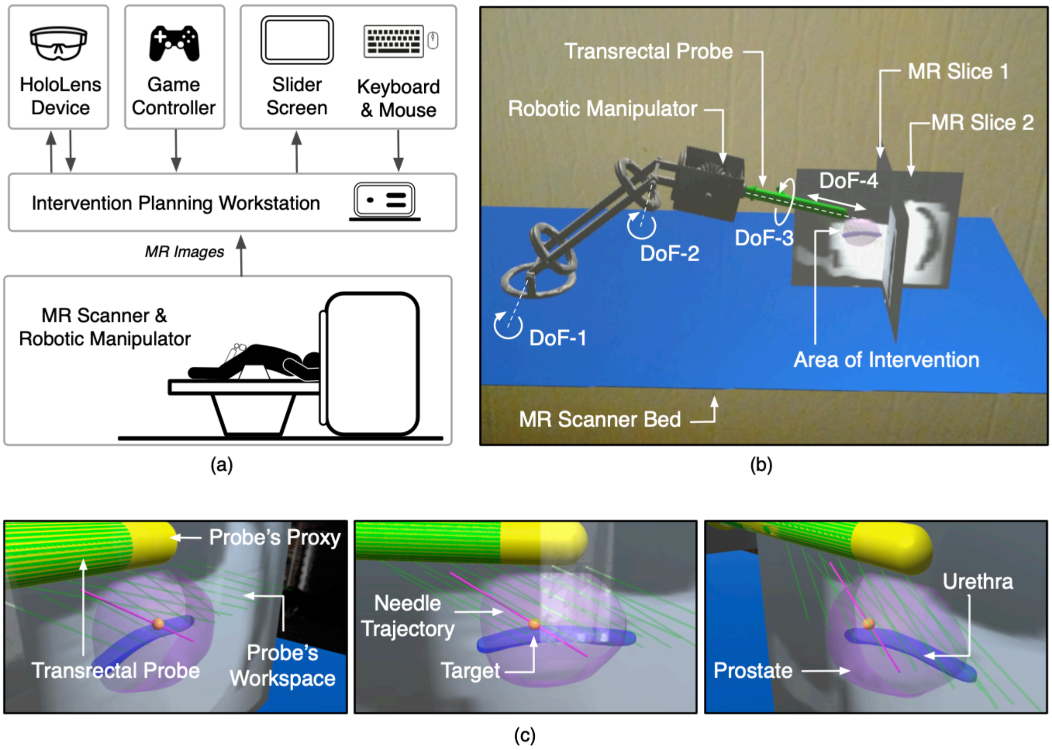

Fig. 1: (a) Schematic representation of the study setup illustrating the different components and their interaction: (i) The interventional planning workstation receives MR images from the scanner and computes the actuation commands to manipulate a virtual robotic manipulator for placement of the probe. (ii) the human-machine-interfaces: HoloLens device, joystick, slider screen, and mouse/keyboard, (iii) the MR data library, and (iv) a virtual manipulator. (b) Virtual representations of physical entities related to area-of-intervention rendered in the form of a hologram presented to the HoloLens device, (c) three close-up views of the area-of-intervention.

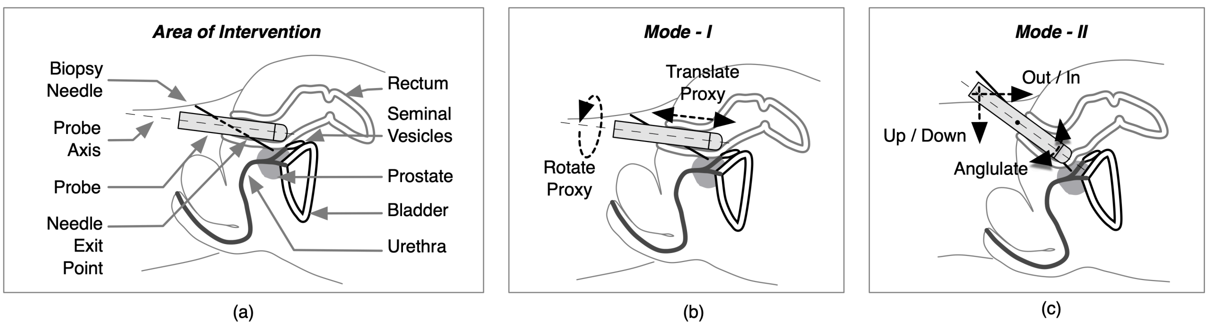

Fig. 2: (a) Schematic representation of the augmented planning environment, (b) Mode-I of operation allows side-firing of the needle during biopsy. It enables probe to be rotated and translated. (c) Mode-II of operation allows end-firing of the needle during biopsy operation. In addition to Mode-I motion, it enables the probe to be move up/down, out/in, and angulated.

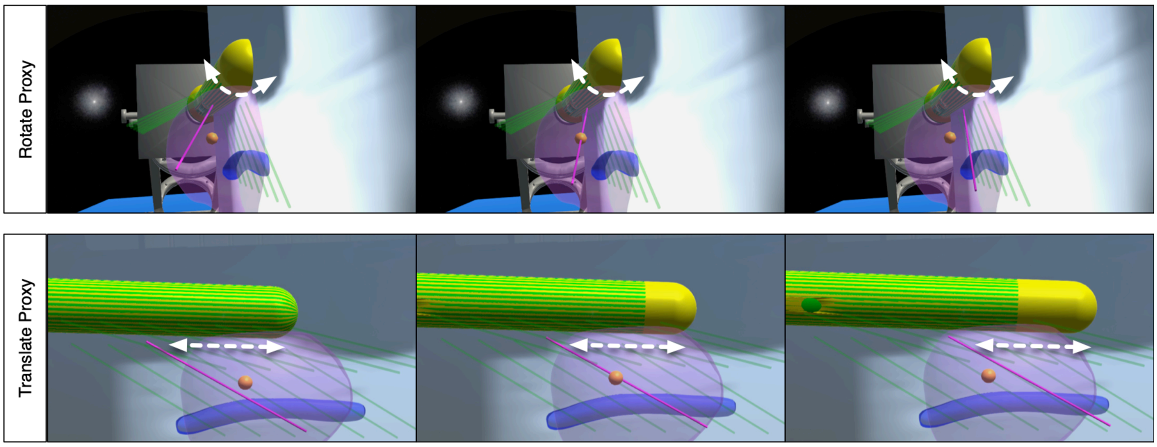

Fig. 3: These captures present the holograms viewed by the operator, demonstrating the rotation and translation of the probe's proxy along the probe's axis for Mode-I. The motions indirectly adjust the DoF-3 and DoF-4 of the robotic manipulator.

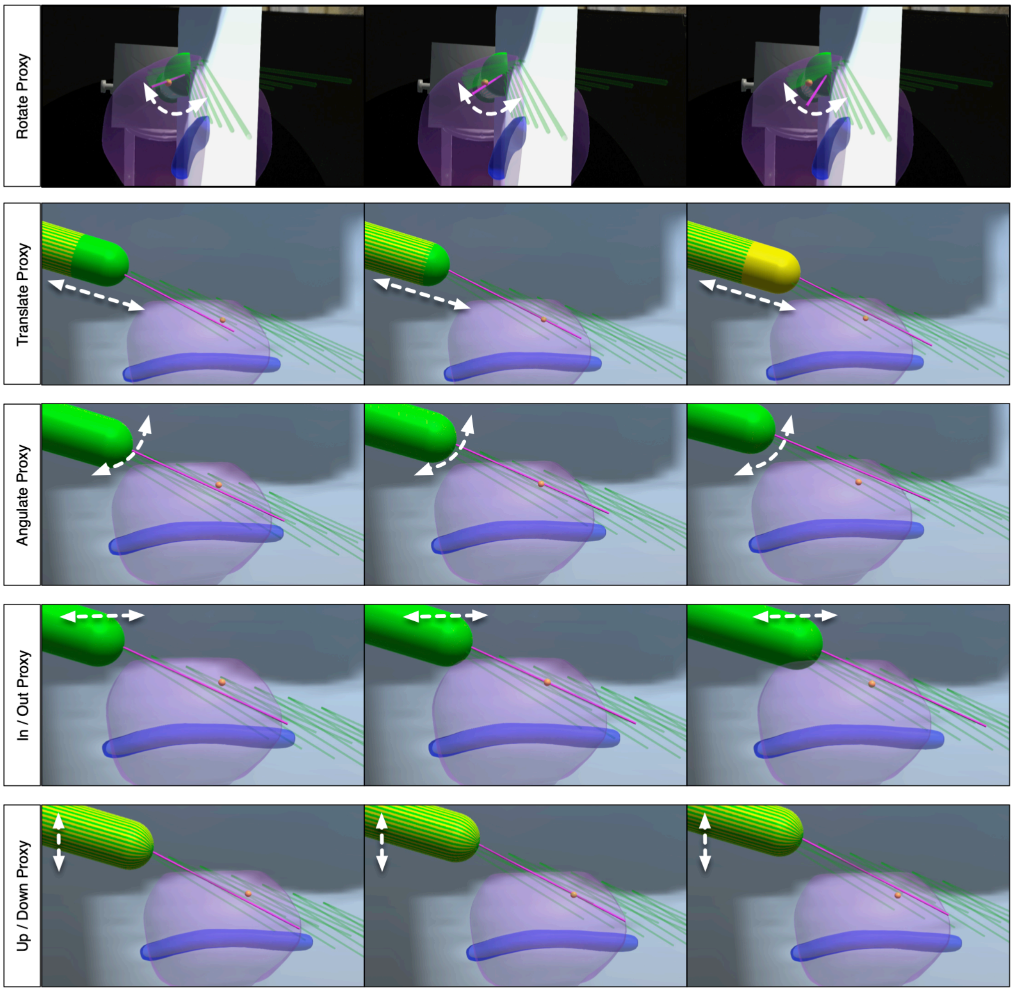

Fig. 4: These captures present the holograms viewed by the operator, demonstrating the motion of the probe's proxy for Mode-II. Rotate and translate motions are similar to Mode-I's rotation and translation. In addition, up/down, in/out, and angulate motions are available for Mode-II, which indirectly adjust DoF-1, DoF-2, DoF-3, and DoF-4 of the robotic manipulator.

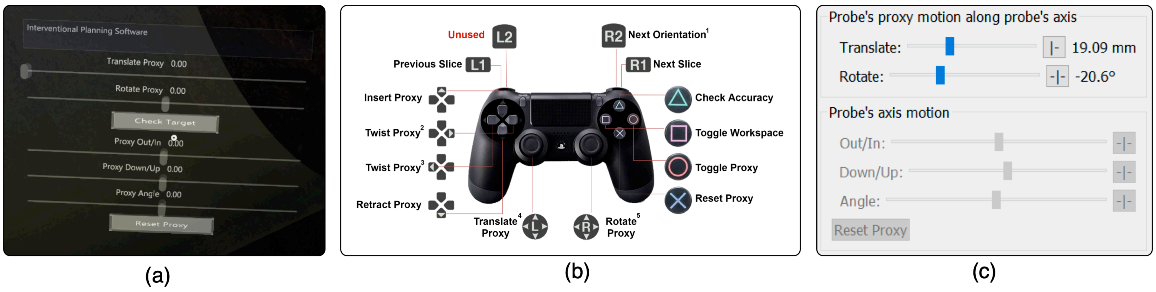

Fig. 5: The three interfaces used for manipulating the augmented interventional environment: (a) Holograms representing AR (augmented reality) menus, (b) Joystick, (c) sliders on a screen.

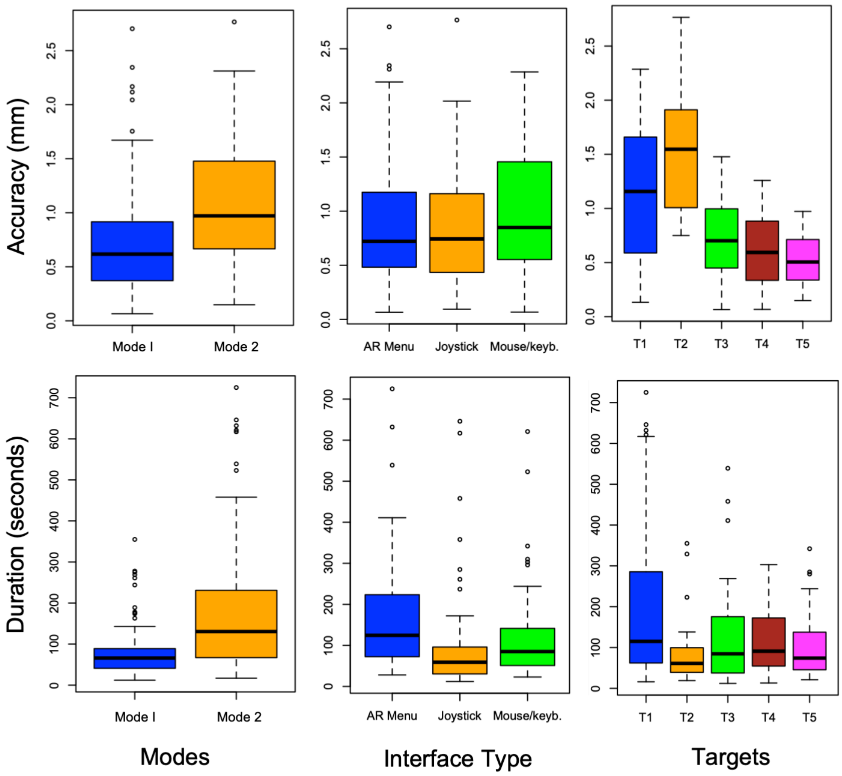

Fig. 6: Distribution of duration and accuracy data for modes, interface type, and targets during virtual biopsy planning. The modes of operation comprised of Mode-I and Mode-II. The interface types used were Augmented Reality (AR) menu, Joystick, and Mouse/Keyboard. Five targets (T1, T2, T3, T4, T5) were set as lesions for virtual biopsy.

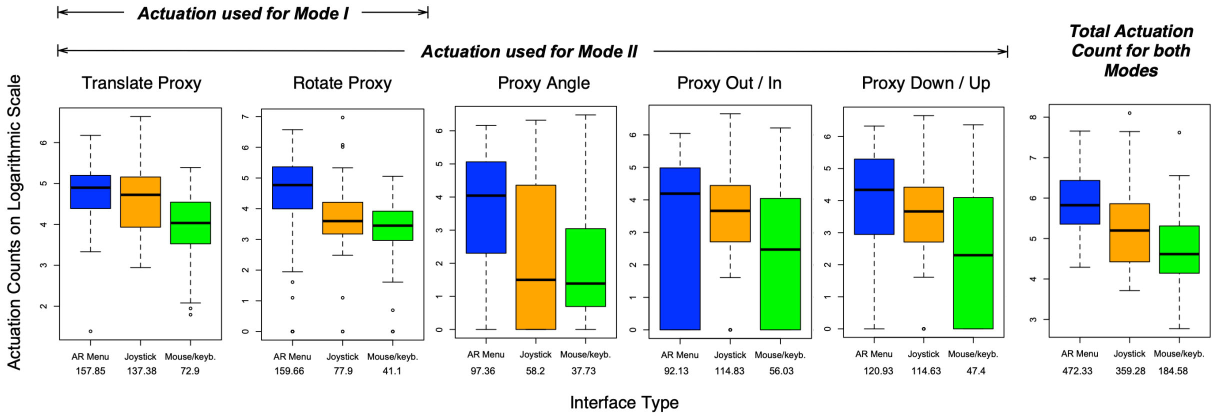

Fig. 7: Distribution of individual actuation counts for manipulating probe's proxy via translating, rotating, angulating, moving it out/in and down/up. Translate and rotate proxy are used for both Mode-I and Mode-II, whereas angulation, out/in, and down/up motion are used for Mode-II only. The total actuation count combines both the modes.

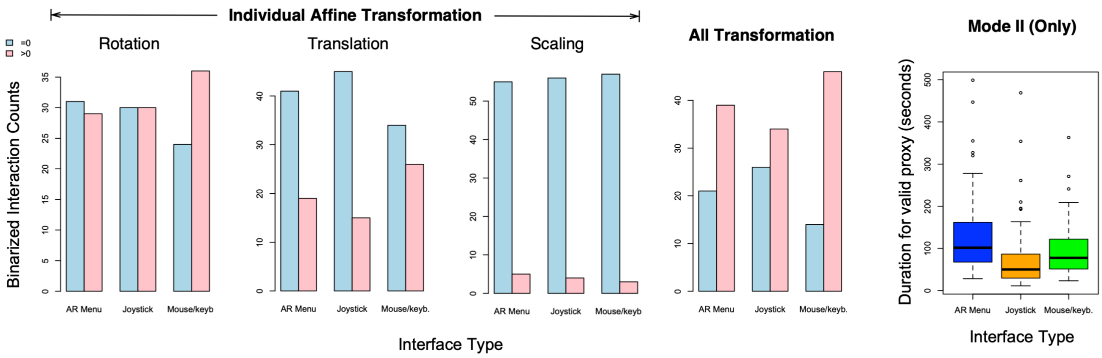

Fig. 8: (a) The binarized interaction counts shows if the operator has interacted with the augmented environment by either rotating, translating, or scaling the hologram using the interfaces. Rotation, translation, and scaling correspond to individual affine transformations. (b) Duration for which the proxy pose remains valid in Mode II when using the different interfaces.