Interactive and Immersive Image-guided Control of Interventional Manipulators with a Prototype Holographic Interface

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***Abstract*—The emerging potential of augmented reality (AR) to improve 3D medical image visualization for diagnosis, by immersing the user into 3D morphology is further enhanced with the advent of wireless head-mounted displays (HMD). Such information-immersive capabilities may also enhance planning and visualization of interventional procedures. To this end, we introduce a computational platform to generate an augmented reality holographic scene that fuses pre-operative magnetic resonance imaging (MRI) sets, segmented anatomical structures, and an actuated model of an interventional robot for performing MRI-guided and robot-assisted interventions. The interface enables the operator to manipulate the presented images and rendered structures using voice and gestures, as well as to robot control. The software uses forbidden-region virtual fixtures that alerts the operator of collisions with vital structures. The platform was tested with a HoloLens HMD in silico. To address the limited computational power of the HMD, we deployed the platform on a desktop PC with two-way communication to the HMD. Operation studies demonstrated the functionality and underscored the importance of interface customization to fit a particular operator and/or procedure, as well as the need for on-site studies to assess its merit in the clinical realm.**

***Index Terms*—augmented reality, robot-assistance, image-guided interventions.**

I. INTRODUCTION

An important challenge in image-guided interventions (IGI) is the effective visualization and use of three dimensional (3D) imaging [1]–[7]. This information is critically important for an accurate appreciation of special relationship, to accurately reach the targets and to avoid harming healthy tissue or vital structures. Magnetic Resonance Imaging (MRI) is one of the most valuable modalities offering unique features. In parallel, robot assisted interventions and surgeries are being established and evolving, motivated by the potential to improve patient outcome. MRI-guided robot-assisted interventions are also an evolving area of potential clinical interest [8].

In practice, most interventionists perform mental extraction of 3D features and their spatial relationships by viewing numerous 2D MRI slices from a 3D set [9]. Many ground-breaking rendering techniques have been introduced for 3D visualization [2]–[4], but 2D visualization remains the standard practice. Augmented reality (AR) visualization has shown potential for the above challenges. By fusing and co-registering images, segmented anatomical structures, patient models, vital signs, and other data into a combined model projected onto the physical world, information is contextualized. This concept of operator immersion into information was further enhanced with the introduction of head-mounted displays (HMD) [2]–[4]. Such devices enable visualization of AR holographic scenes. A growing number of studies demonstrates the potential of AR and HMD in different medical domains, including IGI [1]–[7], [10]–[12].

In this work, we describe a platform of an AR holographic interface for performing image-guided and robot-assisted interventions, for MRI and using a three degree-of-freedom (DoF) custom-made manipulator. We propose interactive manipulation of images, objects and robot. Furthermore, 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 the processing to eliminate latencies and enable efficient computation. As an interface, the HMD is used for registering with the physical world and presenting the

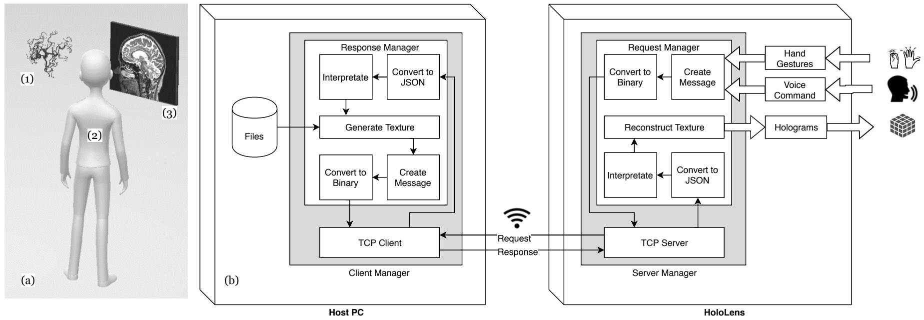

Fig. 1. (a) Topology of the holographic AR interface; the operator (1) is immersed into a scene that includes the holographic structures (2) and an embedded 2D window (3). (b) Communication of the Host PC and HoloLens.

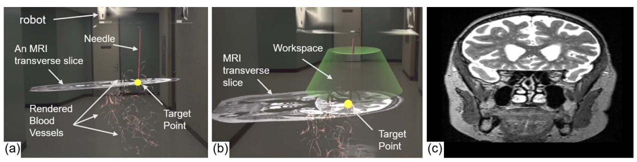

Fig. 2. (a) and (b) are holographic views that include MIR slice, blood vessel and 3D models of the robot and needle. (c) is the embedded 2D window.

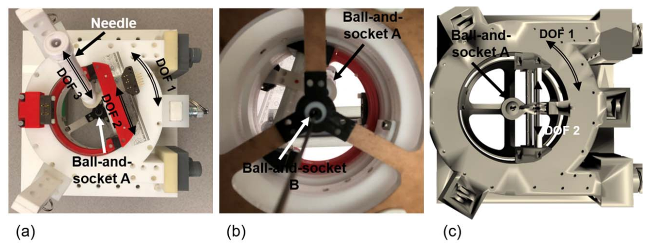

Fig. 3. Photographs of the robot's top (a) and bottom (b). The 3D virtual model (c) was captured from the Unity3D console.

holographic scene and receiving gesture and voice commands. Our team pursued a hardware-independent approach, however, for the presented work, we customized the output for use with the Microsoft HoloLens HMD [13]. Finally, the platform was tested in silico to assess latencies and functionality for the specific neurosurgical clinical paradigm of accessing a brain meningioma with a needle-based tool.

II. Methods

A. Overview of the Framework

Figure 1(a) shows the topology of the entities in the holographic scene that includes (1) the operator, (2) hologram structures, and (3) an embedded 2D virtual display. To address the limited computational power and memory of the Microsoft HoloLens and enable real-time interaction, all processing of the MRI data sets are handled on the Host PC. Figure 1(b) illustrates the interaction between the HoloLens and the Host PC. The operator requests data by using hand gestures or voice commands, to which the PC responds accordingly.

The holographic scene in Figure 2(a) includes an MRI slice, segmentations of segmented structures (blood vessels) extracted from those sets, a model of the manipulator, and a needle. Figure 2(b) illustrates the workspace and Figure 2(c) displays the 2D virtual window to show individual slices.

B. Robot Model

Figure 3 shows the physical prototype and the model of the three-DoF MRI-compatible robot [14], [15]. The manipulator has two actuated DoF: a rotating ring and a prismatic joint that carries the tool with a ball-and-socket A. With the combined actuation of DoF-1 and DoF-2, point A can be positioned inside a circle of radius 25 mm. Since the distal end of the tool is carried by ball-and-socket B, which is permanently anchored onto the frame of the robot, the tip of the tool can be at any location of a spherical cone workspace. To enable the movement of the virtual robot, we divided the components of the robot and programmed each component's movement independently. The user can manipulate components by using voice commands and specifies the extent of movement using hand gestures (Figure 4(b)).

C. Human-Machine Interfacing

We used gestures and voice recognition to enable the operator to interact with the holographic scene and robot control in order to perform the above procedures. This was necessary to streamline the operation without the need to sterilize the equipment and the operators access to the equipment (keyboards, mouse, etc.) or an assistant. Table I lists the voice commands and the corresponding functions. Other voice commands could be implemented depending on operational needs and the kinematic structure of the manipulator.

D. Planning and Robot Control

The operator can select a target point T and interactively set the needle by moving the virtual robot components. The operator can also place an insertion point B (mimicking an actual neurosurgical access) for future stereotactic planning. Table II reports the workflow concluded from in silico tests. An important step in the workflow is the positioning of the

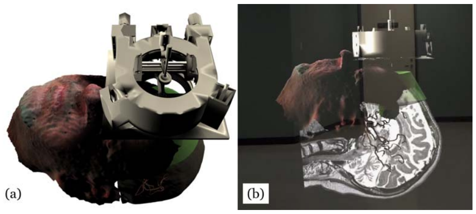

Fig. 4. Perspectives of the holographic scene as shown on the Unity Editor (a) and on the HoloLens (b).

TABLE I
VOICE COMMANDS AND THEIR FUNCTION

Command	Function
	Robot Manipulation
Robot	Toggle between presenting and not-presenting Robot Rendering
Workspace	Toggle between presenting and not-presenting Robot Workspace
Operate	Activate robot, i.e., joints can be manipulated
Rotate	Activate rotational joint (DoF 1)
Translate	Activate prismatic joint (DoF 2), i.e., translation of the needle carriage
Insert	Activate needle prismatic joint (DoF 3), i.e., insertion of the needle
Adjust X, Y, Z	Adjust position of the robot in relationship with the subject's head
Stop	Disable the movement of the robot
	HoloScene & Image Manipulation
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
Length	Change the window-length value
Width	Change the window-width value

robot. Robot positioning is performed after MRI inspection and entails visualizing the workspace and manually adjusting it.During planning, as the operator maneuvers the virtual robot, the software collision module checks (i) whether the needle passes through a vital structure (as defined by the forbidden areas) and (ii) whether the distance from point T to point B of the robot is longer than the insertable length of the tool.

E. System Testing

A total of four operators tested the platform. One clinical personnel, computer science and engineering school faculty and graduate students. During the operation of the system, we recorded (i) what action was taken and for what purpose and (ii) comments of the operator regarding whether the action was (a) inferior, equal, or superior to, and (b) slower, equivalent, or faster than standard practice. In these studies, we only used subjective evaluations and no quantifiable metrics were used.

III. Results

Figure 5 shows different frames captured from the HoloLens output illustrating the AR interface seen by the operator during a holographic session. The holographic AR visualization was subjectively found to be superior over desktop-based volume rendering in regards to (1) 3D appreciation of the spatial relationship of rendered structures, (2) detection and collision avoidance of critical structures, and (3) controlling the robot. These studies also demonstrated that controlling the robot in the joint space was suboptimal and non-intuitive.

IV. Discussion

Holographics introduces to the clinical realm the immersion into the imaging data and imaging-based 3D or 4D

TABLE II
WORKFLOW OF ROBOT ASSISTANCE PLANNING AND MANEUVERING.

Load MRI data sets and pre-rendered structures
Activate 2D Virtual Display and present the slice
Activate hologram and collision module Inspect hologram and images on the 2D Virtual
Display images to identify the targeted pathologic foci
Place the target point T on the scene.
Operator adjusts the virtual needle.
On-the-fly constraints are applied for (i) collision with forbidden zones, (ii) robot positioning constraints, and (iii) needle length.
(1) All calculations and maneuvering is performed in the MRI coordinate system, assuming that for in situ studies the robot will be registered to the MRI scanner
(2) Placement of the robot model corresponds to drilling the patient's scalp at a location I (or equally B)

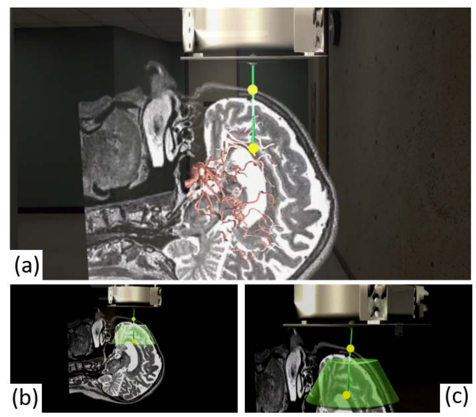

Fig. 5. HoloLens output for a case of planning with the selected target and insertion points (yellow spheres). In the different perspectives collected as the operator moves around the hologram, images, rendered vessels and the workspace can also be appreciated. The needle is colored green since its body does not collide with any forbidden zone.

segmentations [4]–[7], [10], [11]. The design of our system incorporates a Host PC/HMD to provide the needed computational resources for current as well as future tasks. The holographic interface offers superior visualization of complex structures. Additionally, integration of the robot workspace and its interactive placement with holographic visualization of images and rendered structures provided an intuitive and time-efficient tool.

While the described implementation is a proof-of-concept, the presented work has certain limitations. First, only three clinical personnel contributed to the specification of our system and we used only three patient cases. Second, this preliminary work did not include the qualitative assessment of functionality and ergonomics of the platform. Third, the robot kinematic structure was rather limited; however, it proved sufficient to implement the computational framework and explore it within silico studies. We are designing quantitative studies that incorporate metrics for comparing functionality and ergonomics. We will evaluate the benefits of using this holographic tool for planning robot-assistance interventions in comparison to traditional methods of planning. This includes the user's performance, outcome, and collisions (errors). Our studies demonstrated that future development should incorporate an intuitive alternative to voice control in the joint space, as well as the incorporation of image-based force-feedback for improved immersion to 3D and 4D information (as shown before in [16]). Currently, we are incorporating appropriate image processing and optimizing it with multithread implementation [17] and GPU acceleration [18].

V. Conclusions

Medical-data immersion is achievable with today's technologies, and we may expect major developments on this front. However, the merit of immersive technologies will eventually be determined in the clinical realm. Clinical adoption is typically based on patient outcome and cost-effectiveness. Within this context, a surgical planning visualization interface would have merit and impact if it can be seamlessly integrated into the daily workflow of a clinical site. This notion was also the underlying conclusion of the presented studies: the front-end must reduce workload, streamline a procedure, ensure error avoidance, be intuitive, and be ergonomic. In response, we incorporated a voice and gesture control of imaging and robot manipulation and collision avoidance. The experience from developing this platform further elucidated the need for studies to assess merit in clinical practice and, secondary to the inclusion of a new computational layer in patients management, to establish appropriate legal regulations.

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