Augmented Reality in Ventriculostomy

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Abstract

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Freehand ventriculostomy is one of the most common neurological procedures performed when the cerebrospinal fluid increases in the ventricular system. This procedure is most often performed in the emergency room or intensive care unit and thus without a navigation system to help surgeons locate the ventricles. Surgeons instead use anatomical landmarks on the face and skull to determine the best location of the burr hole and trajectory for moving catheter through the brain to the ventricles to drain excess cerebrospinal fluid (CSF) and decrease intracranial pressure (ICP). Freehand ventriculostomy has an associated catheter misplacement rate of over 30% which can lead to a number of complications including mortality and morbidity.

In this dissertation, we propose an augmented-reality pipeline for ventriculostomy using an optical-see-through head-mounted device, the Microsoft HoloLens. Our system, projects a 3D constructed model of the patient's skull and ventricles directly onto the patient's head to guide the surgeon to locate a target on the ventricle. As part of this pipeline, we implemented an API to send real-time tracking information from the optical tracker to the the HoloLens, provided a manual gesture-based registration method, as well as a colored-based depth visualization to help users understand the spatial relationship between the patient's ventricular anatomy and surgical tool.

In a study with 15 subjects, we found that the proposed gesture-based registration has an accuracy of 10.75 ± 4.01 millimeters and target hitting accuracy of 12.28 ± 2.40 millimeters. In terms of usability our developed system received a score of 74.5 on the System usability scale (SUS), indicating that the system is easily usable. Our preliminary results suggest that augmented-reality systems can be helpful for neuronavigation procedures that require target localization.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

Ventriculostomy, one of the commonly performed neurosurgical procedures, is done to reduce intracranial pressure (ICP) in cases of hydrocephalus, brain tumours, traumatic brain injuries, spina bifida, and hemorrhage. The procedure involves drilling a hole in the skull, and dura mater, and guiding a catheter or external ventricular drain (EVD) through the brain to the ventricles to extract the cerebral spinal fluid (CSF) thereby decreasing ICP.

In some cases, surgeons have access to pre-operative images (e.g. computed tomography images (CT) or magnetic resonance images (MRI)) and conventional image-guided surgery systems for guidance. More commonly, however, ventriculostomy is performed in emergent settings or at bedside without any guidance systems. In this case surgeons rely on anatomical landmarks on the skull, to determine the best entry point and best trajectory for safe EVD placement [1]. In these types of emergency settings, poor targeting of the ventricle is associated with over 30% misplacement [2] due to human error. Complications resulting from EVD misplacement, including hemorrhage, inability to control ICP, etc., can lead to increases in the length of hospital stays, morbidity and even mortality. Thus, computer-aided guidance got greatly improve the success of this procedure.

1.1 Image-guided Neurosurgery

Understanding an individual's patient anatomy, as well as the spatial location of the anatomy of interest is pivotal to the success of a surgical intervention. Image-guided neurosurgery (IGNS), also known as neuronavigation systems aim to provide this type of guidance information in the operating room. Neuronavigation systems require a tracking system to track surgical tools and patient location in the operating room and a registration or mapping between the patient and their pre-operative images. These two things enable real-time localization of the surgical tools with respect to the patient anatomy thus guiding the surgeon to the anatomy of interest (e.g. the ventricles, a tumour, aneurysm, etc).

Despite the high accuracy of these systems, there are some shortcomings to current

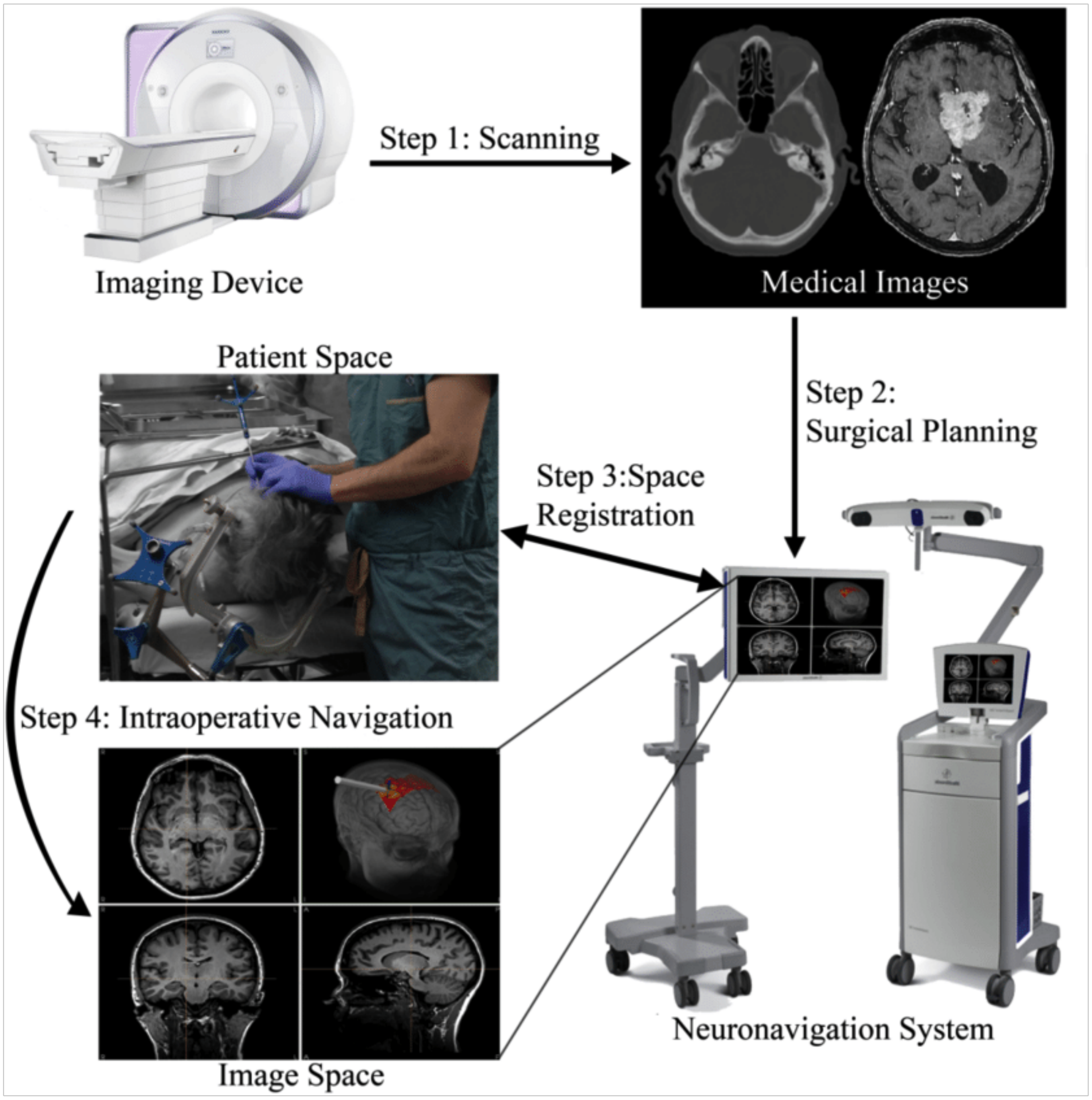

Figure 1: An augmented reality based image guided neuronavigations system. All components of IGNS system and their relations with surgical environment are shown [3].

commercial systems. One of these is that the surgeon must map the guidance images from the neuronavigation system with the 3D anatomy of the patient which introduces focus shifts between the patient and the system and interruptions in the surgical workflow. A solution that has been proposed to alleviate this is to use Augmented Reality (AR).

1.2 Augmented Reality in Surgery

In contrast to virtual reality (VR), which is a purely digital world, augmented reality (AR) has been defined as the merging of digital elements into the real world. In the case of surgery, the virtual or digital elements are typically the anatomical patient data and the real world, the actual patient. This type of visualization gives the surgeon *Superman X-ray vision* such that they can look below the exposed surface of the brain at the underlying anatomy (e.g. tumours, ventricles, vessels). Augmented reality has been explored in many types of surgery and in neurosurgery in particular it has been shown to improve the accuracy of procedures by addressing issues related to conventional navigation systems including focus shifts and high cognitive load associated with mapping the guidance images from the IGNS system to the 3D anatomy of the patient.

Various hardware devices have been introduced for medical interventions, including tablets, half silvered mirrors, and head-mounted displays. In this thesis, we focus on the Microsoft HoloLens, a head-mounted 3D rendering AR device that became commercially available in 2017. The HoloLens offers features like spatial localization mechanism (SLAM), voice commands, hand gesture interaction, and the ability to render complex 3D models. For these reasons, researchers have explored the use of the HoloLens for various surgical navigation procedures including: ventriculostomy, burr-hull placement, lesion resection, endoscopic surgeries and orthopedic surgeries [4–8].

Given the complications related to ventriculostomy and high chance of catheter misplacement reported, in this thesis we aim to improve this procedure by introducing a guidance system. Current IGNS pipelines suffer from the problems like focus shifts and high cognitive load related to the way the guidance information is presented to the surgeon. To mitigate these drawbacks we used augmented reality via a head-mounted display to shift guidance information from the 2D display of conventional IGNS workstation to the actual patient.

Contribution

In this research, we aimed to mitigate the complications related to ventriculostomy by using a OST-HMD augmented reality device (Microsoft HoloLens 1st generation). To do so, we developed an augmented reality pipeline and determined the accuracy of the developed system using a high end optical tracking system. Specifically, the main contributions of this thesis are:

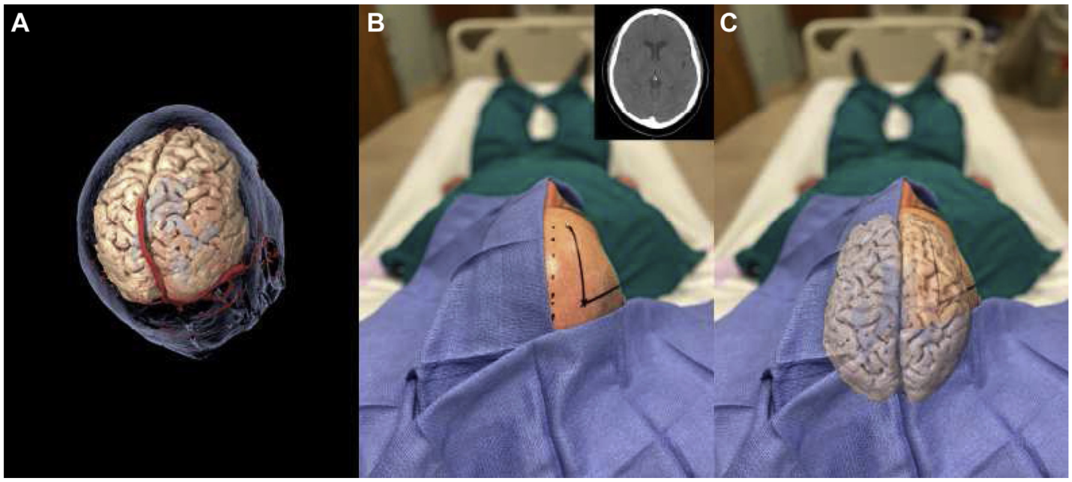

Figure 2: Virtual and augmented reality in surgery. (A) Virtual reality display of 3D brain model. (B) Augmented reality use for displaying pre-operative scans in the field of view of the surgeo. (C) Augmented reality projection of brain model directly on the patient [9].

- Development of an augmented reality pipeline for ventriculostomy using the Microsoft HoloLens (VentroAR) (Section 3.3.2)
- Development of an API to send real-time tracking information from the optical tracker to the HoloLens (Section 3.3.3)
- Quantification of manual image-to-patient registration using hand gestures (Sections 3.4.1 and 3.5.1)
- Implementation of a color-based depth feedback visualization method to improve the depth understanding of anatomical data (Section 3.3.4)
- Evaluation of VentroAR for a ventricle targeting task, including an evaluation of the manual registration method used and an in-depth analysis of the direction of the error (Section 3.4)

Outline

The structure of this thesis is as follows. In Chapter 2 we discuss ventriculostomy, describe image-guided neuronavigation systems and augmented reality in neuronavigation. We also provide an overview of previously developed augmented reality-based navigation systems for the specific intervention of ventriculostomy. In Chapter 3, we describe the implementation of VentroAR, the augmented reality platform offered for ventriculostomy using the Microsoft HoloLens. Finally, in Chapter 4, we conclude the thesis and discuss possible areas of focus for future research.

Chapter 2

Background

In this chapter, we review the use of augmented reality technology in image-guided surgery systems (IGS). We begin with a description of the ventricular system anatomy in Section 2.1 and then describe ventriculostomy in Section 2.2. In Section 2.3, we give an overview of image-guided surgery systems and their main components. In in Section 2.4, we discuss limitations of IGS systems and review augmented reality systems for different clinical interventions with a focus on ventriculostomy.

2.1 Ventricular System Anatomy

The ventricular system consists of four ventricles which are all connected and filled with CSF: two lateral ventricles and the third, and fourth ventricles (see Figure 3). The lateral ventricles and third ventricle are connected through the Foramen of Monro (also called interventricular foramen), and the third and fourth ventricles are connected through a cerebral aqueduct. Each lateral ventricle consists of frontal (anterior), occipital (posterior), and temporal (inferior) horns, body, and atrium, which all have a roof, floor, and anterior, medial, and lateral walls. In the center of the ventricular system is located the third ventricle which is a thin and narrow space located in the center of the head. The fourth ventricle is a diamond-shaped cavity located in the infratentorial region of the brain. In most people, the ventricular system is symmetric however it not uncommon that one of the lateral ventricles is slightly larger than the other.

2.2 Ventriculostomy

Ventriculostomy is a neurosurgical procedure done to drain cerebrospinal fluid (CSF) in order to decrease intracranial pressure (ICP). ICP increases in cases of traumatic brain injury (TBI), hydrocephalus, hemorrhage, intracranial tumours, and other traumas and diseases. Ventriculostomy is most typically done in emergent settings or at bedside in intensive care units. The procedure involves the surgeon making a

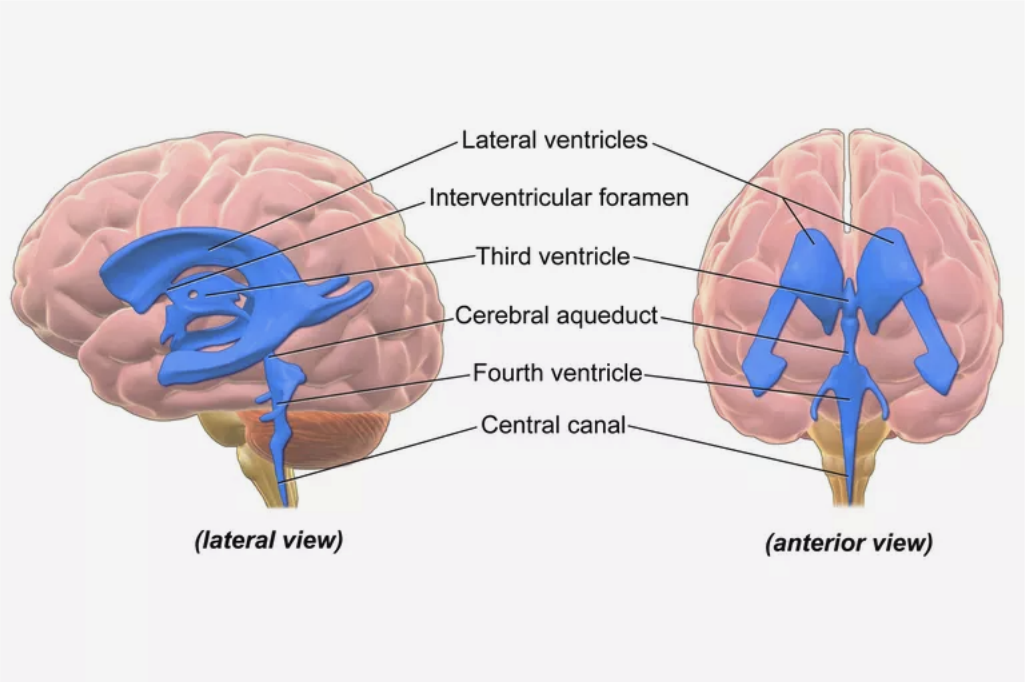

Figure 3: Ventricular System Anatomy [10]

burr hole into the skull and guiding an external ventricular drain (EVD) or silicon catheter through the brain to the patient‘s ventricle. Most frequently, surgeons use the *freehand* technique which involves using anatomical landmarks on the face and skull to determine the best entry point location and best trajectory for safe EVD placement [4, 11]. Despite the fact that freehand ventriculostomy is one of the most repeated neurosurgical procedures, poor targeting of the ventricles has been reported to be between

$.Poorormis-targetingcancausevariouscomplicationsforthepatientincludinghemorrhage, dislodg$

2.2.1 Freehand Ventriculostomy

Several approaches can be used in order to access the ventricular system using the freehand method including: Kocher's, Kaufman's and Tubbs' point for anterior access sites, Bohl's and Sanchez's points for Lateral Access, and Frazier's, Dandy's and Keen's points as posterior approach. Using Kosher's or Frazier's point is most common to access the lateral ventricles. Kosher's point is most often used to access the frontal horn of the lateral ventricles and Frazier's point for accessing the occipital horn of paired lateral ventricles (see Figure 5). In the Kosher point approach, the insertion point should be placed 11-12 cm superior to coronal suture at the mid pupillary line and 2-3 cm away from the midline. The Frazier entry point is located approximately 6-7 cm above the inion (one of the anatomical landmarks of human skull, refer to Figure 4) and 3-4 cm lateral to the midline [13].

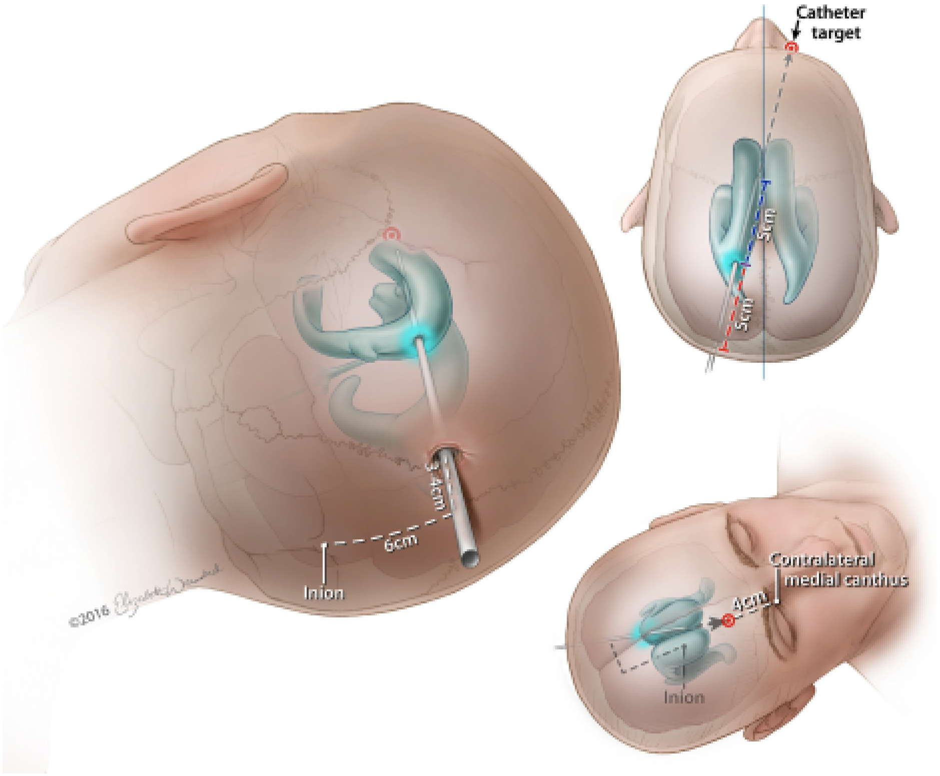

Figure 4: Frazier's point localization using anatomical landmarks [13].

Kosher's point is one of the commonly used anterior access techniques which is used for neurosurgical procedures like ventriculoperitoneal shunt catheter insertion, endoscopic third ventriculostomy, endoscopic removal of colloid cysts and endoscopic removal of intraventricular hemorrhage. Despite the popularity of this method does, misplacement of the EVD or shunt ranges from 4 to 40%. Frazier's point is a posterior ventricular system access method. Lee *et al.* did a user study using MRI to evaluate this method and found a 100% success rate [15]. Despite the high accuracy in accessing the ventricles using Frazier's access point, the position of head creates limitations for this technique which makes it unsuitable for emergency cases [16]. Despite the fact that freehand access can be done easily it is challenging and thus methods that use navigation or or other localizing devices are considered when and where possible.

2.3 Image-guided Surgery

Computer assisted surgery systems have a great history in medical applications, particularly in operating rooms. Such systems aid surgeons in tasks such as surgical planning, diagnosis and image-guidance. In image-guided surgery, surgical tools are

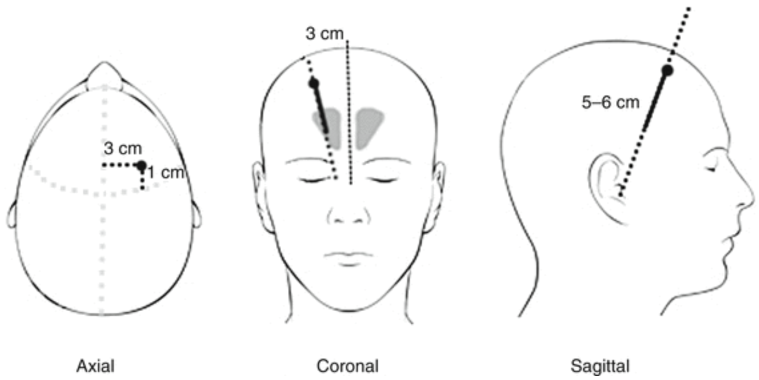

Figure 5: Kosher's point localization using anatomical landmarks [14]

tracked in real-time and visualized relative to pre-operative patient scans on a computer system in the operating room. Three things are necessary for image-guidance, tracking of the patient and surgical tools, registration of the pre-operative images to the patient in the operating room, and visualization of this data for guidance. Various registration, tracking and visualization methods has been proposed and evaluated to improve surgical procedures. Previous research has shown that IGS systems can help less experienced surgeons to be more confident and accurate in their procedures as well as increase the accuracy of more experienced surgeons [17–19].

2.3.1 Pre-operative Imaging

One of the main components in computers assisted systems is pre-operative images of the patient. Pre-operative images allow for the visualization of patient specific anatomy that can be used for diagnosis, surgical planning, and guidance. For surgical navigation, pre-operative images (typically CT or MRI) are most often segmented, reconstructed and visualized intra-operatively to guide the surgeon.

Magnetic Resonance Imaging (MRI) is another imaging modality that enables soft tissue visualization. This feature makes MRI well suited to visualize organs and soft tissues. In recent years, there has been significant improvements in MRI imaging technology that makes it faster and more detailed [20].

Computed Tomography (CT) is an X-ray imaging method that is used to show tissue density. Since most human tissues have similar density CT may not be the best imaging approach in many clinical applications like tumor detection. On the other hand, in orthopedic procedures CT is one of the most used imaging techniques since human bones and implants have much higher density and can be well visualized. CT is also most often used in emergent cases such as those requiring ventriculostomy.

2.3.2 Tracking

Tracking devices are used in image-guided surgery to locate the position and orientation of objects (e.g. surgical instruments or the patient) in the the operating

Figure 6: Optical tracking systems. The Atracsys Fusion 500 Tracking Camera is an infrared optical tracking camera that is able to track the pose of markers [22] (top). The OptiTrack V120 is capable of recognizing various types of reflective markers like stickers, gloves, and spheres [23] (bottom). Two different markers are also shown. Passive markers consist of reflective tags whereas active markers have reflective diodes that constantly communicate with the camera.

room. A number of different tracking technologies exist, including optical tracking, electromagnetic, acoustic and mechanical.

Optical Tracking System

Optical tracking systems, which use stereoscopic cameras and infrared light to track reflective markers are the most accurate tracking systems with an accuracy of under 1 mm [21]. One of the known limitations of optical tracking cameras is the need for line of sight in order to achieve real-time localization of markers. Two examples optical trackers used in clinical navigation systems are shown in Figure 6.

Electromagnetically Tracked Navigation Systems

Electromagnetic tracking works by producing a magnetic field in the operating room and then tracking surgical tools or objects that are equipped with coils that disturb the magnetic field. As opposed to optical tracking systems, they do not require line of light, however, since these systems are based on electromagnetic fields, any metallic object close to the navigation field will cause distortions and may decrease accuracy. For this reason they are not as commonly used as optical tracking systems [24, 25].

Figure 7: Electromagnetic tracking systems work by introducing a magentic field into the operating room. Top: Different electromagnetic trackers. Bottom: tracking sensors are equipped with coils that disturb the magnetic field [26].

Figure 7 shows various models of electromagnetic trackers and sensors.

Mechanical Tracking

Mechanical arms were one of the fist tracking devices used in image-guided surgery systems. A mechanical tracker consist of a mechanical arm with angular sensors to determine the position of a known geometry. Mechanical tracking is useful for robotic surgery such as deep brain stimulation (DBS) but for other surgeries the mechanical arm can interfere with the procedure. Another drawback of such systems is the inability to track pointing tools, these trackers is that the patient position must stay fixed during the surgery [27].

Acoustic Tracking

Acoustic tracking systems, also known as ultra-Sound systems, consist of emitters attached to the patient and devices, and microphones around the room that receive transmitted waves and calculate the distance of the emitter based on the sound's speed. These systems suffer several disadvantages including a lack of accuracy, limited number of tracked devices per time and their sensitivity to room temperature as this can affect the sound's speed. For these reasonns acoustic trackers are rarely used in navigation systems [27].

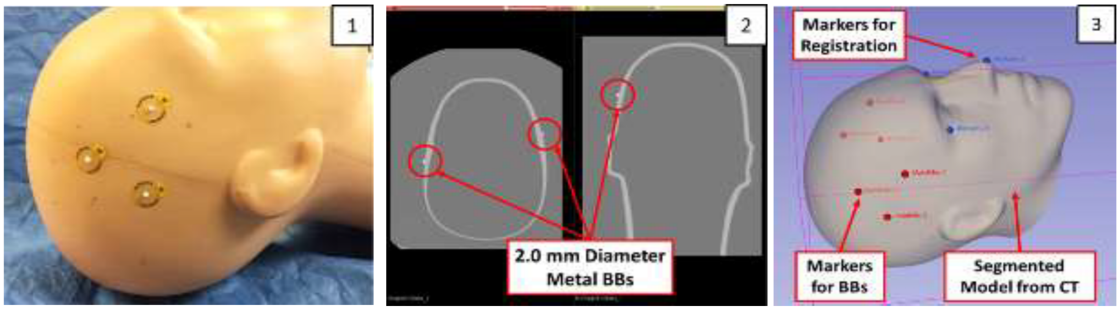

Figure 8: An example of using landmark-based registration registration [7]

2.3.3 Registration

Registration is the task of mapping two or more datasets into the same coordinate system. In image-guided surgery this is done to align pre-operative patient images or models (image-space) to the patient lying on the operating room table (physical space). It is important to have a highly accurate registration in order to have accurate surgical guidance. Registration is typically point-based (i.e. using landmarks) or surface-based. However, in augmented reality systems manual registration has also been proposed. We briefly describe these different registration procedures.

Landmark-based Registration

Landmark-based (or point-based) registration is the most commonly used method for registration in image-guided surgery. In this method, corresponding points (e.g. bridge of nose, canthi of the eye) are chosen on the pre-operative image(s) (image space) and then actual patient using the tracked surgical pointer. From the known transform of each of the corresponding points in image and physical space, the global transform can be computed. The accuracy on this registration method varies based on the tracking technique used and the ability of the user to choose corresponding points accurately but is typically on the order of 2-3 mm for neurosurgery. An example of landmark-based registration in a phantom study is shown in Figure 8.

Surface-based registration

In surface-based registration, the transformation among two surfaces (typically represented as point clouds) is calculated. In image-space, the skin surface is extracted from the preoperative MRI or CT. In physical space, a pointer is used to trace the surface of the patient, for example the pointer is moved across the skin of the surface and skull. The two surfaces are then aligned typically using an iterative method such as iterative closest point (ICP). Although, this registration technique is most typically done with a surgical pointer, surface scanners that can generate surface point clouds have also been explored [28].

Manual Registration

Manual registration is one of the basic methods that has been used in IGS. In this method the user moves the pre-operative patient images or models (typically using a mouse or gestures) to align with real anatomy of the patient. In this method the accuracy of registration is solely dependant on the ability of user to match image-space to physical-space accurately. Manual registration can be implemented with different techniques including gesture-based [29], using a game controller [5] or by specified user interface implementation like virtual buttons or voice command in augmented reality devices [7]. To date manual registration techniques have only offered accuracy in the range of 4-10 millimeters. Furthermore, in some cases there is a learning curve associated with these techniques that makes them not easily usable.

2.3.4 Neuronavigation Workstation

The last component of an IGS system is the workstation that usually consists of a computer and a monitor. The computer is equipped with customised software for implementing steps like image acquisition, registration, calibration, segmentation of targeted tissues, 3D construction of models and tissues, etc. The monitor is used to display the guidance (i.e. pre-operative scans combined with the tracked virtual models of tracked surgical tools. The most popular commercial IGNS systems are the Medtronic StealthStation (see Figure 9) and BrainLab. Two of open-source research IGS platforms are IBIS [30] and 3D Slicer [1] which have all the modules required for a navigation system.

2.4 Augmented Reality In Neuronavigation

Neuronavigation or IGNS systems have been used for different surgical procedures including tumor resection [31], endoscopic neurosurgery [32], neurovascular surgery [33, 34], craniotomy procedures [35] and spine [36]. Despite, the many advantages of IGNS systems, a few shortcomings of these systems have been described. Two of these are: the required focus shifts between the guidance workstation and the surgical field, and the cognitive load of transforming 2D information from the guidance display to the three-dimensional patient anatomy [37, 38]. Augmented reality visualization has been proposed as a solution that can address these two problems via direct visualization of virtual information on the surgeon's view. AR can provide better perception, ergonomics, hand-eye coordination and finally may improve the surgical outcome.

The first AR neuronavigation system was introduced in 1985 by Roberts *et al.* [39]. In their work, the authors projected virtual models into the oculars of the operative microscope for cranial surgery. Since then various AR technologies has

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[1] https://www.slicer.org/

Figure 9: Medtronic StealthStation is a commercial surgical navigation system.

been explored for IGNS including more advanced microscope overlays [40], projectors and silver mirrors [41], tablets [42], and head-mounted displays [43].

2.4.1 Augmented Reality Hardware

In the context of neurosurgery specifically, hardware that has been used for AR includes: the neuronavigation workstation monitor [44], the neurosurgical microscope [34] [33], a tablet [29], projectors, and more recently head mounted displays (HDM) [45, 46]. HMDs are a convenient and user-friendly device as they provide user-centered perspective and are hands-free [47]. HMD devices are categorized as video see through (VST) or optical see through (OST). With VST devices, a video stream is merged with computer generated virtual data. VST has several advantages including advanced possibilities for video processing algorithms for segmentation and registration, and more synchronized output after merging virtual content with the live video feed. On the other hand VST devices have limited video bandwidth, a chance of vision blockage through system errors and distorted spacial perception [48]. Furthermore, not having direct vision of surgical field is not desirable for many surgeons [49].

With OST HMDs, computer generated information of the patient is presented between the surgeon's line of vision and targeted surgical field. This technology provides an obstacle free view of real surrounding world without any lag for surgeon that is suitable for clinical applications. On the downside, these devices require more complicated registration of augmented data, can lead to static errors in registration, aa latency in visualization when users move, complicated calibration and unnatural occlusions (e.g. when a virtual object closer to user does not block a real object behind) [50]. In the remainder of this thesis we focus on OST HMDs.

Various OST HMDs technologies have been introduced commercially, for example, the Magic Leap 1[2] [51], the Microsoft Hololens [3] [52], xVision[4] [53], and Google Glass[5] [54]. Among these different HMDs, the Microsoft Hololens is one of the most promising with features such as spatial mapping technology, head localization, voice commands, gaze control and gesture-based interactions which make this device highly suitable for clinical applications. Perhaps for this reason, many researchers have evaluated the effectiveness of the Microsoft HoloLens for neuronavigation [4, 5, 7, 55].

Microsoft HoloLens

In our research we use the Microsoft HoloLen first generation. The Microsoft HoloLens is a mixed reality platform that was introduced by Microsoft Corporation, Redmond,

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[2] https://www.magicleap.com/en-us

[3] https://docs.microsoft.com/en-us/hololens/hololens1-hardware

[4] https://augmedics.com/

[5] https://www.google.ca/glass/start/

Figure 10: Different 3D Augmented Reality HMDs. From left to right: Magic Leap 1, Google Glass, Microsoft Hololens 1st generation, xVision

Washington, USA, in 2017. The HoloLens combines multiple sensors, accelerometers, infrared sensors, microphones and cameras, into a wearable device with significant ergonomic features. This HMD device is capable of projecting holograms into the real world in the field of view of the user. This feature is implemented via two main technologies: pico projectors and the device's spacial mapping. The pico projectors are two mini projectors located exactly above the user's eyes that produce the light required for hologram display. The light is reflected to user's eyes to generate augmented reality visualizations.

The HoloLens contains six cameras, two on left, two on the right and two at the center of the device. One of the cameras is allocated for spacial mapping and is responsible for scanning the room via capturing 2D perspective images. The remaining five cameras are constantly constructing a point cloud of the user's environment to produce a depth map representation of the environment. The point cloud along with the simultaneous localization and mapping (SLAM) algorithms gives a representation of the user's surrounding and location.

2.5 HoloLens for Surgical Targeting

In order have better depth perception and localization in augmented reality systems, various visualization methods have been proposed. For example, Heinrich *et al.* used a crosshair-shaped mark for guiding a needle insertion procedure using the Microsoft

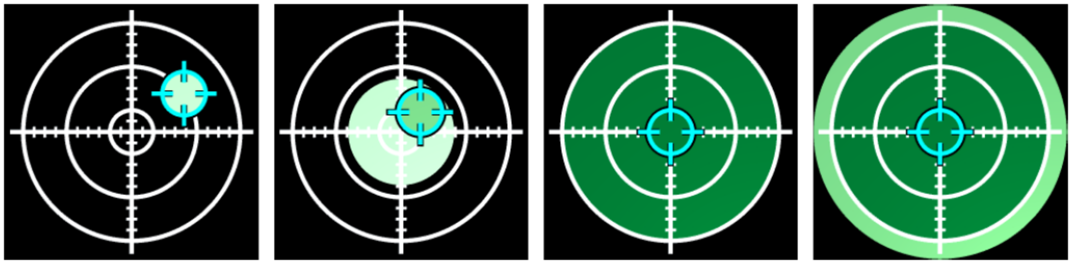

Figure 11: Depth feedback proposed for needle insertion. The blue bordered circle represents the needle orientation and as the needle gets closer to the target, the green radius get filed in. The right-most image depicts that the needle has passed the target. [56]

HoloLens [56]. They designed a color-based feedback system for depth and angle of insertion (see Figure 11). In their proposed guidance solution the color of radius is changed based on the distance of tip of the needle from the target. Henrich *et al.* did a comparison study on different augmented displays for a needle insertion task and based on the phantom study they performed, direct 3D augmentation through a head-mounted display and projector had the most correlation among hand and eye for user. Lin *et al.* [6] developed an AR-based needle insertion navigation system for non-rigid needles. In this work, the authors use an optical tracking system to track the phantom, HoloLens and needle. They project a 3D reconstructed model of the needle in real-time inside the patient's body visualizing the deflection that might happen. Real-time visualization of surgical tools has also been assessed in other studies with various visualization techniques with results showing that augmented visualization of the surgical tool or surgical path improves the depth perception of users and guidance accuracy [4, 42, 57].

2.6 Augmented Reality in Ventriculostomy

As described above, ventriculostomy is a procedure done to reduce intracranial pressure by draining increased cerebospinal fluid (CSF) from the ventricular system. Early proposed systems for better targeting and intervention purposes like ventriculostomy focused on virtual reality technologies for simulation and training. For example, Yudkowsky *et al.* [11] developed a head and hand tracked virtual simulator using the ImmersiveTouch System [58] for ventriculostomy training. They prepared a library of 15 virtual brains coupled with haptic and virtual feedback to train neurosurgeons. They assessed the effect of the proposed system on the performance of 16 neurosurgical residences on real ventriculostomies performed by trainees (6 months before the training and one month after the training). The results found only a 26% targeting success rate after neurosurgeons trained using the developed system. The authors

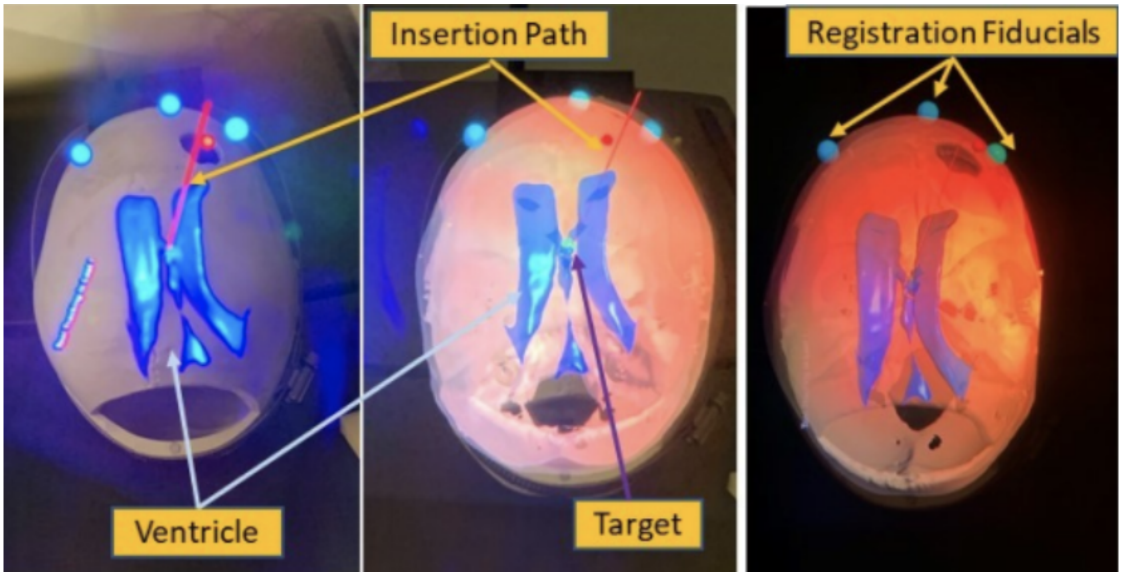

Figure 12: An augmented reality system proposed for ventriculostomy. The target and ventricles are augmented onto the patient (here a phantom). The trajectory is also visualized to improve targeting guidance [4].

suggest that that low rate was due the difficulty of registering 2D CT scans to 3D brain anatomy to intra-operatively determine ventricle location and distance.

In terms of AR, a number of research groups have implemented AR navigation pipelines using the Microsoft Hololens for the purpose of ventriculostomy. Schneider *et al.* [59] developed an AR-based navigation tool, using the Microsoft HoloLens, which did not require the patient's head to be fixated during the surgery. Rather, an automatic registration technique via image targets attached to patient's head and a control based manual re-alignment was used. In order to guide the surgeon, the target area and entry point are visualized as a 3D hologram on the head of the patient. The authors evaluated their system using a phantom study with 11 neurosurgeons and found a 62% success rate and $5.2 \pm 2.6mm$ error rate was reported for the target hitting task.

Azimi *et al.* [4] tested another approach to mitigate complications of ventriculostomy, they augmented the target ventricles directly on the patient's head using the Microsoft HoloLens in order to guide the surgeon to navigate the catheter along a specified trajectory. In their system, the patient and surgical pointer are tracked using Aruco tags and the Vuforia Engine and a landmark-based registration is done to map the patient images to the patient (see Figure 12). A phantom user study with 10 participants was performed. To determine the distance between the target (ventricles) and the tip of the pointer (representing a catheter) a computer vision (Vuforia Engine) based method was used. A target error of 7.63 mm was reported.

In similar research, Li *et al.* [55] studied the efficiency of a mixed reality holographic system for external ventricular drain insertion versus freehand EVD placement. They tested their proposed system on 15 patients. For evaluation purposes data of 15 other patients who had received freehand EVD was recorded. CT scans of all patients in both groups were acquired before and after 48 hours of the operation. In the AR group, radio-dense markers were attached to patient's head before the CT scan was performed and these markers were used for the registration of a hologram on the patient's head. The holograms consisted of the patient's skull, lateral ventricles, position markers, entry point, and desired trajectory. The target deviation reported was 4.34 ± 1.63 millimeters using their proposed system, and registration accuracy and number of passes to access ventricles using this system reported 1.07 ± 0.258 times.

Not many augmented reality systems have been proposed specifically for ventriculostomy, but a number of general neuronavigation research systems have suggested their methods could be used for ventriculostomy. Rae *et al.* proposed an augmented reality solution for burr hole placement using the Microsoft Hololens. They offer a manual registration algorithm and evaluated the system with a phantom study and seven participants. They reported a 98% success rate for registering the holograms and an accuracy of less than 10 mm by inexperienced users [7]. Baum *et al.* used the Microsoft Hololens in an AR neuronavigation system proposed for lesion removal. Their results did not show a significant improvement in distance to lesion (10 mm) versus conventional methods (11 mm). They evaluated their system in the operating room on 15 real patients [5].

As can be seen from the related research, augmented reality based navigation systems can improve the accuracy of targeting the anatomy of interest. Also, previous research suggests that Microsoft HoloLens has sufficient performance as a visualization device for IGNS. Based on the information gained in this chapter we offer an augmented reality based platform using an optical tracking camera and Microsoft Hololens to mitigate complications associated with ventriculostomy as described in the next Chapter.

Chapter 3

VentroAR: Augmented reality platform for ventriculostomy using the Microsoft HoloLens

The following chapter presents a prototype augmented reality system for ventriculostomy. A version of this chapter has been submitted to the Computer Assisted Radiology and Surgery international conference in January 2022 [60].

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- Contributions: study and design concepts: N.A; É.L.; software development: N.A. ; data collection: N.A. ; data preparation and analysis: N.A ; supervision: M.K.-O.; manuscript preparation: N.A; manuscript revision: all authors; editing and final version: All authors

Abstract

Freehand ventriculostomy is one of the most common neurological procedures performed when the cerebrospinal fluid increases in the ventricular system. This procedure is most often performed in the ER or ICU and thus without a navigation system to help surgeons locate the ventricles. Surgeons use anatomical landmarks to locate the burr hole on the skull and guide a catheter through the brain to the ventricles to drain excess cerebrospinal fluid (CSF) and decrease intracranial pressure (ICP). Freehand ventriculostomy has an associated catheter misplacement rate of 23-68% which can lead to a number of complications including mortality and morbidity. In this paper, we explore the use of augmented reality to facilitate freehand ventriculostomy. Specifically, we developed a HoloLens pipeline for neuronavigation and in a study with 15 subjects found that the proposed gesture-based registration has an accuracy of 10.75 ± 4.01 millimeters and target hitting accuracy of 12.28 ± 2.40 millimeters. In terms of usability it received a score of 74.5 on the System usability scale (SUS), indicating that the system is easily usable.

3.1 Introduction

Ventriculostomy is a neurosurgical procedure that accesses the cerebrospinal fluid (CSF) to reduce intracranial pressure (ICP). Ventriculostomy is required in many neurosurgical settings, such as after hemorrhage, severe head trauma, in some tumor cases, spina bifida, or hydrocephalus [61]. It is one of the most commonly performed neurosurgical procedures and is primarily performed at a patient's bedside or in an emergency room setting. The procedure involves drilling a hole into the skull (i.e., a burr hole) and guiding a silicone catheter through the brain to the ventricles to drain the excess CSF. In some cases, surgeons might have access to pre-operative images like computed tomography (CT) or magnetic resonance (MR) scans to understand a specific patient's ventricular anatomy better. Furthermore, when possible and most commonly in an elective setting, image-guided neurosurgical (IGNS) systems can be used to facilitate ventriculostomy. However, in emergency cases, guidance is not available. Surgeons thus rely on anatomical landmarks on the skull to locate the ventricles, determine the best location for the burr holes, and find the best angle and depth for catheter insertion. In these emergency cases, accurate targeting of the ventricles is associated with an over 30% misplacement rate due to human error [2]. Such errors can lead to increases in the length of hospital stays, morbidity, and even mortality [62].

Augmented reality (AR), i.e., the merging of real and digital elements, is increasingly being studied for diverse image-guided surgery (IGS) procedures, including neurosurgery [9]. AR visualization merges pre-operative patient data (e.g., a segmented tumor, vessels, ventricles) with the patient on the operating room table to enable more intuitive guidance and improve surgical workflows. Augmented reality can decrease a surgeon's cognitive load by allowing the surgeon to focus on the surgical site and patient [11] rather than continually shifting focus between the monitor of the IGNS system and the patient [63]. In neurosurgery, in particular, AR has been shown to help tailor craniotomies [64], distinguish between veins and arteries in neurovascular cases [44], and determine resection corridors to minimize invasiveness in brain tumor resection surgery [3].

Different hardware devices and various AR visualization techniques have been tested and analyzed for image-guided neurosurgery systems, including microscope overlays, projectors, half-silvered mirrors, mobile devices, and most recently, head-mounted displays (HMDs). The core of all these solutions is merging virtual data (e.g., anatomical models, tool trajectories) with the surgical field to guide the surgeon throughout the operation. To increase the accuracy of HMDs researchers have explored combining HMDs with conventional IGS systems [65, 66]. However, such pipelines have not been directly evaluated for ventriculostomy.

In the following paper, we propose a navigation pipeline for ventriculostomy using a Microsoft HoloLens, "VentroAR" for augmented reality guidance and an optical tracker for evaluating the system's precision and updating the visualization parameters of the virtual models. Specifically, a manual registration method using simple hand gestures is used to align the patient's segmented head model with the actual patient, and a color-based depth feedback algorithm is used to help the users understand the target's location and the depth for the catheter tool. We assessed the system in a user study with 15 participants on a 3D printed phantom and found that the proposed gesture-based registration has an accuracy of 10.75 ± 4.01 millimeters and the target hitting accuracy was by 12.28 ± 2.40 millimeters. In terms of usability "VentroAR" received a score of 74.5 on the System usability scale (SUS), indicating that the system is easily usable.

3.2 Related Work

Many researchers have evaluated the effectiveness of different augmented projection technologies for targeting specific anatomy such as for biopsies, needle or catheter placement [67]. For example, Heinrich *et al.* [56] did a comprehensive phantom study for comparing different AR displays for needle insertions. They compared traditional monitor-based systems, a video see-through stationary display (tablet), an optical see-through head-mounted display (Microsoft HoloLens), and a spatial projector-based system. The results of their study showed that the direct projection of augmented data on the patient's body and the insertion site enabled the best hand-eye coordination and the least mental demand on the user.

The Microsoft Hololens is one of the most promising HMDs with features such as spatial mapping technology, head localization, voice commands, gaze control and gesture-based interactions which make the device highly suitable for clinical applications. Zuo *et al.* [68] evaluated the efficiency of the Microsoft HoloLens for medical purposes in systematic survey with 72 participants and found that 100% of surgeons who used the device believe that it has sufficient features to be used for clinical applications and they are willing to use it. However, the accuracy that the SLAM localization feature of the HoloLens is not accurate enough to make applications for highly sensitive surgeries like neurosurgery. To improve the localization accuracy in clinical application, numerous groups have looked at various methods to improve the registration between the augmented elements and the real world. Rae *et al.* [7] implemented a manual landmark registration for burr hole placement using the HoloLens, where the user aligns three landmarks on the hologram with their counterparts on a phantom using virtual buttons. They reported that 98% of experienced users successfully performed registration in a "clinically acceptable range" (less than 10mm). In similar research, Zachary *et al.* used a wireless game controller for landmark registration of the virtual models to the patient. The registration accuracy was not reported in their work, but they reported distance to lesion accuracy of 10 mm for expert neurosurgeons and 21 mm for inexperienced trainees [5].

Precise alignment of the virtual data can also be done by taking advantage of the RGB camera of the HoloLens and computer vision algorithms to locate and track an image-based targets or markers and align holograms with respect to these markers. The Vuforia engine is perhaps one of the more popular marker tracking SDKs supported by the Microsoft HoloLens. Azimi *et al.* [4] used the Vuforia Engine to develop an automatic registration and trajectory planning system for Ventriculostomy. Landmark-based registration is done using a pointer outfitted with a Vuforia marker. The accuracy of this registration was found to have a 37% improvement in tip placement compared to the manual registration method that was used as baseline, and tip distance to target was calculated to be 10.96 mm. In the work of Lin *et al.*, [59] a Vuforia marker was attached to the patient's head in order to localize the projection of the ventricle 3D models. Since the automatic tracking of the surface of the skull is not feasible with current versions of the Microsoft HoloLens, the authors used game controllers to more precisely align the holograms with the patient. This re-alignment is necessary for many applications that use the Vuforia SDK since the tracking does not offer clinically relevant accuracy. Lin evaluated their proposed system on 15 real ventriculostomy operations performed by neurosurgeons. They reported that the number of passes of insertion decreased from an average of 2.33 to 1.07 and the target deviation was 4.34mm. Lastly, Li *et al.* also developed a system using the HoloLens that displays the segmented ventricles as well as the desired trajectory of the catheter [55]. The results of their work showed 4.34 ± 1.63 millimeters error in target deviation and decrease in number of passes of catheter from 2.33 ± 0.98 passes to 1.07 ± 0.258 times using the holographic guidance using HoloLens.

Building on this previous research, we developed an AR-based application for ventriculostomy using the Microsoft HoloLens.The proposed system uses a manual registration step using simple hand gesture interaction to align the patient's specific head and ventricle segmentation with the real patient. This is similar to Rae *et al.*'s work where fiducials are used for guidance and evaluation of registration [7]. For targeting similar to Li *et al.* [55] the trajectory of the tool is not visualized and only ventricle segmented model and target point is visualized. In our system, we track the tool using an optical tracker and in order to improve the understanding of the distance of the catheter tip to the ventricles, we designed a color-feedback method to guide the user. This was possible via an custom API for real-time data transmission between the optical tracker and the HoloLens. The optical tracking system also allowed us to evaluate the accuracy of the proposed system.

3.3 System Design

The following section describes the implementation details in terms of the hardware used and developed software for the proposed system.

3.3.1 Hardware

The developed system uses a Microsoft HoloLens First Generation[1] (4-core 1GHz processor, 2 GB memory, 1268 × 720 Resolution, ToF Depth sensor), an Atracsys

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[1] https://docs.microsoft.com/en-us/hololens/hololens1-hardware

FusionTrack 500 [2] and a workstation computer (i7-6850K 3.6 CPU, NVIDIA GTX 1080 GPU, Gigabyte GC WB867D-I wireless PCI card, running Windows 10).

3.3.2 Tracking Pipeline

A pipeline was developed to provide the HoloLens with tracking information from the Atracsys FusionTrack (see Figure 13). First, the PlusServer receives the transforms (3D poses of tracked markers) from the Atracsys tracking system. The PlusServer is capable of receiving these transforms and translating them into standard OpenIGTLink [69] messages. An OpenIGTLinkIF client is created to receive the transform data from the PlusServer, and an OpenIGTLinkIF server is then used to send the transforms from 3D Slicer to the HoloLens.

3.3.3 OpenIGTLink API for HoloLens

There is no open-source OpenIGTLink supported API for the HoloLens, so a custom API using C#, which receives the OpenIGTLink message bites through a TCP client-server connection, was developed. This API developed for the latest OpenIGTLink version (Version 3). The size of each OpenIGTLink is variable based on the size of data, but each message consists of the following sections: a header (58 bytes), extended Header (variable length), the content (variable length), the metadata (variable length) and the size of variable components of message are indicated in the header. Details about the header bites can be found in the online OpenIGTLink developer documents[3]. Each transform message received from 3D Slicer has a size of 106. After reading each data bite, they were converted to float values and divided by 1000 as 3D Slicer and HoloLens use different metrics (3D Slicer uses millimeter as unit whereas HoloLens uses meter) and then stored in a 4×4 isometric matrix. Unity uses a 3 element vector for representing transforms of an object and quaternions for showing rotation. To have reliable information in Unity, the first three elements of the last column of the isometric matrix were assigned to the transform values using the internal Unity functions, such as EulerAngle, of the isometric matrix was calculated and used as input for the Quaternion object to show the rotation.

3.3.4 HoloLens Application

To display the virtual anatomy as holograms in the HoloLens, we developed software using the Unity Engine (Version 2012.2.8f1) development environment (in C# using Visual Studio 2019). The default HoloLens setting profiles offered by Mixed Reality Toolkit (Version 2.5.0) were used to have the proper settings for HoloLens 1st Generation in Unity. Mixed Reality Toolkit (MRTK) scripts (i.e., Object Manipulator and

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[2] https://www.atracsys-measurement.com/products/fusiontrack-500/

[3] http://openigtlink.org/developers/spec

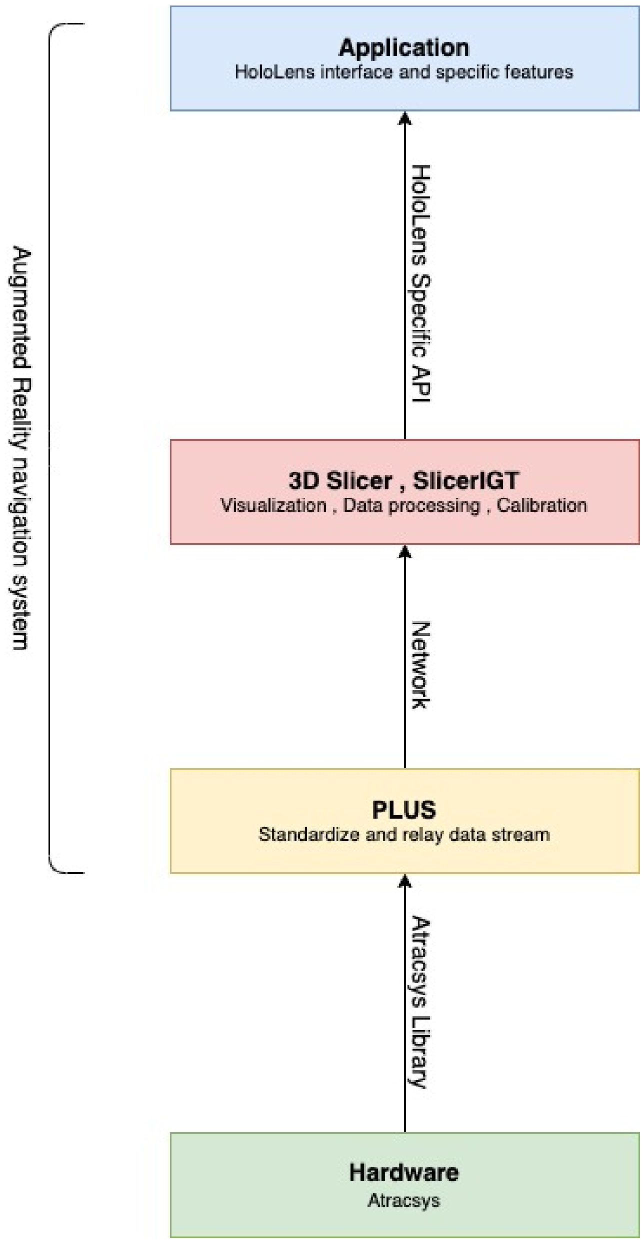


Figure 13: The tracking data information pipeline: Tracking information from the Atracsys are received by **PlusServer**. Calibration of the stylus, segmentation of all ventricles are performed using **3D Slicer**. A Unity application for the **HoloLens** was developed for visualizing ventricles, registration, and the depth visualization algorithm.

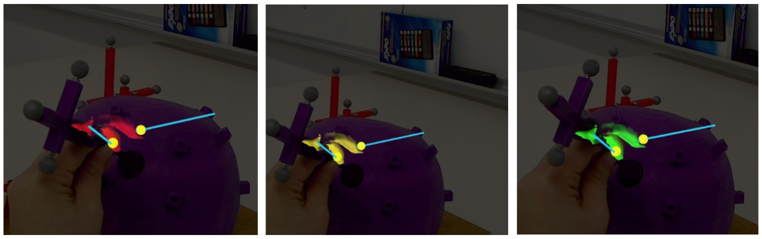


Figure 14: Depth encoding of ventricles to tool tip: red represents far from target ($>= 30mm$), yellow represents closer to target ($> 20mm$ & $< 30mm$) and green represents very close to target distance ($<= 10mm$)

Interaction Gradable) were used to allow for manual registration of the virtual patient anatomy to the 3D printed phantom using the gesture features of the HoloLens.

The proposed application uses 3D Slicer, an open-source software library with various tools and plug-ins for clinical and biomedical image computing applications. Slicer was used to segment the head and ventricles and for receiving and sending transforms through OpenIGTLinkIF [69] module of SlicerIGT [70]. The Slicer-Atracsys connection is made using the PLUS Toolkit [71] which provides live streaming and recording of pose tracking data.

In terms of visualizing the holograms (i.e., ventricles), a color-coded depth visualization method was used. Specifically, the color of the ventricles changed based on the distance of the pointer tip to the target point on the ventricle. When the distance of the tip of a given tool is more than 30mm, the ventricles are red; when less than 20mm, they turn yellow, and then they turn green when the distance of surgical tool tip to target is less than 10mm. This color feedback aims to help participants better understand the depth of the tool with respect to the surgical target when it is inside the brain (see Figure 14).

3.4 User Study

To evaluate VentroAR, we conducted a user study where participants used the HoloLens to navigate to a target placed within the ventricle. The study used a 3D printed hollow head phantom (created from segmentation of an MRI) as described in [42]. Seven landmarks were added to the CAD model for registration purposes (see Figure 15). Furthermore, there are two burr holes on the phantom: one to target the left lateral ventricle and one to target the right lateral ventricle. The 3D printed model was attached to a rigid surface, and a 3D printed marker served as the world reference. A gelatin brain model was inserted into the head phantom to simulate brain tissue. A 3D printed pointer with a tracker was used to simulate the catheter. All components used during this study are illustrated in Figure 15.

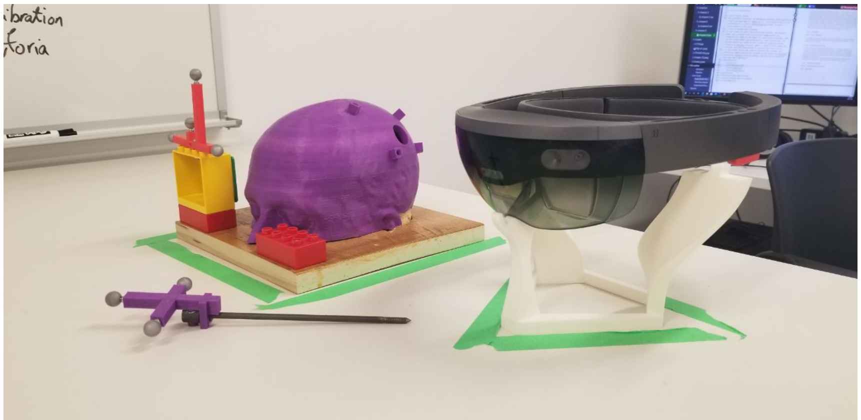


Figure 15: User study set-up: 3D printed head phantom (in purple) and world reference, 3D printed Stylus (in purple), and Microsoft HoloLens 1st Generation.

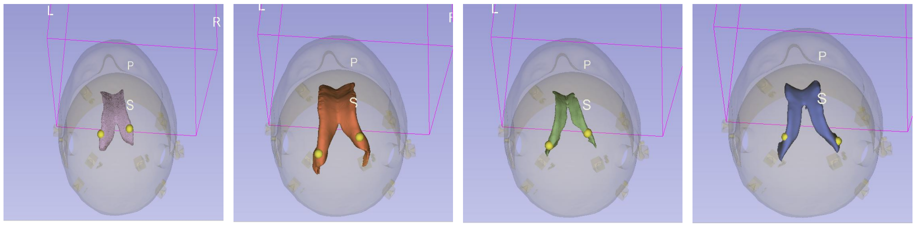


Table 1: Four different segmented ventricles were used in the study. Each ventricle was segmented from CT images of different individuals using the OASIS brain database [72]

3.4.1 Task Description

The task of the participants was to navigate a pointer to a specific target on the ventricle. Prior to navigation, participants performed a manual registration using gestures to align the 3D hologram with the 3D printed phantom. This step is facilitated by allowing the user to align the 7 landmarks of the phantom to the hologram (see Figure 16). However, in a real case the user could simply use landmarks like ear, nose, eyes, etc. for registration. Once the user was satisfied with the registration, to evaluate the registration accuracy, we asked participants to perform a landmark based registration with the tracked pointer using the seven landmarks on 3D model. Root mean square error (RMSE) was calculated using the Fiducial Registration wizard module of 3D slicer.

Participants did registration once and then targeted four ventricles (see Table 1) with target points on both the left and right ventricle for a total of 8 targeting trials. Each trial ended when the participant announced they were at the target to the test administrator. The position of the tip of the pointer tip was then captured in 3D Slicer. Captured positions were used to calculate the accuracy of targeting.

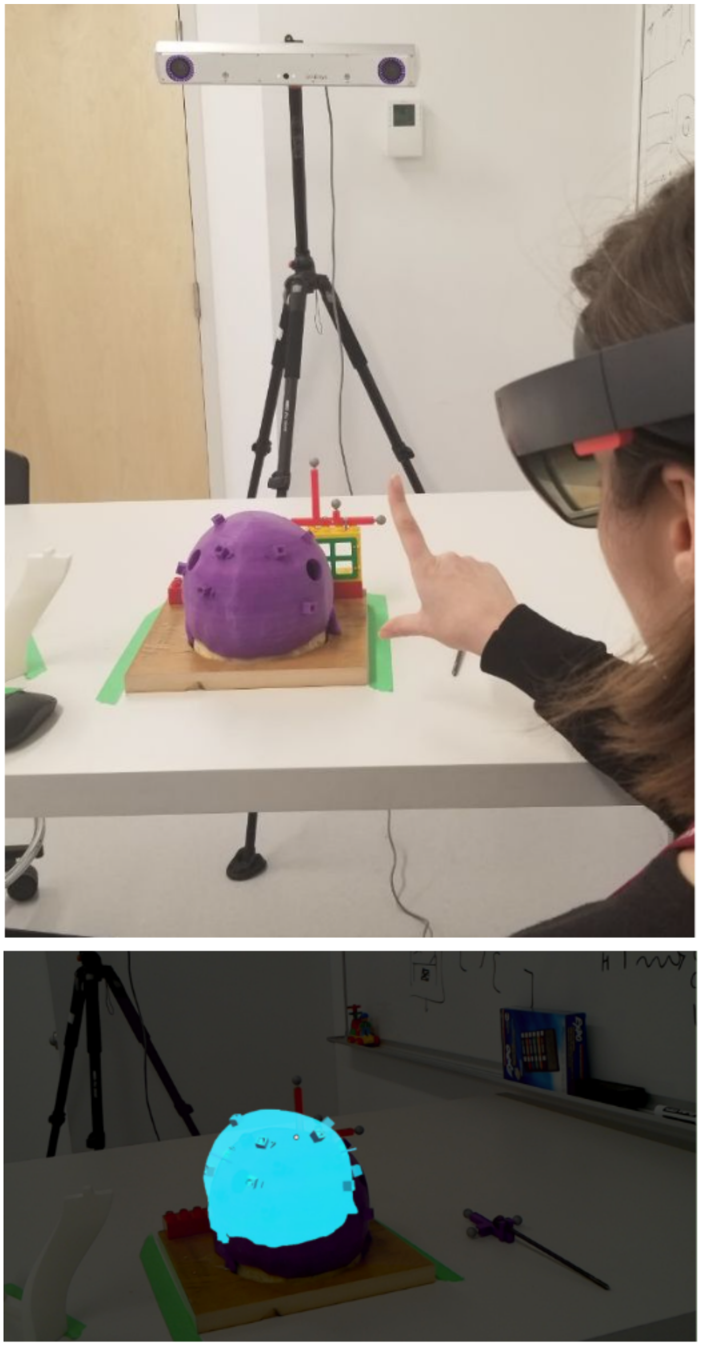


Figure 16: For registration the participant used Microsoft HoloLens gestures like air tap to drag and move the hologram and align it with the phantom. Seven landmarks on the hologram and their counterparts on phantom are used to determine registration accuracy.

3.4.2 Experiment Procedure

Prior to the study, each participant filled a pre-test questionnaire to gather basic information about their level of experience with the involved technologies. Next, each participant was trained with the system and each experiment task was explained in detail. Participants had a training session to get acquainted with HoloLens, air tap gestures, and the overall flow of the experiment. When they were comfortable they did the eight trials, after which all participants filled out a post-test questionnaire with the System Usability Scale (SUS) and NASA Task Load Index (TLX) questions.

3.5 Results

A total of 15 participants (7 female and 8 males) participated in the study. Seven users reported previous experience with HMDs. Almost half of the users did not have previous knowledge and experience with image-guided surgery systems (53%) and medical imaging (40%). Two-thirds of our participants did not wear glasses, and only one wore contact lenses. No color blinded user participated in the experiment.

3.5.1 Registration Accuracy

We evaluated the manual registration using the HoloLens with tap gestures and found RMSE of 10.76 ± 7.3 millimeters for all trials. If outliers are removed (three standard deviations more than average) registration accuracy is 8.27 ± 4.0 millimeters. This registration accuracy is inline with previous works that used gesture-based manual registration and were also on the order of 10 millimeters [5, 7].

3.5.2 Targeting Accuracy

Based on 15 users targeting four ventricles with a left and right target (120 trials), we found a target accuracy of 12.5 ± 8.5 millimeters. We considered records with three standard deviation more than the mean as outliers and seven records with distance to target more than 25mm were eliminated. Results after omitting seven outliers calculated 10.64±5.0 millimeters Distance error rate of all targets is illustrated at 4. Figure 18 shows the deviation of each sampled point of targets in 3D. We calculated the distance error for each dimension separately, and found a mean error of -8.58 ± 10.52 in the $x - axis$ (positive X represents right direction), -1.25±7.51 in the $y - axis$ (positive Y represents up) and 11.67 ± 9.34 in the $z - axis$ (positive Z aligns toward the user). The high error in the z dimension points to the known limitation of the HoloLens to provide effective depth perception.

3.5.3 Depth Accuracy

To further understand the targeting error, we calculated the depth error as illustrated in Figure 17. We projected each subject's hitting point on the trajectory line shown

DHtT	**DPtT**	**DHtP**
10.64 ± 5.0	4.98 ± 4.06	9.41 ± 5.23

Table 2: **DHtT** (Distance of user's Hitting point to the Target) that has been calculated as targeting accuracy , **DPtT** (Distance of Projected point of user's hitting point on trajectory line to Target) and **DHtP** (Distance between user's hitting point and the projected point on the trajectory line)

during to the user during the study. Two distances were calculated to quantify this error. First, the distance between the subject's hitting point (shown in purple in Figure 17) and the projected point (shown in black) on the trajectory line. Second, we compute the distance between the projected point on the trajectory and the target (shown in yellow). Based on these two distances, we can determine the user's deviation from the trajectory point and the second distance to determine if the users undershot or overshot the target. Table 2 illustrates all averages of three distances calculated based on subject's hitting point, **DHtT** (Distance of user's Hitting point to the Target) that was calculated as targeting accuracy, **DPtT** (Distance of Projected point of user's hitting point on trajectory line to Target) and **DHtP** (Distance between user's hitting point and the projected point on the trajectory line). DHtT was calculated 12.5 $\pm 8.5, DPtT 5.96$ ± 5.5 and DHtP 11.32 ± 8.7. Outliers, defined as a data point three times greater than the standard deviation, were removed. Seven outliers for DPtT, seven for DhtT and eight for DPtT were eliminated. Table 2 shows data after outlier elimination. In order to determine whether the majority of undershot or overshot the target, we used a convention in calculating average of DPtT. Based on this convention distances of projected points that were before the target on the trajectory line indicated negative values and distance of projection points after the target point were signed positive (50 overshot cases). In Figure 17 the distance of the green point to the target point (shown in yellow) will be signed negative (70 undershot cases). We believe this may be the result of the color-based feedback as users might stop when the ventricle turns green but prior to reaching the target.

3.5.4 System Usability Scale

The System Usability Scale (SUS) was used to evaluate the system. SUS is a software evaluation test consisting of 10 different questions scaling from 1 to 5 with a full score of 100. Questions are related to system usability and complexity. The overall SUS score calculated for this system is 74.5. Based on SUS evaluation scoring, any system with a score higher than 68 is indicated a good system in terms of ease of usability for users . [73]. Table 4 gives the detailed results of the SUS.

3.5.5 NASA TLX

The NASA Task load index (TLX) was used to assess the cognitive load of each task on users. This evaluation system calculates a subjective mental work load in six

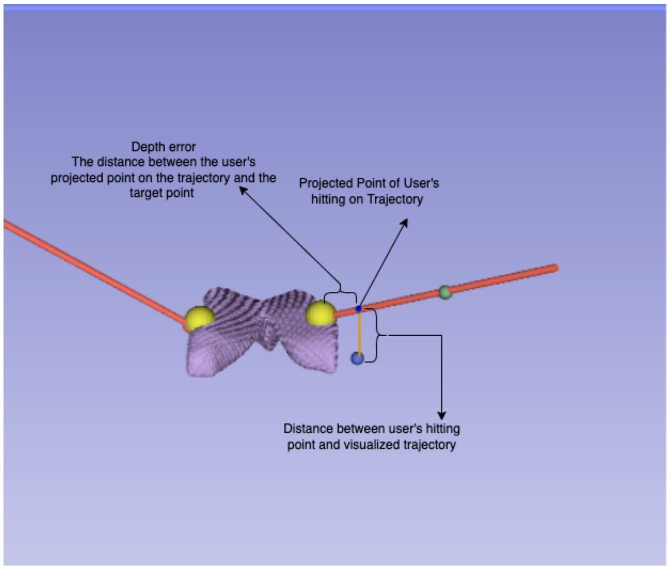


Figure 17: Depth error calculation: the yellow point on the ventricle indicates the target and red line is the trajectory shown to user. The green point on trajectory was used as the second point on trajectory for calculations. The blue point indicates the user's hitting point. The black point on the trajectory illustrates the projection of user's hitting point onto the trajectory line. The two distances are used to quantify the depth error associated with the user's hitting point.

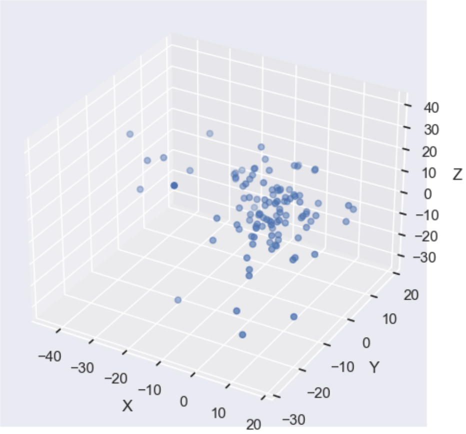


Figure 18: 3D illustration of target hitting data

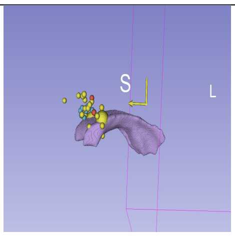
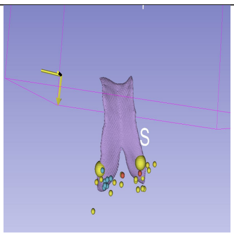
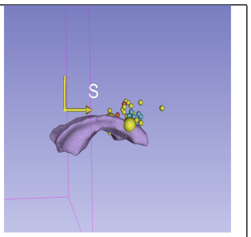
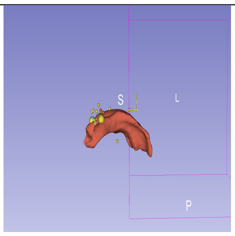
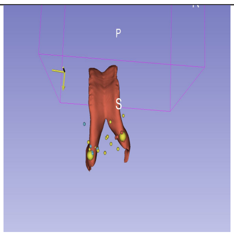
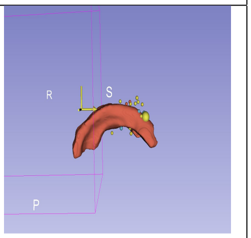
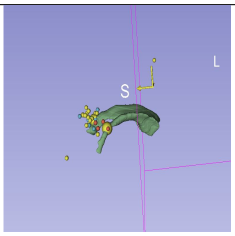
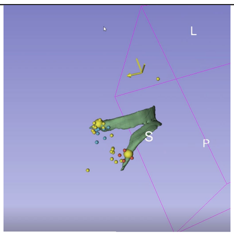
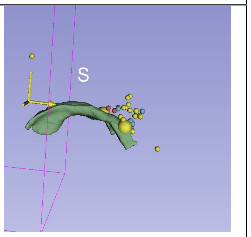
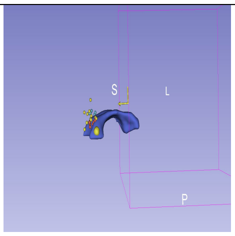
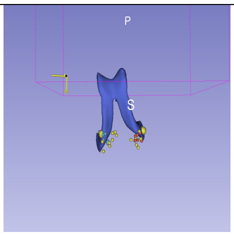
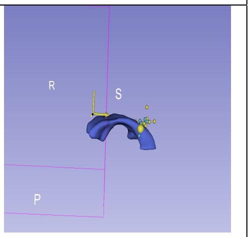
Ventricle 1			
Ventricle 2			
Ventricle 3			
Ventricle 4			

Table 3: Demonstration of target points of all users for each ventricle. Figures from three different views to show the deviation in z-axis. Blue points in left target and red point for right target present data records closer that 10mm to the target.

	Ventricle1	Ventricle2	Ventricle3	Ventricle4
Left	7.86 ± 5.79	9.95 ± 5.32	9.815 ± 4.58	9.06 ± 4.54
Right	14.23 ± 7.44	10.68 ± 5.95	10.98 ± 4.21	13.24 ± 5.31

Table 4: Root mean square error (RMSE) for left and right targets of all four ventricles

System Usability Scale Questions	Average
I think that I would like to use this system frequently	1.73
I found the system unnecessarily complex	3.66
I thought the system was easy to use	1.93
I think that I would need the support of a technical person to be able to use this system	2.53
I found the various functions in this system were well integrated	3.93
I thought there was too much inconsistency in this system	2.13
I would imagine that most people would learn to use this system very quickly	3.93
I found the system very cumbersome to use	2.13
I felt very confident using the system	3.4
I needed to learn a lot of things before I could get going with this system	2.13

Table 5: The 10 questions of the System Usability Scale (SUS) with the average score from 1 (strongly disagree) to 5 (strongly agree).

categories: mental demand, physical demand, temporal demand, performance, effort and frustration. We used scaling from 1 to 10 for each individual question. The overall cognitive load of using the system was calculated to be 24.83. Figure 19 shows in detail information gathered from this survey.

3.5.6 Qualitative Feedback

Furthermore, we asked users a number of questions about their experience of using different parts of the system. We found 50% of users found the registration task easy to perform, 29% found it hard and 21% were neutral. Two-thirds of users (64%) found the target hitting task easy, 22% found target hitting task hard and 14% were neutral. Only 21% of users felt confident in determining the depth of the ventricles using the HoloLens, 43% were neutral and 36% of them struggled with the depth perception of ventricles. This result is not surprising given the limitation of the OST-HMDs for providing accurate depth perception. Only one of the users reported discomfort in the eyes after the study and two participants found the HoloLens very heavy to use.

3.6 Discussion

The results of our study confirm that gesture-based registration can be used with clinically acceptable accuracy for certain procedures [5, 7]. To the best of our knowledge, gesture-based moving holograms have not been evaluated before as a method

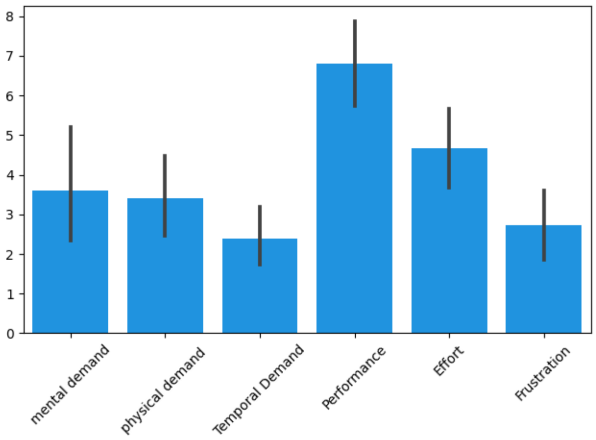


Figure 19: NASA TLX

for manual registration. Qualitative evaluations of the system (SUS and TLX) prove that the proposed method has a good usability and limited cognitive load on users.

Compared to previous works on using AR for ventriculostomy, based on our knowledge, VentroAR is the only system that uses an optical tracker for evaluation and color-depth feedback for improving the depth perception of user. Optical tracking makes the evaluation of system more accurate and reliable. Furthermore, we provide a much more in depth evaluation of errors in terms of directionality and depth. The color-depth feedback was also a novel method developed for improving the spacial understanding between the target and tool when inserting the catheter in the brain. In reviewing previous works in the field, Heinrich *et al.* [56] was the only similar work with the feedback mechanism. Specifically, they used a cross-hair target projected on the surgical field as this can interfere with the surgeon's view of the patient in our work we used the ventricle model for implementing feedback to the user.

The results of our work, however, suggest that the accuracy of VentroAR is not currently sufficient for clinical practice because of the limitations we observed. Despite the simplicity of manual registration methods and although with expert users the registration should be better there are limitations including frustration, a learning curve, and the fact that the system's accuracy is up to the user's judgment. The preciseness of the registration step can highly project the level of user's performance in navigation systems.

The other limitation of our system was related to the user's depth perception of the target. Having a better understanding of the depth of virtual data is also related to the hardware limitations of Microsoft HoloLens. However, earlier research in other navigation systems using HoloLens have shown that showing the virtual trajectory or surgical tool may improve this drawback [42]. In order to visualize the surgical instrument virtually, real-time tracking of the tool is necessary. Tracking can be implemented using an external tracking camera (i.e., optical tracking cameras). In order to use the pose tracking information of an external tracker in HoloLens, a precise calibration step is necessary to find the transformation between the external camera coordinate system and the HoloLens RGB camera's coordinate. Having accurate calibration between HoloLens and optical tracking cameras has been an area of interest for researchers, and different methods and accuracy have been reported [6] [74]. Using computer vision methods to track image markers is another method for visualizing the surgical tool via the RGB camera of HoloLens(i.e., Vuforia Engine[4]). The advantage of this method is eliminating an external tracking device that helps to have a low-cost system with accuracy less than 10 mm [4].

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[4] https://www.ptc.com/en/products/vuforia/vuforia-engine

Chapter 4

Conclusion and Future Works

In this dissertation we developed a pipeline for one of the most common and perhaps most error-prone neurosurgical procedures, ventriclustomy. This procedure is coupled with complications and risks thus requiring solutions for navigation assistance especially in emergent settings. After reviewing conventional image-guided neurosurgery systems and discussing some of their drawbacks like cognitive load and focus shifts, we described how augmented reality may solve these limitations.

With this in mind we developed VentroAR, an augmented reality based navigation pipeline for ventriculostomy, that uses the Microsoft HoloLens. In the first prototype of VentroAR, we used an optical tracker (Atracsys) for locating the patient and pose of the surgical tool. An API was developed for sending real-time tracking information from the Atracsys camera to the HoloLens. Gathering tracking information from a highly accurate tracking device like the Atracsys in HoloLens is a method that has not been evaluated in earlier studies in the context of ventriculostomy. We believe that such accurate information about for localization can improve the HoloLens spatial understanding compared to image tracking solutions that have been previously used. In order to use the optical tracking information a customized API was developed. To the best of our knowledge no similar API was developed before for the Atracys and HoloLens.

Furthermore, we evaluated a gesture-based registration technique as a manual registration step in our pipeline. Assessments of the proposed system showed that the gesture-based registration had similar results to other techniques of manual registration proposed for Microsoft HoloLens like voice command, game controller and virtual buttons. Specifically, we found that 80% of users were able to register the patient model within less than 10 mm error range. This information suggests that hand gesture registration can be used as a manual registration method. Manual registration methods can be used as complementary registration for re-alignments necessary during the surgery based on a patient's position changing or brain shift.

Furthermore, we used a color-based feedback algorithm to improve the user's perception of the target's depth with relation to the surgical tool. In 71.7% of cases users were able to reach the target with less than 10mm error [7] [5]. The analysis of the effect of the color feedback on user's showed that the majority underestimated the depth of the target and did not reach the ventricle. Lastly, our proposed system had a good usability scale and minimal cognitive load on user.

4.1 Limitations and Future Work

Even though the results of our system are promising, they are not yet acceptable for clinical practice. There are multiple ways to improve this system in the future, which we describe below.

Depth perception was one of the main problems we encountered through this research. Having better understanding of depth of virtual models is a known problem associated with AR technology and a number of researcher groups are trying to address this issue. One way to improve depth perception for users in our system is to show a virtual catheter aligned with the physical counterpart. This can help user to have better understanding of the depth and angle of catheter when it's inserted in patient's brain. However, real-time tracking of the physical catheter is necessary to have the virtual model alight with it. This tracking can be done by an external tracker (e.g. an optical tracker) or via computer vision techniques using the RGB camera of the HoloLens (e.g., the Vuforia Engine).

Since we already track patient's head and catheter with an optical tracker, what would be needed for this is a precise calibration step to find the transformation between the optical tracking coordinate system and HoloLens. There is no specific method for this calibration but some researchers have described methods for this [74] [6].

In order to calibrate the HoloLens, we evaluated an open-source implementation of a pin-hole video camera calibration [1]. In order to use this calibration reflective markers were attached to HoloLens in addition to markers on the surgical pointer and patient reference. A chessboard grid was used to calibrate the HoloLens RGB camera with the tracking camera. All components of this experiment are shown in Figure 20. Unfortunately, even with tweaking the code we could not get the accuracy of the calibration to be suitable for the Microsoft HoloLens and the accuracy of final result was considered a failed experiment. However, more investigation into calibration of the HoloLens will be future step of this research.

Visualizing the virtual catheter using the optical tracker gives us the option to run comparative studies between our pipeline and similar pipelines with much more promising accuracy such as the tablet AR system of L'eger *et al* [42] and the HoloLens system of Lin *et al.* [6]. Such a comparison would enable a better understanding about different 3D AR displays and their effectiveness on ventriculostomy. In general, more research is needed to compare various technologies in terms of ergonomics, user-friendliness, as well as accuracy for the procedure of ventriculostomy.

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[1] https://github.com/VASST/SlicerPinholeCameras

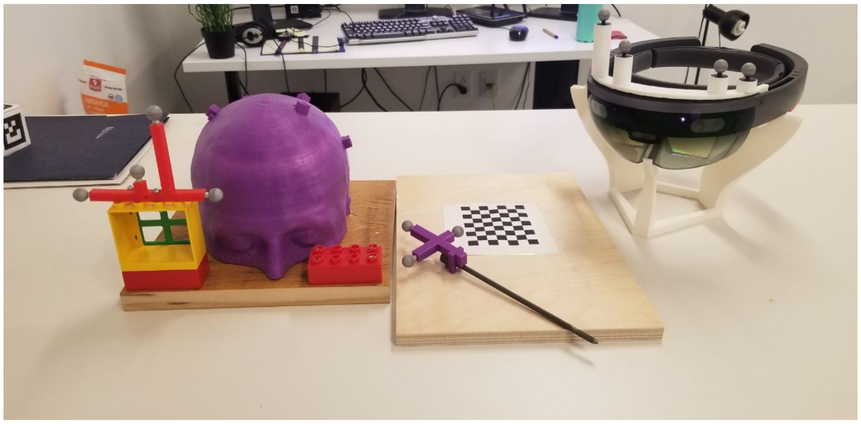

Figure 20: Components for HoloLens calibration

An similar avenue of research would to rather use the RGB camera of the HoloLens for localization and visualization of the virtual catheter or trajectory. Computer vision image tracking algorithms have some limitations in term of accuracy, but on the other hand they eliminate the need of an optical tracker from the pipeline and make the navigation system more cost efficient.

Some of the limitation of the Microsoft HoloLens like the depth camera, limited field of view and ergonomic features have been improved in new version of Hololens[2]. Having a comparison among two versions of Microsoft HoloLens and other HMDs would also be useful.

Lastly, it would be important with a more developed system to begin clinical trials to access the accuracy of an AR system in comparison to the current freehand techniques.

Augmented reality guidance is a promising tool that may improve the accuracy and cognitive load associated to surgical procedures. At the same time more research is required to to recognise all the limitations of augmented reality visualization in the operating room, to achieve the desired accuracy, and ensure that the systems are user-friendly in order for it to be ore widely used in clinical practice.

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[2] https://www.microsoft.com/en-us/hololens/buy

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