AR-Assisted Surgical Guidance System for Ventriculostomy

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ABSTRACT
Augmented Reality (AR) is increasingly used in medical applications for visualizing medical information. In this paper, we present an AR-assisted surgical guidance system that aims to improve the accuracy of catheter placement in ventriculostomy, a common neurosurgical procedure. We build upon previous work on neurosurgical AR, which has focused on enabling the surgeon to visualize a patient’s ventricular anatomy, to additionally integrate surgical tool tracking and contextual guidance. Specifically, using accurate tracking of optical markers via an external multi-camera OptiTrack system, we enable Microsoft HoloLens 2-based visualizations of ventricular anatomy, catheter placement, and the information on how far the catheter tip is from its target. We describe the system we developed, present initial hologram registration results, and comment on the next steps that will prepare our system for clinical evaluations.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality;

1 INTRODUCTION
The surgical field of view can often be limited when looking through an endoscope or working through a narrow incision. Especially in neurosurgery, a surgeon often prefers to take minimally invasive approaches to avoid inadvertent injuries to vascular or nervous structures due to a limited field of view [6]. In the case of bedside cranial procedures, the surgeons rely on their expertise, external anatomical landmarks, and imaging such as computed tomography (CT) to “see through” the skull. Among these neurosurgical procedures, ventriculostomy involves the placement of an external ventricular drain (EVD), a procedure that entails placement of twist drill craniotomy and subsequent placement of a catheter in the lateral ventricles to drain cerebral spinal fluid. EVD placement is one of the most common neurosurgical procedures, practiced more than 20,000 times annually in the U.S. alone [7]. However, while this procedure relies on external landmarks, internal ventricular anatomy can vary by patient and pathology. Hence, we developed an AR-assisted guidance system for neurosurgery with EVD as the target application.

Our AR-assisted surgical guidance system, shown in Fig. 1, uses an external 6-camera OptiTrack system for real-time tracking of a collection of optical markers, attached to different objects, enabling Microsoft HoloLens 2-based intraoperative visualization of both the hologram of patient’s ventricles and the hologram of the inserted EVD catheter. OptiTrack is often used for precise motion capture in video games, movie production, and Virtual Reality (VR). Unlike previous work which uses a single fiducial marker to enable displaying the hologram of patient’s ventricles alone, our system’s use of multiple optical markers allows displaying multiple holograms, including holograms of moving objects (i.e., the EVD catheter).

We enable OptiTrack and HoloLens 2 to work together via the transformation of their coordinate systems. Towards this, we developed a localization procedure that uses a combination of optical and fiducial markers. In this paper, we compare the results for two variants of this procedure. We also demonstrate a complete workflow for AR-assisted ventriculostomy, including the generation of a ventricular hologram from a patient’s CT scan, tracking and holographically representing the catheter, and calculating the distance from the tip of the inserted catheter to the point the neurosurgeons aim to reach (ipsilateral foramen of Monro). We believe that our system is the first to integrate tool tracking with image registration in EVD for adding more contextual guidance to AR-assisted ventriculostomy.

In the rest of this paper, we discuss the related work in Section 2, describe our system architecture in Section 3, detail our system’s AR-based visualizations in Section 4, share our preliminary results in Section 5, and comment on our future work directions in Section 6.

2 RELATED WORK
Image registration, specifically overlaying a 3D model of the preoperative scan of the patient’s view, has been explored for different types of surgeries [4,5,10]. The most common approach

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The video of AR-assisted ventriculostomy is provided at https://sites.duke.edu/sangjuneom/arevd/
to it is the use of fiducial or optical markers to determine the hologram overlay location [2]. Fiducial markers within the Vuforia engine, which is natively integrated with the Microsoft HoloLens software stack, have been used in several neurosurgical AR applications [10]. This method achieves a mean hologram registration error of 1-3mm. Similar results have been demonstrated with other types of fiducial markers, namely ARToolKit [1, 8] and AprilTags [3].

The use of a single fiducial marker limits the line of sight and robustness of marker detection. For example, Vuforia uses feature extraction for identifying trackable features and ARToolKit uses contour detection for identifying corners of fiducial markers. Both algorithms require the fiducial marker to be in the line of sight and marker pattern to be clearly visible to the camera, thus compromising the robustness of marker detection. These limitations affect the accuracy of hologram alignments for image registration.

The OptiTrack system overcomes both limitations by expanding the line of sight to a broader angle with multiple cameras, and providing robust real-time tracking with multiple optical markers while maintaining high accuracy of hologram alignment. Multiple optical markers were used with a flattened camera system in [11], however, instead of an AR device, an external monitor was used to display an augmented video to assist the surgeons.

Various types of surgeries involve the tasks of instrument manipulations where the image registration brings guidance to surgeons in improving the accuracy results of the tasks. EVD placement (which is typically a freehand procedure) with no visualization of internal anatomy can result in inaccurate placement of the catheter, especially for more junior surgeons [7]. The overlay of a ventricular hologram has been shown to improve the accuracy of catheter placement. Table 1 shows the accuracy results of instrument manipulation for various applications. In particular, the EVD application reported a reduction in the distance between the tip of the catheter and its intended target from 11.26mm [5] to 4-5mm [5, 10]. The drift of hologram over time or when erratic user movement is observed, and low first attempt success rate remain as challenges for the image registration. The mean drift of 1.41mm using Vuforia marker detection was reported for EVD [10].

Integrating tool tracking with image registration can enable providing additional contextual guidance to the surgeons [12]. In EVD, both the angle and the inserted length of the catheter are important for its accurate placement, yet surgeons have a limited view of the catheter that is inserted. A holographic representation of the catheter can provide an important visual reference for the surgeon. In this work, we enable catheter tracking and demonstrate catheter tracking-based contextual guidance.

### 3 Overall Architecture

In this section, we describe our system’s hardware specifications, our approach to tracking different objects that comprise our integrated setup, and the transformation of world coordinate systems between the two core components of our system, HoloLens 2 and OptiTrack.

#### Hardware Setup

The proposed setup includes a surgeon-worn HoloLens 2 and six Flex 3 OptiTrack cameras, shown in Fig. 1, with lens specs of 57.5 degrees in field of view and 800nm of long-pass infrared (IR) range. The OptiTrack cameras are distributed around the table to capture full 360 degrees of angular view for stable and accurate tracking of optical markers. We use the OptiTrack cameras to track all objects including the HoloLens 2; tracked object positions and orientations are transmitted back to the HoloLens 2 for visualization within our Unity-based AR app. HoloLens 2 only tracks one fiducial marker (e.g., the ARToolKit-based marker shown in Fig. 2a) to localize in order to transform its world coordinates to OptiTrack’s coordinate system.

The HoloLens 2 and the OptiTrack system are communicating via a desktop-based server, set up with the Motive Application Programming Interface (API). The server receives marker positions from the OptiTrack cameras 100 times per second, via wired USB-based connections. Tracked objects’ coordinates, calculated on the server, are transmitted to the HoloLens 2 wirelessly in real-time at the same rate. These settings achieve imperceptible latency and minimize visual artifacts that can be associated with lower frame-rate object tracking (spatial jitter, judder, unexpected disappearance of holograms).

#### Tracked Objects

There are a total of four objects that the OptiTrack system is tracking in real-time. 1) HoloLens 2 has three optical markers attached to it, and is tracked in real-time to adjust the AR view with the surgeon’s perspective. 2) A localization marker that allows HoloLens 2 and OptiTrack to operate in the same coordinate space, as described in detail in the next paragraph. We designed two localization markers: a 2D Vuforia marker, shown in Fig. 1b, and a 3D ARToolKit marker, shown in Fig. 2a. 3) The phantom model of the patient’s head, shown in Figs. 2c and d. We created the phantom model to be anatomically similar to a patient’s head, for testing, analysis, and evaluation of our system. The phantom model has eight optical markers attached to its surface, as shown

Figure 2: (a) 3D printed localization marker attached with both fiducial (ARToolKit) and optical markers. (b) H-shaped 3D printed mount for the catheter, attached to the inner stylet. (c) Dimensions of the phantom model attached with eight optical markers and Kocher’s points. (d) A mold filled with jello inside the phantom model.
which in EVD serve as the entry points for the EVD catheter. In Track operate in different world coordinates. To be able to perform

values. To enable this, we created a custom rigid object (i.e., the

software commonly used in medical applications. Then, we applied a

to be extracted from the patient’s CT scan (since ventricular anatomy

is sufficient for the EVD. The extraction of the ventricular model from

the patient’s DICOM data is a preoperative step that will increase

surgery preparation time. In our experience, it has been taking

30 minutes on average. We believe that the extraction time can be

shortened by automating the threshold selection. Examples of ventricular hologram overlays can be seen in Figs. 1 and 5.

The phantom model of a patient’s head we use for our experiments

(shown in Fig. 2c) does not correspond to a specific patient for

whom we have the ventricular CT scan. Thus, to evaluate our image

registration, we obtained the CT scan of the phantom model and

extracted its 3D model by using the filtering approach. This allows

us to directly measure the misalignment between the physical and

the virtual (i.e., AR) representations of the phantom model; we

report these results in the next section.

In EVD, once the catheter is inserted through a small opening in

the skull, the tip of the catheter is no longer visible, making it
difficult for surgeons to estimate its true location. A hologram of

the inserted catheter can bring additional guidance by showing the

depth and the angle of the insertion, and the distance from the tip

of the catheter to the ventricle. Since EVD catheters have standard
dimensions, we represent the catheter with a similarly-shaped virtual object: namely, a cylinder with 3.3mm diameter and 36cm length. The resulting visualization is shown in Figs. 1b and 5. We are

currently working on improving the robustness of catheter tracking.

Currently, while providing useful visualizations in some conditions,

it results in spatial jitter in others. We will report on these results in

future work.

5 Preliminary Results

Our system is intended to be used as follows. First, during the

system initialization phase, the user performs the eye calibration for

HoloLens 2, and the connectivity between the HoloLens 2 and the

OptiTrack is established. Following the initialization, the surgeon

navigates around the localization marker until a white cube hologram

appears, as shown in Fig. 1, which indicates that the fiducial marker

is detected. Once the cube hologram is accurately positioned on the

marker, the surgeon presses a button to compute the transformation

of the world coordinate system using the detected location. After the

transformation, the holograms of the ventricle and the EVD catheter

appear in the surgeon’s view, and the surgeon performs the insertion

of the catheter through Kocher’s point. The surgeon removes the

inner stylet when catheter placement is complete.

Localization: The performance of the two marker detection meth-
ods we examined (namely, ARToolKit and Vuforia) differed signifi-
cantly. We summarize our observations in Table 2. Over 15 trials,

we observed that the ARToolKit localization marker was detected

more readily while Vuforia localization marker was sensitive to

user distance and orientation. The detection stability was unreli-
able for ARToolKit, subsequently maintaining a poor alignment that

depended on the user’s movement, however for Vuforia, a good

threshold value to extract the lateral ventricle with foramen of Monro

and the skull, as seen in Fig. 4, rendered the combined 3D model, and

exported it to load into Unity. The 3D model of the skull was initially

extracted together with the ventricle to evaluate the alignment with

the phantom model; however, the ventricular hologram alone is

required.
alignment of the cube hologram was observed, once detected. The mean ± standard deviation time of user navigation was 15.11 ± 7.57 seconds for ARToolKit, and 12.71 ± 7.05 seconds for Vuforia. The average latency of data communication between OptiTrack and HoloLens 2 was 12.32 ms. The data stream of marker positions maintained a seamless AR experience of reflecting changes in tracked models with no data loss.

**Catheter Placement:** After the catheter is inserted, the surgeon removes the inner stylet and the jello maintains the position of the catheter placement, as shown in Fig. 5. In our system, we added contextual guidance of a text display above the ventricle hologram, which shows the calculated distance from the tip of the catheter to the foramen of Monro (which the surgeons target in EVD). This distance calculation is obtained in real time, using the tracked positions of the phantom model and the catheter. We believe that our system is the first to provide such guidance for the EVD procedure, which may enable its use in training novice neurosurgeons in conducting this procedure. However, the guidance we currently present is subject to object tracking errors. We will evaluate its correctness by comparing the distance we calculate with the physical distance between the foramen of Monro and the tip of the catheter.

**6 Conclusions and Future Work**

Among various surgical applications of AR, neurosurgery benefits from AR guidance to maintain minimal invasiveness while ensuring safety. In this paper we integrate AR into a neurosurgical application by creating an AR-assisted surgical guidance system with image registration and tool tracking. We demonstrate the visualization of the ventricular anatomy for guidance to the surgeons and the projection of the catheter tip for the EVD catheter placement.

We are currently preparing our system to be evaluated in clinical settings, for the accuracy of AR-assisted catheter placement and for other potential benefits of contextual guidance that our system will provide. We have identified the following next steps to prepare our system for the user studies. First, we will continue to improve the robustness of tool tracking by optimizing the number and the distribution of markers on the 3D-printed mount, and by configuring the number, positions, orientations, and other parameters of the OptiTrack cameras. Furthermore, we will develop more user-friendly and intuitive workflows for the surgeons. The current procedure requires pre-operative steps of extracting a patient-specific ventricular model and intraoperative steps for performing the localization, increasing the overall surgery preparation time. We will improve our system by automating threshold selection of different DICOM data, and by providing additional AR-based visual guidance for system localization. We expect to start conducting initial user studies, which will evaluate different elements of our system with both novice and experienced neurosurgeons, within the next 6 months.

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