AR-Assisted Surgical Guidance System for Ventriculostomy

Sangjun Eom*
Department of Electrical and Computer Engineering
Duke University

Seijung Kim†
Department of Computer Science
Duke University

Shervin Rahimpour‡
Department of Neurosurgery
University of Utah

Maria Gorlatova§
Department of Electrical and Computer Engineering
Duke University

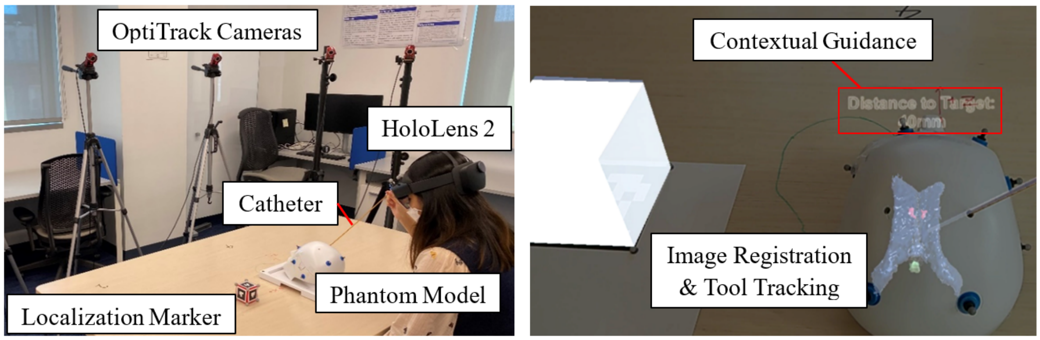


Figure 1: The overall setup of our system using OptiTrack cameras for real-time tracking and HoloLens 2 as an AR device (left), and the AR view of ventricle and EVD catheter holograms overlaid for surgical guidance, and a cube hologram for localization (right).

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.[1]

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 with the surgeon's view, has been explored for different types of surgeries [4,5,10]. The most common approach

*E-mail: sangjun.eom@duke.edu
†E-mail: seijung.kim@duke.edu
‡E-mail: shervin.rahimpour@utah.edu
§E-mail: maria.gorlatova@duke.edu

[1]The video of AR-assisted ventriculostomy is provided at https://sites.duke.edu/sangjuneom/arevd/

Table 1: Accuracy results of instrument manipulation on a hologram overlaid target in various surgical applications.

Papers	Areas	Devices	Results (mm)
Schneider et al. [10]	EVD	HoloLens 1	5.20 ± 2.60
Li et al. [5]	EVD	HoloLens 1	4.34 ± 1.63
Andress et al. [1]	Orthopedic	HoloLens 1	4.47 ± 2.91
Rose et al. [9]	Otolaryngology	HoloLens 1	2.47 ± 0.46

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 flatbed 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

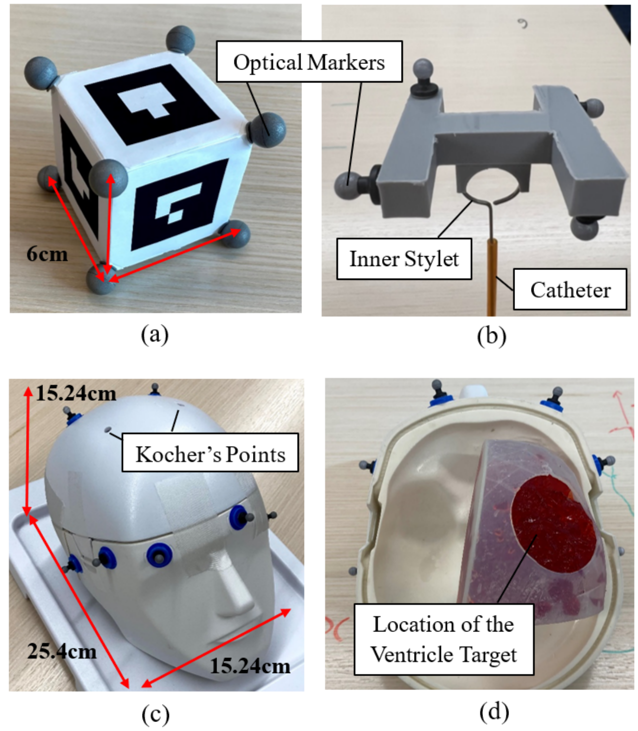


Figure 2: (a) 3D printed localization marker attached with both fiducial (ARToolKit) and optical markers. (b) H-shaped 3D printed mount for the catheter, attached to the inner stylet. (c) Dimensions of the phantom model attached with eight optical markers and Kocher's points. (d) A mold filled with jello inside the phantom model.

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 transmits 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] 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

[2]This approach to *headset pose tracking* is similar to the methods used in modern VR systems, such as Oculus Quest 2 and HTC Vive.

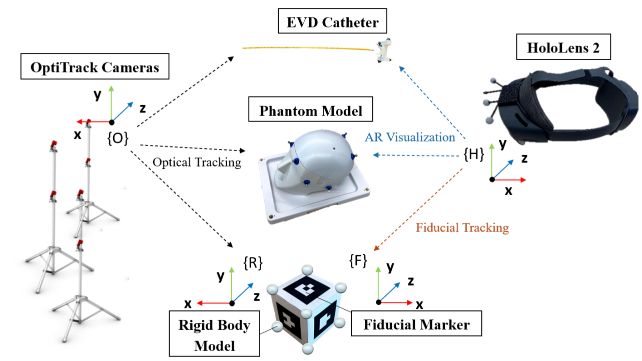


Figure 3: Transformation between two world coordinate systems through the tracking of a localization marker. This diagram shows a 3D ARToolKit marker; we also experimented with a 2D Vuforia marker.

in Fig. 2c. The phantom model also shows two Kocher's points, which in EVD serve as the entry points for the EVD catheter. In the phantom model we pre-drilled holes at these points, each with a diameter of approximately 6mm. Inside the phantom model, there is a 3D printed mold filled with red jello to imitate the target, as shown in Fig. 2d. We used jello as a low-cost material that imitates the texture of the ventricle and is capable of holding the catheter position after the placement. 4) The EVD catheter. It is not possible to attach optical markers directly to the catheter, which is a thin tube with a 3.3mm diameter. Rather, we designed a 3D printed mount, and attached four optical markers to it, each facing in a different direction. The 3D printed mount is attached to the top of the inner stylet, inserted inside the catheter to maintain the tube's rigidity for the insertion. EVD catheter mount design and attachment are shown in Fig. 2b.

Transformation of World Coordinates: HoloLens 2 and OptiTrack operate in different world coordinates. To be able to perform transformations between the different coordinate systems, both the HoloLens and the OptiTrack need to locate the same target, to be used as a reference when calculating the differences in coordinate values. To enable this, we created a custom rigid object (i.e., the localization marker) that can be tracked by both OptiTrack and HoloLens 2, and compute the same centroid point to calculate the differences.

The transformation of world coordinates from OptiTrack, $\{O\}$ to HoloLens 2, $\{H\}$, T_O^H is shown in Eq. 1 and Fig. 3. The transformation between HoloLens 2 and fiducial markers, $\{F\}$ on the localization marker, T_F^H is obtained by either ARToolKit or Vuforia marker detection methods. We placed the optical markers on the localization marker to register it as a rigid body, $\{R\}$, and calculate the same centroid point as possible as the fiducial markers. This minimizes the transformation between the fiducial marker and rigid body, T_R^F. The transformation between the rigid body of localization marker and OptiTrack, T_O^R, is then obtained by OptiTrack's real-time tracking.

$$T_O^H = T_F^H \cdot T_R^F \cdot T_O^R \tag{1}$$

4 Holographic Visualization

High accuracy of image registration is of utmost importance in surgical applications. We take advantage of OptiTrack with high accuracy tracking of each marker position, as seen in Fig. 3, for registering ventricular hologram and tracking the EVD catheter.

In EVD applications, a patient-specific ventricular model needs to be extracted from the patient's CT scan (since ventricular anatomy varies by patient). We first imported the DICOM data of a patient's CT scan into 3D Slicer, open-source image analysis and visualization software commonly used in medical applications. Then, we applied a 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 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.

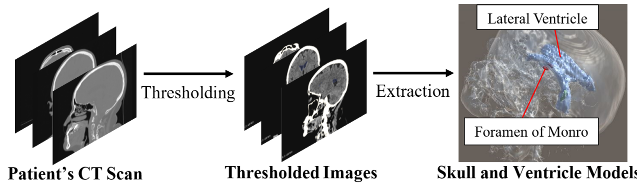


Figure 4: Extraction of 3D models of skull frame and ventricle from the patient's CT scan.

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.

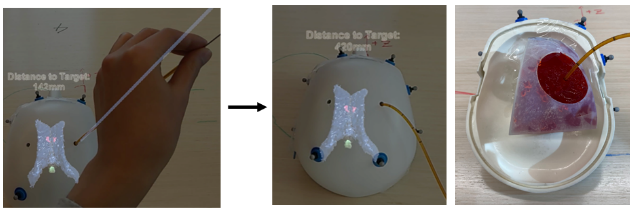
5 Preliminary Results

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 methods we examined (namely, ARToolKit and Vuforia) differed significantly. 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 unreliable for ARToolKit, subsequently maintaining a poor alignment that depended on the user's movement, however for Vuforia, a good

Table 2: Comparison between ARToolKit and Vuforia localization methods in detection and hologram alignments.

Detection Method	ARToolKit	Vuforia
Marker Type	3D Fiducial	2D Fiducial
Localization Time (s)	15.11 ± 7.57	12.71 ± 7.05
	x: 1.39 ± 0.57	x: 0.96 ± 0.43
Registration Error (mm)	y: 1.17 ± 0.83	y: 1.11 ± 0.27
	z: 1.39 ± 0.88	z: 1.44 ± 1.05
Detection Flexibility	Easy, Flexible	Strict to angle, distance
Detection Stability	Unreliable	Reliable



Inner Stylet Removal **Completion of Catheter Placement**

Figure 5: Procedures of AR-assisted ventriculostomy in placing the catheter at the foramen of Monro.

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.

Hologram Alignment: Over 15 trials, we measured the difference in the alignment between the physical phantom model and its holographic representation, using a digital caliper in x, y, and z coordinates (in the coordinate system shown in Fig. 3). As shown in Table 2, we observed the mean (x, y, z) registration errors of (1.39 ± 0.57, 1.17 ± 0.83, 1.39 ± 0.88)mm when using ARToolKit, and (0.96 ± 0.43, 1.11 ± 0.27, 1.44 ± 1.05)mm when using Vuforia. The detection stability and higher accuracy of Vuforia are the key to maintaining the image registration robust and accurate. We will thus use Vuforia as our localization method in our subsequent research.

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.

Acknowledgments

We thank Emily Eisele for her work on this project during an NSF REU Program at Duke University. This work was supported in part by NSF grants CSR-1903136 and CNS-1908051, NSF CAREER Award IIS-2046072, IBM Faculty Award, and by an AANS Neurosurgery Technology Development Grant.

References

[1] S. Andress, A. Johnson, M. Unberath, A. F. Winkler, K. Yu, J. Fotouhi, S. Weidert, G. M. Osgood, and N. Navab. On-the-fly augmented reality for orthopedic surgery using a multimodal fiducial. *Journal of Medical Imaging*, 5(2):021209, 2018.

[2] L. Chen, T. W. Day, W. Tang, and N. W. John. Recent developments and future challenges in medical mixed reality. In *Proc. IEEE ISMAR*, 2017.

[3] W. Gibby, S. Cvetko, A. Gibby, C. Gibby, K. Sorensen, E. G. Andrews, J. Maroon, and R. Parr. The application of augmented reality–based navigation for accurate target acquisition of deep brain sites: advances in neurosurgical guidance. *Journal of Neurosurgery*, 1(aop):1–7, 2021.

[4] N. Haouchine, J. Dequidt, I. Peterlik, E. Kerrien, M.-O. Berger, and S. Cotin. Image-guided simulation of heterogeneous tissue deformation for augmented reality during hepatic surgery. In *Proc. IEEE ISMAR*, 2013.

[5] Y. Li, X. Chen, N. Wang, W. Zhang, D. Li, L. Zhang, X. Qu, W. Cheng, Y. Xu, W. Chen, et al. A wearable mixed-reality holographic computer for guiding external ventricular drain insertion at the bedside. *Journal of Neurosurgery*, 131(5):1599–1606, 2018.

[6] A. Meola, F. Cutolo, M. Carbone, F. Cagnazzo, M. Ferrari, and V. Ferrari. Augmented reality in neurosurgery: a systematic review. *Neurosurgical Review*, 40(4):537–548, 2017.

[7] B. R. O'Neill, D. A. Velez, E. E. Braxton, D. Whiting, and M. Y. Oh. A survey of ventriculostomy and intracranial pressure monitor placement practices. *Surgical Neurology*, 70(3):268–273, 2008.

[8] L. Qian, A. Deguet, and P. Kazanzides. ARssist: augmented reality on a head-mounted display for the first assistant in robotic surgery. *Healthcare Technology Letters*, 5(5):194–200, 2018.

[9] A. S. Rose, H. Kim, H. Fuchs, and J.-M. Frahm. Development of augmented-reality applications in otolaryngology–head and neck surgery. *The Laryngoscope*, 129:S1–S11, 2019.

[10] M. Schneider, C. Kunz, A. Pal'a, C. R. Wirtz, F. Mathis-Ullrich, and M. Hlaváč. Augmented reality–assisted ventriculostomy. *Neurosurgical Focus*, 50(1):E16, 2021.

[11] S. Skyrman, M. Lai, E. Edström, G. Burström, P. Förander, R. Homan, F. Kor, R. Holthuizen, B. H. Hendriks, O. Persson, et al. Augmented reality navigation for cranial biopsy and external ventricular drain insertion. *Neurosurgical Focus*, 51(2):E7, 2021.

[12] T. Song, C. Yang, O. Dianat, and E. Azimi. Endodontic guided treatment using augmented reality on a head-mounted display system. *Healthcare Technology Letters*, 5(5):201–207, 2018.