An Interactive Mixed Reality Platform for Bedside Surgical Procedures*

"anonymous"

"Anonymous Organization"
`***@***.***`

Abstract. In many bedside procedures, surgeons must rely on their spatiotemporal reasoning to estimate the position of an internal target by manually measuring external anatomical landmarks. One particular example that is performed frequently in neurosurgery is ventriculostomy, where the surgeon inserts a catheter into the patient's skull to divert the cerebrospinal fluid and alleviate the intracranial pressure. However, about one-third of the insertions miss the target.
We, therefore, assembled a team of engineers and neurosurgeons to develop an interactive surgical navigation system using mixed reality on a head-mounted display that overlays the target, identified in preoperative images, directly on the patient's anatomy and provides visual guidance for the surgeon to insert the catheter on the correct path to the target. We conducted a user study to evaluate the improvement in the accuracy and precision of the insertions with mixed reality as well as the usability of our navigation system. The results indicate that using mixed reality improves the accuracy by over 35% and that the system ranks high based on the usability score.

Keywords: Surgical Navigation · Neurosurgery · Augmented Reality.

1 Introduction

In many surgical procedures, surgeons rely on their general knowledge of anatomy and relatively crude measurements, which have inevitable uncertainties in locating internal anatomical targets. One example procedure that is frequently performed in neurosurgery is ventriculostomy (also called external ventricular drainage), where the surgeon inserts a catheter into the ventricle to drain cerebrospinal fluid (CSF). In this procedure, often performed bedside and therefore without image guidance, the surgeon makes measurements relative to cranial features to determine where to drill into the skull and then attempts to insert a catheter as perpendicular to the skull as possible. Although it is one of the most commonly performed neurosurgical procedures, about one quarter to one third of catheters are misplaced or require multiple attempts [13, 9], potentially resulting in brain injury and increasing healthcare costs [2].

---

* Supported by *****.

We propose a portable navigation system, based on mixed reality (MR) on a head mounted display (HMD), specifically HoloLens (Microsoft, Redmond, WA) to provide image guidance in less structured environments, such as at the patient bedside in an intensive care unit, where it is not practical to install a separate tracking camera, computer, and display. Furthermore, the mixed reality guidance can provide an ergonomic benefit because it is visually overlaid in the surgeon's field of view, thus avoiding the need to look away from the patient to observe an external monitor.

2 Previous Work

HMDs have been used in the medical domain for treatment, education, rehabilitation, and surgery [6, 10]. In [7], the researchers presented the use of a head-mounted display to visualize volumetric medical data for neurosurgery planning. Together with a haptic device, the system allows the user to scroll through the image slices more intuitively. In [3], a picture-in-picture visualization is adopted for neurosurgery navigation with a custom built HMD. With the advent of Google Glass, around 2013, many research groups started to explore using an HMD as a replacement for traditional radiology monitors [15, 1]. A generalized real-time streaming system based on OST-HMDs was proposed, which is suitable for image-guided surgeries (i.e., percutaneous screw fixation of pelvic fractures) [12]. In other research, HMDs give the surgeon an unobstructed view of the anatomy, which is rendered inside the patient's body [14]. More recently, an ecosystem was proposed for performing surgical tasks in mixed reality [4]. The most similar work to our own was reported by Li et al. [11], where they used the Microsoft HoloLens HMD to provide augmented reality guidance for catheter insertion in ventriculostomy. However, they did not track the skull and instead relied on preventing patient motion, which increases the risk of misplacement due to undetected motion.

3 System Description

As a surgical navigation system, our system (Fig. 1) and workflow (Fig. 2) comprises of the following necessary components, including tracking, image segmentation, registration, guidance, and visualization:

Marker tracking: Our system tracks the patient using a marker (reference frame) mounted on the patient's skull. We initially used a headband to attach the reference frame, as in Fig. 1-left, but based on surgeon feedback have changed to a post that is screwed into the skull, as in Fig. 1-right (in a clinical procedure, this post would be located closer to the burr hole), with an adjustable linkage to enable the marker to be positioned in the field-of-view of the HMD tracking camera. At the same time, we need to be able to identify points for surgical path planning or to select fiducials for registration. Therefore, we also track a second marker that is affixed to a pointer tool, shown in Fig. 1-left. We thus designed two image target markers that can be tracked using Vuforia Engine.

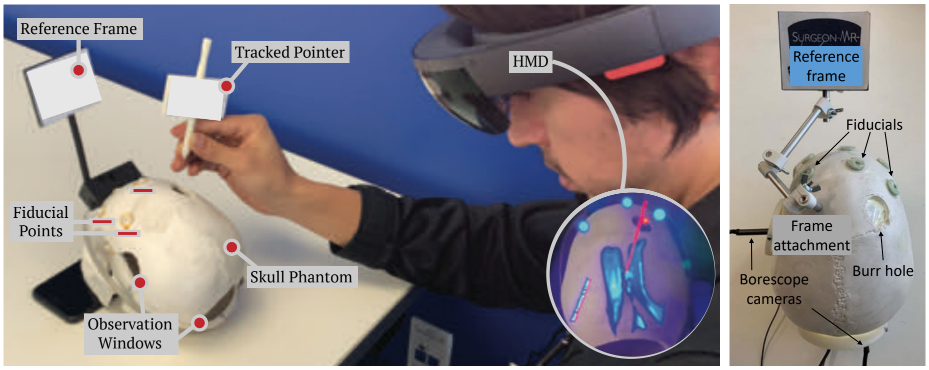

Fig. 1: Left: User wearing HMD and holding tracked pointer to perform registration. Right: Updated skull phantom (new fiducials, reference frame attachment and borescope cameras for measurement).

Segmentation: Our MR navigation requires a model that matches the subject of interest. To that end, we segment the CT scan of the patient. The ventricles are segmented using the connected threshold filter of SimpleITK (www.simpleitk.org), which uses user-specified coordinates, or "seeds," as well as the expected threshold, to create a binary labelmap from the medical image data. The skull, on the other hand, can be easily segmented in 3D Slicer (www.slicer.org) using its built-in threshold filter. Both the ventricle and skull segmentations are then used to create 3D models for the navigation system.

Registration: Mixed reality overlay of the 3D models requires registration of the medical imaging data to the actual patient's anatomy. To this aim, fiducials are affixed on the skull prior to the CT scan and their positions are identified using 3D Slicer. The surgeon then selects the corresponding points on the patient's skull by touching the fiducials using the tracked tool. We implemented a paired point registration method that uses these two sets of points and finds the transformation that registers the CT data to the actual anatomy.

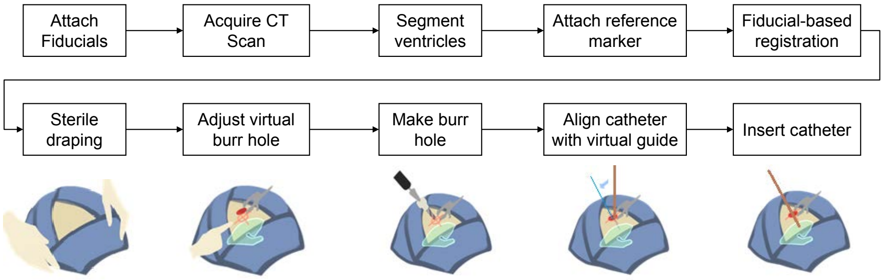

Fig. 2: Procedure workflow for ventriculostomy

User Interface and Visualization: The user interface was designed in Unity 3D (www.unity.org) and supports the workflow shown in Fig. 2, where registration fiducials are attached to the patient prior to acquisition of a CT scan.

Registration is the first procedural task that benefits from mixed reality visualization. The surgeon holds the tracked pointer tool and the HMD overlays a red sphere at the tip of the tool. This provides the surgeon with visual verification that the system is well calibrated (if not, the calibration can be repeated). The surgeon uses the pointer tool to touch each fiducial, with a voice command to trigger position capture. The system then overlays a green sphere at the captured position, which provides visual feedback that the voice command was recognized and also that the captured position is correctly aligned with the physical fiducial (if not, the point can be recollected). After collecting the positions of at least three fiducials, the surgeon issues a voice command to perform the registration. The surgeon can issue another voice command to “show skull”, at which point the skull model (segmented from CT) is overlayed on the patient, enabling visual confirmation of the registration result. The surgeon can issue the command “hide skull” to turn off this overlay.

The next use of mixed reality visualization occurs prior to making the burr hole. Here, the system overlays a virtual circle at the nominal position of the burr hole, based on the registered CT scan, but the surgeon can use the tracked pointer to adjust this position, if necessary. After the surgeon makes the burr hole, the system overlays a virtual line that passes through the burr hole and to the intended target (Foramen of Monro). The surgeon then aligns the real catheter with the virtual line and advances to the target, thereby completing the procedure. Sample mixed reality visualizations are shown in Fig. 3.

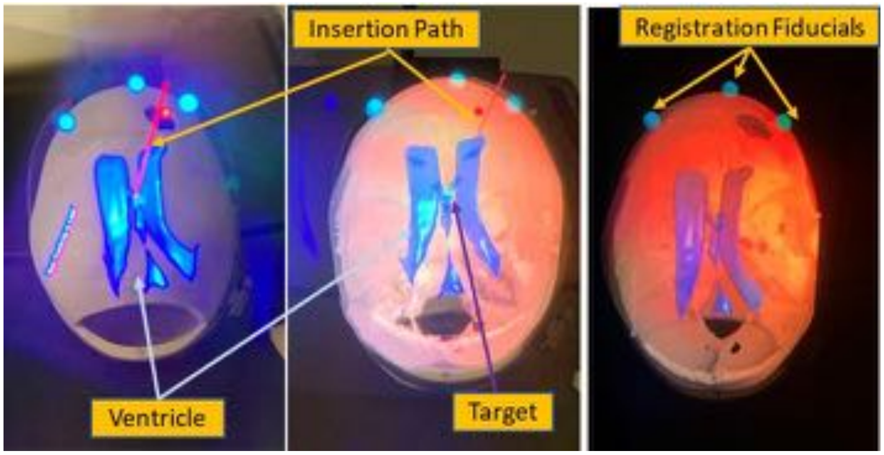

Fig. 3: Guidance and visualization in mixed reality captured from the user’s view. The virtual skull is overlaid on the real skull and 3 registration points are shown. The red line is the virtual guidance path for the catheter.

4 Experiments

We created an experimental setup to evaluate our system in a user study.

4.1 Phantom Design

The phantom is constructed from a plastic skull with a cranial cap that is magnetically attached (Fig. 4). A clear acrylic box is inserted to hold gel that mimics the brain tissue. We determined that 1.25 teaspoons of SuperClear gelatin powder (Custom Collagen, Addison, IL) in 1 cup water provided a gel that, according to the neurosurgeons, approximated the feel of brain tissue.

We placed three spheres near the bottom of the acrylic box to use as targets. One sphere was located at the nominal position of the Foramen of Monro to represent normal anatomy. The other two spheres were offset to represent abnormal anatomy. Because our focus is to evaluate MR guidance for inserting the catheter, we created a large burr hole in the skull, thereby skipping the steps in Fig. 2 where the subject creates the burr hole. Note, however, that our burr hole is significantly larger than one created clinically so that the subject has some flexibility to adjust the catheter entry point.

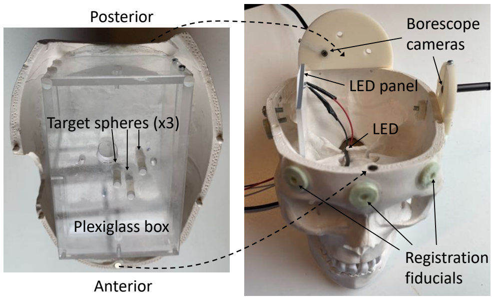

Fig. 4: Left: top of skull showing plexiglass box and targets. Right: bottom of skull showing borescope cameras and LEDs.

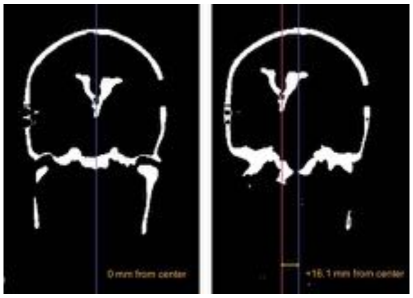

Fig. 5: Coronal views of two synthetic CT scans (left: nominal; right: abnormal).

4.2 CT Generation

After acquiring a CT scan of our phantom, we used 3D Slicer to extract the model of the skull, the positions of the fiducials, and the positions of the target spheres. Using data from another CT scan with a ventricle phantom, we created synthetic CT scans, as shown in Fig. 5. Specifically, we digitally removed the spherical targets from the CT scan and then used 3D Slicer's transform module to place the ventricle model such that its Foramen of Monro was coincident with each of the three targets. These synthetic CT scans are provided to subjects in the control group, who do not have the benefit of mixed reality visualization and would normally consult the CT scan.

4.3 Embedded Optical Measurement

We constructed a computer vision system to measure the 3D coordinates of the catheter and target, as well as to record videos (Fig. 4). One camera is fixed on the left side of the skull, and the other is on the back. Due to the different refractive indices between the gel and air, the intrinsic calibration of each camera is separately performed with a checkerboard in the gel. The extrinsic parameters, which do not change with the medium, are calibrated in air. The accuracy of the optical measurement system was obtained by identifying each of the three spherical targets inside the skull and computing the distances between them, which are 10.57 mm, 18.54 mm, and 18.43 mm. These three distances are compared to the same distances computed in the CT scans (0.68 mm axial dimension and 1 mm slice spacing), which are 11.05 mm, 18.18 mm, and 18.53 mm. This results in distance errors of 0.48 mm, -0.36 mm, and 0.10 mm, which are all within one CT voxel.

Fig. 6 shows images from the measurement software for a catheter insertion. During the experimental procedure, once the catheter reaches the guided position, two images are captured. The target, catheter tip and a second point on the catheter (to determine its orientation) are detected in both images. Consequently, the distances between the spherical target and the catheter tip, as well as the catheter line, are obtained to evaluate the accuracy of the MR guidance system. Our mixed reality guidance shows a virtual path to the users, so they can align their catheter along it, but does not show the insertion depth (i.e., when to stop). Therefore, we expect that mixed reality can better mitigate the distance between the target and the catheter line.

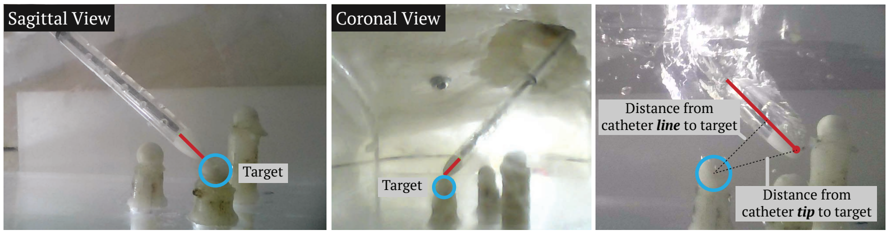

Fig. 6: Left: Sample images from two borescope cameras, showing measurements. Right: Distances from the target to the catheter tip and catheter direction

4.4 User Study

Experimental Design and Participants. We designed a within-subjects study in which each participant performed the catheter insertion task for three targets both with (MR condition) and without (baseline condition) mixed reality guidance. Following IRB approval, we recruited 10 participants. Participant ages ranged from 21 to 35 ($M = 25.44, SD = 5.11$). All had an engineering or medical background. Participants reported that they were somewhat familiar with the mixed reality devices ($M = 2.7, SD = 0.82$) on a 5-point scale, with 5 being very familiar. The majority of participants had never viewed the ventriculostomy procedure; however, we note that one participant is a neurosurgeon, who is experienced in this procedure. All participants were unpaid volunteers.

Procedure. Each participant completed two questionnaires, a pre-task survey and demographics, to provide a baseline and assess their familiarity with the procedure and with mixed reality. Then, each participant watched an instructional video on how to calibrate the HMD and perform the task. For the trials with mixed reality guidance, the user wears the HMD and calibrates the system. Next, using the tracked pointer, the participant touches the fiducials and uses a voice command to acquire its 3D position. After selecting the fiducial points, the registration and alignment is performed using a voice command. The user then plans a path for catheter insertion from the entry point to the designated target. Afterwards, the user inserts the catheter by aligning it with the virtual 3D guide visualized on the HMD and then advancing to the designated depth (~ 6 *cm*). The user determines the insertion depth by reading labels on the catheter. For the trials without mixed reality, each participant viewed the CT image of the phantom with the corresponding target, which provided the measured distance of the target with respect to its nominal position (centerline), and then inserted the catheter to reach the target. The experiment took an average of about 45 *mins* for each participant.

Measures. We included objective and subjective metrics to measure task performance and usability. Objectively, we sought to assess the participant's task accuracy. Each trial was video recorded using the optical measurement system (Section 4.3) when catheter insertion started and recording was stopped when the participant was satisfied with the insertion. We measured the accuracy of each insertion as the distance between the catheter tip and target and as the minimum distance of the catheter (line) to the target. In addition, the participant completed a questionnaire about their experience in terms of usability as measured by the System Usability Scale (SUS) [5] and perceived workload as measured by the NASA TLX [8].

5 Results

We used one-way repeated-measures analyses of variance (ANOVA) where the condition (either *baseline* or *mixed reality*) was set as a fixed effect, and the participant was set as a random effect. Fig. 7 summarizes our results.

Task Accuracy. The ANOVA test suggests that there is a significant difference in the task accuracy, measured as the distance between the catheter line and the target, $F(1, 18) = 6.24, p = .022$. The participants with the mixed reality aid were able to maintain a shorter distance to the target ($M = 7.63, SD = 5.00$) when comparing to using the baseline setup ($M = 12.21, SD = 2.93$). However, we only observed a marginal difference in measured tip distance, $F(1, 18) =$

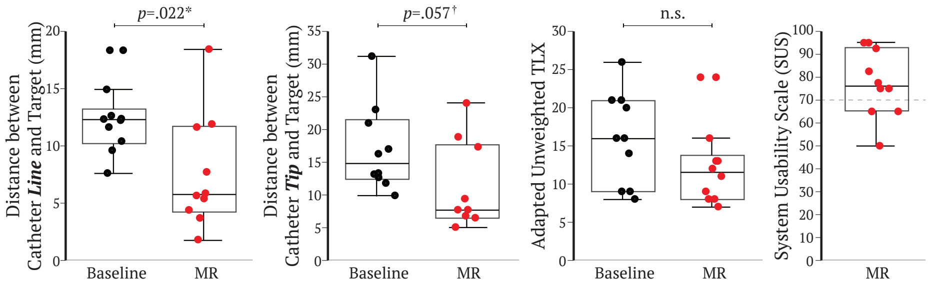

Fig. 7: Experimental results. We note that for the distance and TLX metrics lower values indicate better performance. For the SUS index, higher is better.

$4.14, p = .057$, between the MR condition ($M = 10.96, SD = 6.61$) and the baseline condition ($M = 16.93, SD = 6.52$). Altogether, the results show more than 35% improvement in catheter tip accuracy and more than 37% improvement in catheter direction accuracy using our mixed reality navigation system.

Usability. Our data revealed that participants thought that the mixed reality method ($M = 12.1, SD = 5.04$) required less mental workload than the baseline surgical method ($M = 16.00, SD = 6.07$), although the difference was not statistically significant, $F(1, 18) = 2.44, p = .136$. Moreover, the average scored usability (SUS) of the mixed reality system ($M = 77.25, SD = 14.69$) is above the suggested usability score of 70 [5], indicating that our mixed reality system is reasonably usable for performing the ventriculostomy procedure.

6 Conclusion and Future Work

We proposed an interactive portable navigation system in mixed reality for performing bedside neurosurgical procedures. In this system, an HMD-based application is implemented which allows the surgeon to plan and perform ventriculostomy, which involves inserting a catheter through the skull into the ventricles to divert cerebrospinal fluid.

Through a user study, we show that our MR-based navigation system offered high perceived usability and improved targeting accuracy by more than 35%, suggesting clinical impact for a procedure where about one third of catheter insertions miss the target. Although our system does not currently track the catheter to provide feedback on the insertion depth to the user, thus requiring the user to stop insertion based on visual markings on the catheter, in the actual clinical scenario, as long as the catheter is directed close enough ($\sim 3\ mm$) to the target and reaches the ventricle, the surgeon would see the flow of CSF coming out of the catheter and stop further insertion. Our future work includes integrating catheter tracking so that the system can provide additional feedback during the insertion, such as the catheter depth. We also plan to conduct a user study where all participants are intended users—neurosurgeons—with various level of expertise, to further assess the usefulness and usability of the system.

References

1. Armstrong, D.G., Rankin, T.M., Giovinco, N.A., Mills, J.L., Matsuoka, Y.: A heads-up display for diabetic limb salvage surgery: a view through the google looking glass. Journal of Diabetes Science and Technology **8**(5), 951–956 (2014)
2. Aten, Q., Killeffer, J., Seaver, C., Reier, L.: Causes, complications, and costs associated with external ventricular drainage catheter obstruction. World Neurosurgery **134**, 501–506 (2020)
3. Azimi, E., Doswell, J., Kazanzides, P.: Augmented reality goggles with an integrated tracking system for navigation in neurosurgery. In: Virtual Reality Short Papers and Posters (VRW). pp. 123–124. IEEE (2012)
4. Azimi, E., Molina, C., Chang, A., Huang, J., Huang, C.M., Kazanzides, P.: Interactive training and operation ecosystem for surgical tasks in mixed reality. In: MICCAI Workshop on OR 2.0 Context-Aware Operating Theaters, pp. 20–29. Springer (2018)
5. Brooke, J.: Sus-a quick and dirty usability scale. Usability evaluation in industry **189**(194), 4–7 (1996)
6. Chen, L., Day, T., Tang, W., John, N.W.: Recent developments and future challenges in medical mixed reality. In: IEEE Intl. Symp. on Mixed and Augmented Reality (ISMAR). pp. 123–135 (2017)
7. Eck, U., Stefan, P., Laga, H., Sandor, C., Fallavollita, P., Navab, N.: Exploring visuo-haptic augmented reality user interfaces for stereo-tactic neurosurgery planning. In: Intl. Conf. on Medical Imaging and Augmented Reality (MIAR). pp. 208–220. Springer (2016)
8. Hart, S.G.: Nasa-task load index (nasa-tlx); 20 years later (2006)
9. Huyette, D.R., Turnbow, B.J., Kaufman, C., Vaslow, D.F., Whiting, B.B., Oh, M.Y.: Accuracy of the freehand pass technique for ventriculostomy catheter placement: retrospective assessment using computed tomography scans. Journal of Neurosurgery (JNS) **108**(1), 88 – 91 (2008)
10. Kersten-Oertel, M., Jannin, P., Collins, D.L.: DVV: a taxonomy for mixed reality visualization in image guided surgery. IEEE Transactions on Visualization and Computer Graphics **18**(2), 332–352 (2012)
11. Li, Y., Chen, X., Wang, N., Zhang, W., Li, D., Zhang, L., Qu, X., Cheng, W., Xu, Y., Chen, W., Yang, Q.: A wearable mixed-reality holographic computer for guiding external ventricular drain insertion at the bedside. Journal of Neurosurgery (JNS) (Oct 2018)
12. Qian, L., Unberath, M., Yu, K., Fuerst, B., Johnson, A., Navab, N., Osgood, G.: Towards virtual monitors for image guided interventions-real-time streaming to optical see-through head-mounted displays. arXiv preprint arXiv:1710.00808 (2017)
13. Raabe, C., Fichtner, J., Beck, J., Gralla, J., Raabe, A.: Revisiting the rules for freehand ventriculostomy: a virtual reality analysis. Journal of Neurosurgery pp. 1–8 (2017)
14. Sauer, F., Khamene, A., Bascle, B., Rubino, G.J.: A head-mounted display system for augmented reality image guidance: Towards clinical evaluation for iMRI-guided neurosurgery. In: Intl. Conf. on Medical Image Computing and Computer-Assisted Intervention (MICCAI). pp. 707–716. Springer-Verlag (2001)
15. Yoon, J.W., Chen, R.E., Han, P.K., Si, P., Freeman, W.D., Pirris, S.M.: Technical feasibility and safety of an intraoperative head-up display device during spine instrumentation. Intl. J. of Med. Robotics and Comp. Assisted Surg. **13**(3) (2017)