Visual Computing Magazine

AR for Medical imaging

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1. Introduction

Medical imaging is the field that focuses on the acquisition and analysis of patient specific images acquired by scanner devices. These images can be acquired through various modalities such as the well-known X-ray, Ultrasound (US), Computed Tomography (CT), and Magnetic Resonance Imaging (MRI) [1] (See Fig. 1a and Fig. 1b).

These imaging modalities provide an inner visualization of the tissues or bony structures that are underneath the skin. Those modalities can acquire single 2D images, such as in the case of X-Ray and US images, or as a stack of 2D images which constitutes a 3D volume of the captured anatomy in the case of CT or MRI modalities.

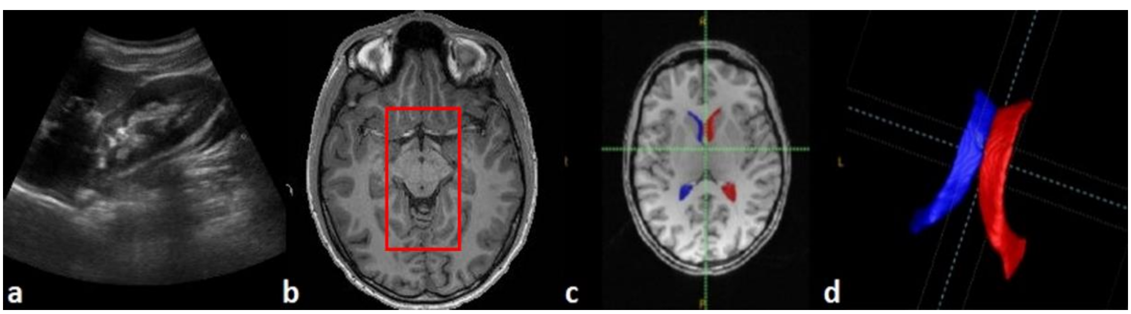

Figure 1. (a): Ultrasound liver scan [2], (b) MRI brain scan [3], (c) ventricles segmentation in a brain MRI image, (d) and 3D reconstruction of the ventricles from an MRI image [4].

The acquired images can be used as a diagnosis tool preoperatively, as a reference during surgery (perioperatively), or as a postoperative tool to evaluate the success of a surgical intervention.

To facilitate the previous tasks, various operations can be performed on the acquired images: detection, classification, segmentation and 3D reconstruction are the most common. For instance, the first one consists of locating brain ventricles (Fig. 1b), the second consists of identifying the type of disease in the image, the third one consists of identifying which part of the image (a group of pixels) represent a certain anatomy (Fig. 1c), and the last one consists of using the 2D stack of images to create a 3D reconstruction of the ventricles (Fig. 1d).

In the case where a surgical procedure is needed, these procedures allow for surgical planning. This procedure consists for instance of defining incision lines, plan drilling trajectories, plan trajectories to reach a target (e.g., tumor), planning implant shape based on the shape of the anatomy, etc.

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However, to localize a tumor that was detected on medical images on the real surgical area, amidst blood and other organs, proves to be challenging and requires experience and adequate knowledge. This is where surgical navigation and image-guided interventions field comes in. This field focuses on the techniques (software/hardware) that would allow the mapping of the medical images and the surgical planning onto the surgical site, in other terms alignment/registration. This means that a surgeon will be capable of knowing where his surgical instruments and planning are with respect to the patient anatomy (patient space/patient's coordinate system). The devices enabling such features are called navigation systems. Conventionally, navigation systems consist of a tracking system, and a screen that allows for the visualization of medical data and the location of instruments in those images (see Fig. 2).

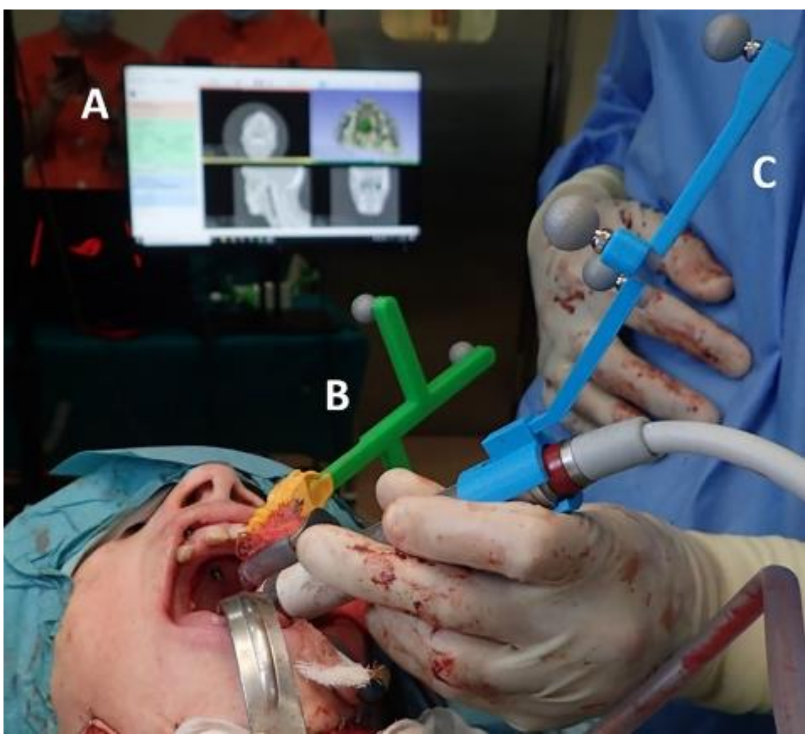

Figure 2. Example of a navigation system for surgery [5].

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2. Multimodal markers for augmented surgical navigation [6]

Image-to-patient alignment is a crucial procedure in surgical navigation. It registers/aligns patient data accurately on the target anatomy in terms of position and rotation. It enables surgeons to locate their surgical planning, and to determine where their instruments are located with respect to the patient's anatomy. Using conventional navigation systems, surgeons need to provide two corresponding sets of points of anatomical landmarks on the patient, by using a tracked pointer for example, and on the patient data's coordinate system (e.g., CT or MRI). Subsequently, the transformation matrix from the patient's coordinate system to the real world is computed.

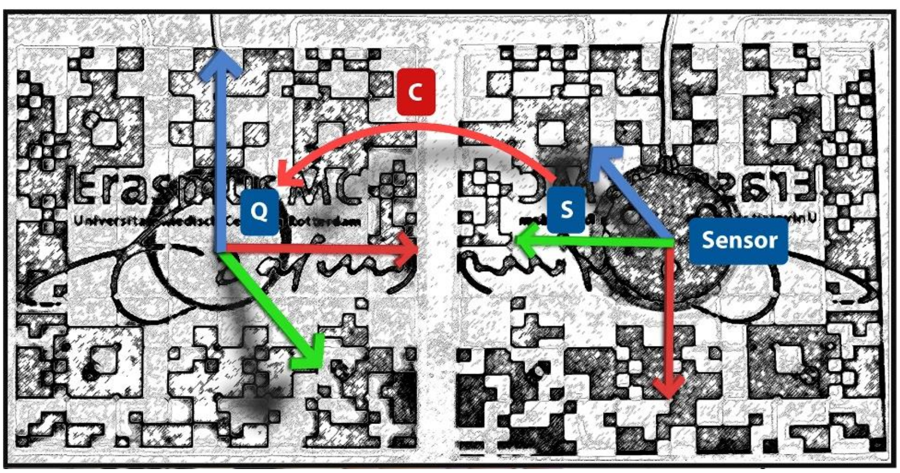

Figure 3. Multimodal marker, Q: 2D pattern coordinate system, S: Electromagnetic sensor's coordinate system, C: The calibration matrix between S and Q.

In an augmented reality (AR) context, image-to-patient alignment is the process that allows to tell the AR device, for e.g., head-mounted displays (HMD) such as the Microsoft HoloLens 2, where the patient is located in 3D space with respect to the user. A common approach in the literature to align a 3D patient model with the patient, is to attach rigidly a 2D pattern (e.g., QR code) on the patient's anatomy (e.g., teeth) based on the CT image at a known location, and estimate its pose [7]. However, this approach requires the printing of 2D patterns for every patient. Therefore, extending preparation times (e.g., sterilization), which is not suitable for trauma cases. Another approach is to attach markers such as reflective spheres (see Fig. 2 B) on the HMD, this way, the conventional navigation system is able to locate the patient, the instruments and the device in the same coordinate system. This approach requires the calibration of every new HMD with the external tracking system, and oblige surgeons to stay within a specific field of view of the tracking system [8].

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We proposed a solution using a multimodal marker, which is made of a 2D pattern on which a tracked marker is attached. Figure 3 shows an example of a multimodal marker where an electromagnetic sensor is attached to a 2D pattern. The latter is tracked by the HMD and the sensor is tracked by an electromagnetic tracking system (EMTS). A calibration matrix (C) is computed between the sensor and the 2D pattern. This transformation allows to link the coordinate systems of the HMD and the tracking system.

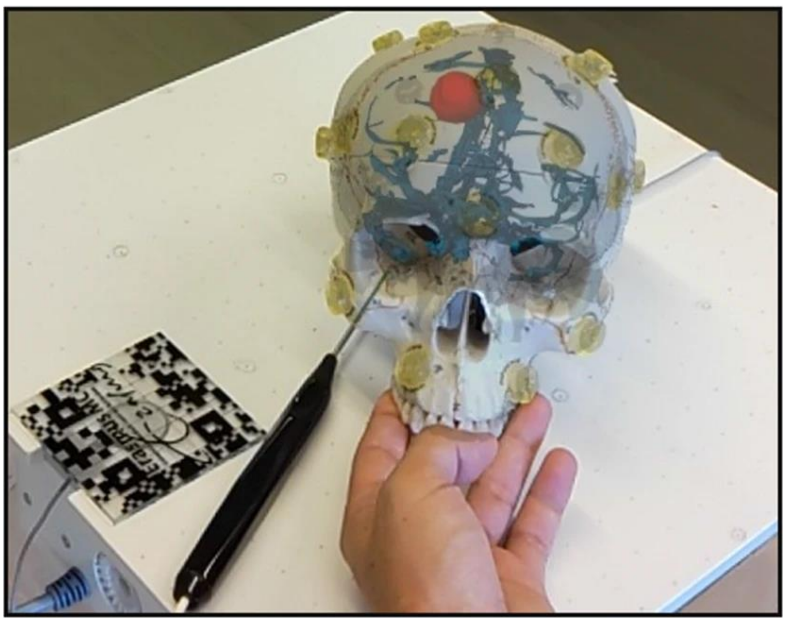

Figure 4. An AR view of a projected skull using the HoloLens 2 and a multimodal marker.

This developed approach allowed the projection of the 3D model of the skull (See Fig. 4) with a mean accuracy of 2.7 mm which is an acceptable accuracy for some surgical interventions for instance in the case if craniosynostosis.

More investigations on marker size, number of markers, depth perception effect on surgical performance.

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3. Virtual extensions improve perception-based instrument alignment using optical see-through devices [9]

Instrument alignment is a common task performed by surgeons when drilling, or inserting a needle to reach a target anatomy. Surgeons would follow a specific preplanned trajectory and align their surgical instrument with it. The need for accurate placement of an instrument in surgical tasks is crucial for the safety of the patient. In augmented reality (AR), it is difficult to perceive the exact location (position and orientation) of a preplanned trajectory visualized as a cylinder. It has been reported in the literature that users performing matching and reaching tasks, find it difficult to estimate depth, especially when using optical see-through (OST) devices (e.g., Microsoft HoloLens). In fact, users tend to underestimate the depth of the projected virtual models i.e., the distance from the user to virtual content [10].
In this study, we evaluate three visualization paradigms on an instrument alignment task in AR when using the OST device HoloLens 2. In the first visualization, only the preplanned trajectory is visualized (Fig. 5 left). In the second visualization, both the preplanned trajectory and a realistic visualization of the instrument are projected (Fig. 5 middle). In the third visualization, we introduce the paradigm of virtual extensions where we attach virtual 3D objects (disks) to both the preplanned trajectory and the instrument (Fig. 5 right).

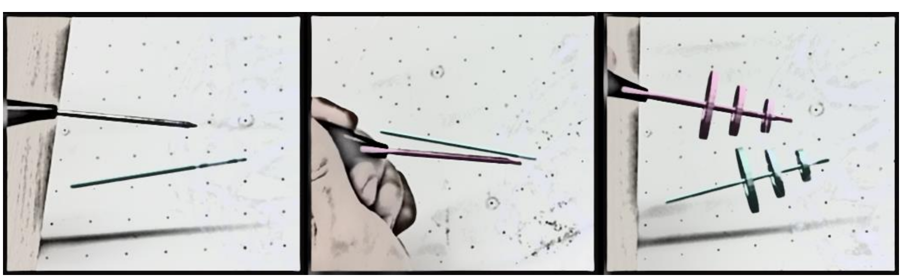

Figure 5. Instrument alignment with a pre-planned trajectory (cyan) under various conditions. Left: No instrument visualization.

18 volunteers participated in this study, where they were asked to perform the alignment task and the tip-to-tip distance and angle between the instrument and the preplanned trajectory was computed. Users performed the best under the virtual extensions paradigm with 2 mm distance and 1.8° compared to the realistic visualization and no visualization of the instrument with 3.8 mm and 2.4°, and 10 mm and 4.4° respectively.

Virtual extensions improved the overall accuracy of all users, reduced their frustration levels and increased their confidence in the performed task. All of these results were reflected on the preference of users where half of the participants (9) appreciated the use of the virtual extensions. Therefore, this study showed the importance of surgical instruments visualization in AR, and proposed a new paradigm which proved to be useful for an accurate alignment.

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4. Towards AR-guided craniosynostosis surgery [11]

Craniosynostosis is a congenital disease in which the skull bones of a baby are joint prematurely. This results in a deformed growth of the skull causing intracranial pressure. This can lead to several health complications such as blindness, seizures or brain damage [12]. The most prevalent type of craniosynostosis is sagittal synostosis which occurs in 40–60% of the single suture synostosis cases and which results in an elongated shape of the head (see Fig. 6).

Generally, a surgical procedure is required to correct for this abnormal growth. It is done by performing a complete remodeling of the skull, or by conducting minimally invasive procedures such as spring-assisted craniectomy which is known to reduce blood loss during the intervention [13].
In spring-assisted craniectomy, surgeons try to feel anatomical sutures with their hands (coronal, lambdoid and sagittal), and based on that, they draw where incision lines should be. These cranial sutures are sometimes hard to feel because of the presence of hair and skin, resulting in a shift of 10-20mm of the preplanned incision lines.
Augmented reality (AR) could be an alternative to this free-hand approach, by providing a visualization of the cranial sutures and/or the incision lines.

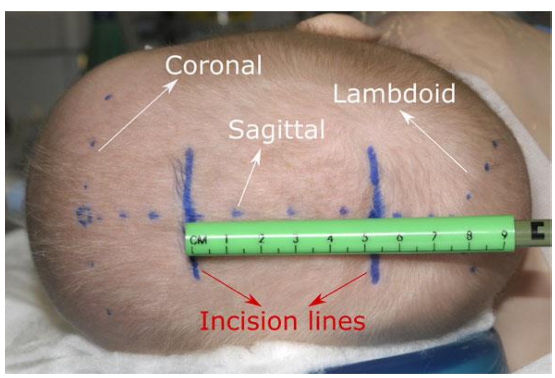

Figure 6. Surgery planning in minimally invasive spring-assisted craniectomy, showing the coronal, lambdoid and sagittal sutures marked by the surgeon, as well as the planned incisions [13]

We investigated the use of AR of this intervention by conducting a user study where 12 volunteers with various backgrounds participated. The AR system previously developed [13], was used to project and visualize CT annotated cranial sutures on a 3D printed skull (See Fig. 7). The participants were asked to delineate the location of these sutures with a pen, and we computed its accuracy by using an optical tracking system (NDI Vega). The distance between the CT annotated sutures and the drawn sutures resulted in an average accuracy of ~ 2 mm for the coronal suture and 3.3 mm for lambdoid suture.

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This study showed an acceptable accuracy using AR compared to the free-hand approach. Therefore, there is a potential for AR to enable surgical navigation for craniosynostosis surgery.

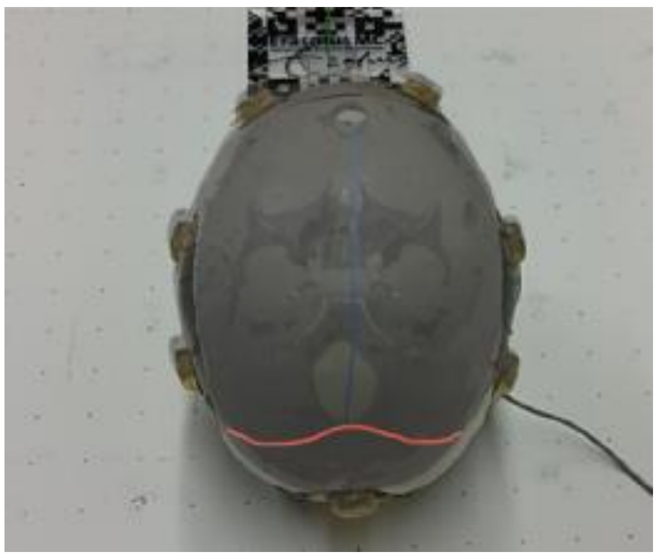

Figure 7. Cranial sutures visualized through the HoloLens 2 for the users to delineate.

5. 3D vs. 2D AR visualization for surgical navigation [14]

Hydrocephalus is a condition where the cerebrospinal fluid (CSF) is accumulated inside the brain ventricles which enlarges them (see Fig. 8). This can cause brain intracranial pressure leading to several health complications [15]. An external ventricular drain (EVD) procedure is generally performed as a temporary solution to release the CSF from the ventricles. This intervention consists of inserting a drain inside the right ventricle, to extract any excess of the CSF. The insertion is generally performed blindly by relying on head measurements (see Fig. 8). However, in a previous study, 23% misplacement occurred in which 40% required reinsertion of the catheter [16].

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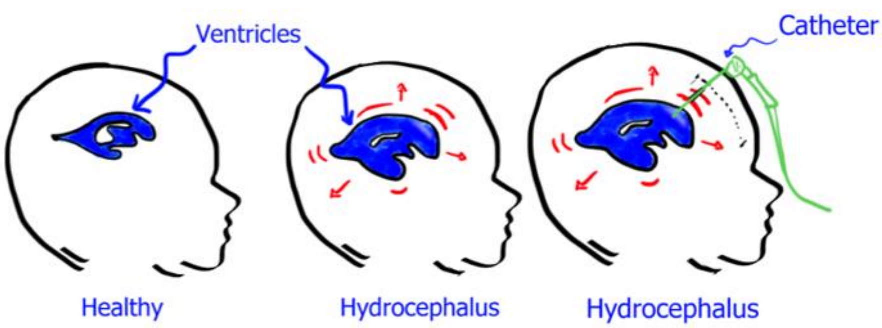

Figure 8. Hydrocephalus and catheter placement in EVD.

Augmented reality (AR) could project ventricles on top of the patient to assist the surgeon.
Several visualization approaches in AR have been proposed in the literature. This study, investigated the adequate visualization for EVD surgical navigation using 3D vs. 2D AR approaches (see Fig. 9).

32 volunteers participated in this study. Their task was to insert a tracked needle inside a phantom skull which contained gelatin to simulate the properties of soft tissue. The needle had to be placed exactly matching the preplanned trajectory shown inside the skull. The results from this study showed a higher performance using 3D approaches in terms of accuracy (~2 mm, ~1.5°), and in terms of user preference. These results provide more evidence and incentive for surgeons to use a stereoscopic head-mounted display instead of a 2D screen for surgical navigation.

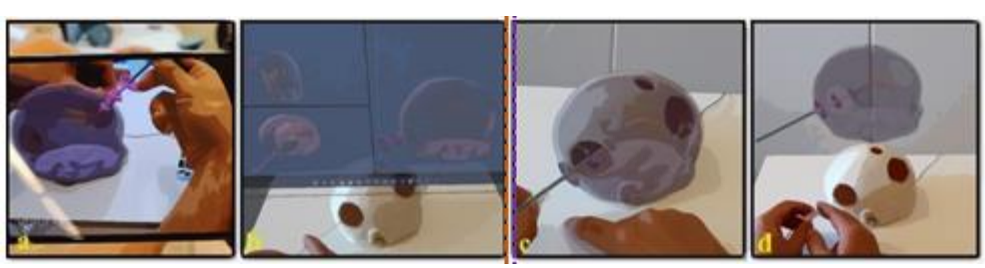

Figure 9. The AR visualization approaches compared in the study. In orange, 2D visualization approaches: smartphone, and a 2D navigation window visualized through the HoloLens. In purple, 3D visualization approaches through the HoloLens: fully aligned model on the phantom skull, and shifted model with rotations aligned with the phantom's rotations.

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Conclusion (AR & surgical navigation)

AR allows to combine data from medically acquired images as 3D reconstructed models. These models are projected on top of the patient by the AR device (e.g., head-mounted displays). It provides the surgeon with a see-through visualization of the underlying anatomy of the patient. The surgeon can include steps of the surgical procedure, including for example drilling and insertion trajectories, to reach the preplanned outcome. AR can become a mainstream navigation technology for currently non-navigated surgical interventions, and enable increased precision and improved surgical outcomes. AR for surgical navigation could mitigate under staffing in hospitals where experienced surgeons are lacking. Indeed, AR navigation could provide assistance to less experienced surgeons in performing similarly to experienced surgeons.

However, a few challenges are still open to be addressed, including accurate image-to-patient alignment, continuous tracking, depth perception in AR and clinical translation to the operating room (OR), which require more improvements on both current hardware and software solutions.

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