

An augmented reality guidance probe and method for image-guided surgical navigation

Ruby Shamir, Leo Joskowicz*
School of Eng. and Computer Science
The Hebrew Univ. of Jerusalem, Israel.

Yigal Shoshan
Dept. of Neurosurgery,
School of Medicine
Hadassah University
Hospital, Israel.

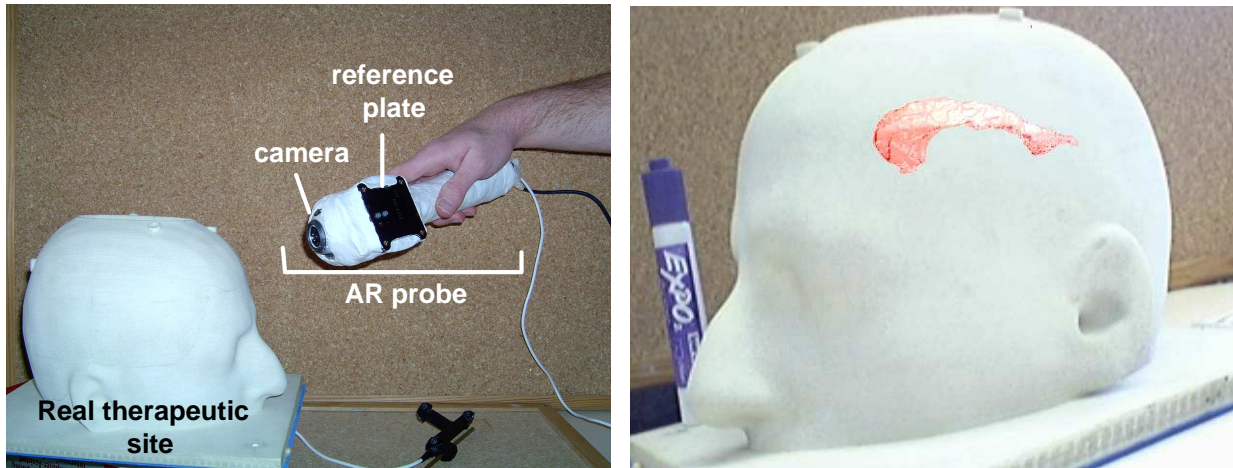


Figure 1: Left: Photograph of the AR (Augmented Reality) probe during the capture of video images of a phantom (the actual therapeutic site). Right: Video image of the phantom with preoperative data (in this case the left ventricle) superimposed on it in real time.

ABSTRACT

This paper presents a novel Augmented Reality (AR) probe and method for use with image-guided surgical navigation systems. Its purpose is to enhance existing systems by providing a video image of the therapeutic site augmented with relevant structures preoperatively defined by the user. The AR probe consists of a video camera and a tracked reference plate mounted on a lightweight ergonomic casing. It directly connects to the navigation tracking system, and can be hand-held or fixed. The method automatically updates the displayed augmented images to match the AR probe viewpoint without additional on-site calibration or registration. The advantages of the AR probe are its ease of use close to the clinical practice, its adaptability to changing viewpoints, and its low cost. Our in-vitro experiments show that the accuracy of targeting under AR probe guidance is 1.9 mm on average.

Keywords: navigation, augmented reality, image guided surgery

1 INTRODUCTION

Image-based computer-aided surgical navigation systems are routinely used in a variety of clinical procedures in neurosurgery, orthopaedics, ENT, and maxillofacial surgery, among others [1]. The systems track in real time instrumented tools and bony anatomy,

and display their position with respect to clinical images (CT/MRI) taken before or during the surgery (X-ray, ultrasound, live video) on a computer screen. The surgeon can then guide his/her surgical gestures based on the augmented images and on the clinical situation. The main advantages of image-based surgical navigation are its support of minimal invasiveness, the significant reduction or elimination of intraoperative imaging and radiation, the increase in accuracy, and the decrease in surgical outcome variability.

Three significant drawbacks of existing image-guided surgical navigation systems are the lack of integration between therapeutic site and the display, the sub-optimal viewpoint of the images shown in the display, and the limited hand/eye coordination. The four main causes of these drawbacks are: 1) the display consists of clinical images and graphical object overlays, with no view of the actual therapeutic site; 2) users have to constantly switch their gaze from the screen to the intraoperative situation and mentally match both; 3) the viewpoint of the computer-generated images is static and usually different from that of the surgeon, and; 4) changing the viewpoint requires the surgeon to ask for assistance or use a manual interface away from the surgical site. These problems become more evident with 2D images, such as intraoperative fluoroscopic X-ray and ultrasound. These drawbacks discourage potential new users, require good spatial correlation and hand/eye coordination skills, and result in a longer, steeper learning curve.

Augmented Reality (AR) has the potential to overcome these limitations by enhancing the actual view therapeutic site view with selected computer-generated objects overlaid in real time in their current position [2]. Previous work on medical AR can be classified into five categories (Table 1): 1) augmented medical imaging devices; 2) augmented optical devices; 3) augmented reality windows; 4) augmented reality displays, and; 5) head mounted dis-

*E-mails: rubke@cs.huji.ac.il, josko@cs.huji.ac.il, ys@md.huji.ac.il

| Augmented Reality approach | No OR registration | Varying viewpoint | 3D view | In-situ visualization | Close to clinical practice |
|--------------------------------------|--------------------|-------------------|---------|-------------------------|----------------------------|
| 1. Augmented medical imaging devices | + | - | - | depends on the approach | - |
| 2. Augmented optical devices | - | - | + | + | + |
| 3. AR monitors | - | - | + | - | - |
| 4. AR window systems | - | + | + | + | - |
| 5. Head-mounted displays | - | + | + | + | - |
| 6. AR probe – our method | + | + | + | - | + |

Table 1: Comparison between five current Augmented Reality approaches and our method. Table entries ‘+’ indicate an advantage, ‘-’ a disadvantage. The first column indicates whether an additional registration or calibration procedure in the operating room is needed. The second column indicates whether the system allows to change the AR viewpoint. The third column indicates whether the AR overlay is spatial. The fourth column indicates whether in-situ visualization of the therapeutic site is supported. The last column indicates whether the AR workflow is close to clinical practice.

plays.

- Augmented medical imaging devices** consist of a video camera or transparent screen mounted on an existing intraoperative imaging device, such as a C-arm fluoroscope, an ultrasound probe, or a CT scanner [3, 4, 5]. By design, the device images are aligned with either the video images or the actual situation, so the displayed viewpoint is always that of the imaging device. The advantage of this approach is that it is simple to use and that no additional calibration or registration is necessary. However, it cannot be used in procedures without intraoperative imaging such as CT/MRI-based navigation, the imaging viewpoint is determined by the imaging device, and the fused image is 2D, not spatial.
- Augmented optical devices** are created by adding relevant graphical information to actual video images from a microscope or an endoscope [6, 7]. The main advantages of this approach are that it allows in-situ visualization and that it is closest to the clinical practice, as users are already familiar with the equipment and the high-quality images. Its drawbacks are that its use is limited to treatments in which optical instruments are used, that it requires an additional procedure for calibration and registration, and that the field of view is determined by the instrument optics, and thus remains narrow.
- Augmented reality monitors** show a real-time video image of the area of interest augmented with informative graphical objects [9, 10]. Their advantage is that they are readily available, do not require additional sterilization, and leave the surgeons hands and head free. However, the visualization is not in-situ, the viewpoint is fixed, and additional calibration and registration are necessary in the operating room.
- Augmented reality window systems** project informative graphical objects on a semi-transparent mirror plate placed between the surgeon and the patient [8]. The display, patient, and surgeon head are tracked, so that the image projected on the mirror is automatically updated. The main advantages of this approach are in-situ visualization and intuitive and automatic viewpoint update. However, it requires on-site calibration and registration, and the window can obstruct the surgeon working area and the tracker line of sight.
- Head-mounted displays** (HMDs) enable in-situ visualization without a video camera, automatic viewpoint update, and free-hands operation [11, 12, 13, 14]. Optical HMDs project graphical objects onto two semi-transparent mirrors (one for each eye). The location of the projections is predetermined from the estimated object distance and scene intensity. Video HMD provide an immersive environment but block the line-of-sight between the surgeon and the surgical site, and can

constitute a safety hazard. Head Mounted Projective Displays (HMPD) use a retro-reflective screen onto which graphical objects are projected placed near the surgical environment. The advantages of HMDs are that they provide in-situ visualization, naturally varying viewpoints, and spatial images. However, they require additional registration and, despite their potential, have poor clinician acceptance and are thus seldom used.

A concept similar to the AR probe presented here is described in [15]. However, it has three significant drawbacks. First, the video camera and tracker are not integrated in an ergonomic frame, so their manipulation is somewhat difficult. Second, the method is specifically tailored to the BrainLab VectorVision system. Third, the one-time calibration procedure is less accurate, as it is visual and not contact-based. In addition, there is no description of how the AR images are created, and no accuracy or experimental results are reported.

2 SYSTEM OVERVIEW AND PROTOCOL

We have developed a novel AR probe and method for use with image-guided surgical navigation systems. Its purpose is to improve the surgeon hand/eye coordination by augmenting the capabilities of navigation systems, thus overcoming some of the limitations of existing AR solutions. The AR probe is an ergonomic casing with a small, lightweight video camera and an optically tracked reference plate (Fig. 1). It can be hand-held or fixed with a mechanical support. The method provides an augmented video image of the therapeutic site with relevant superimposed user-defined graphical overlays from changing viewpoints without the need of additional on-site calibration or registration.

The key idea is to establish a common reference frame between the AR probe, the preoperative images and plan, and the surgical site area with the navigation system tracking. First, the AR probe is pre-calibrated in the laboratory. Preoperatively, a surgical plan is elaborated. It includes relevant structures segmented from the CT/MRI scan, such as tumors and bone surfaces, surgical instruments, and other geometric data such as targets, tool trajectories, axes, and planes.

In the operating room, the AR probe is connected to the navigation system. During surgery, the preoperative data is registered to the intraoperative situation with the same method that is used for navigation. Since the video camera and the preoperative data have now the same coordinate system, the video image is augmented with the relevant preoperative data and shown on a display. The surgeon can adjust the viewpoint by simply moving the AR probe.

The surgical protocol/workflow is nearly identical to that of image-guided navigation systems based on optical tracking. The one-time calibration is done in the laboratory and is not part of the

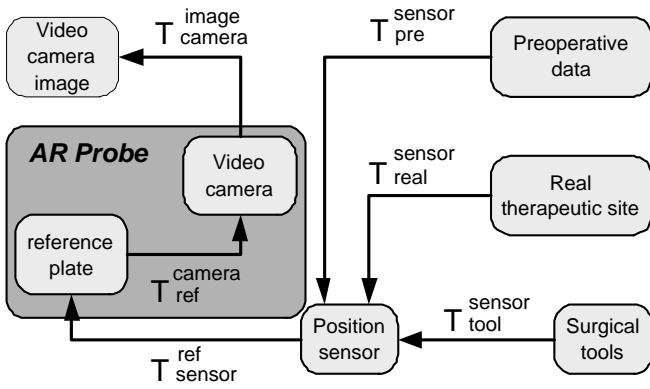


Figure 2: Registration chain

surgical protocol. During preoperative planning, the surgeon identifies the structures of interest and graphical overlays that will be displayed during the surgery. During surgery, the AR probe is connected to the tracking system as an additional tool, before the registration is performed. The augmented reality image is then automatically generated alongside the standard virtual reality image. Therefore, the AR probe works as another plug-and-play tracked tool.

We foresee a variety of uses for the AR probe as an augmentation tool for image-guided navigation systems. It can be useful to determine more accurately the location of the initial incision in open surgery, or the initial entry point in minimally invasive surgery and keyhole surgery, since it directly shows on the video image the position of the scalpel with respect to the relevant anatomical structures below. Once the incision has been made, the view adds realism to the navigation virtual reality image by providing an outside view of the surgical site augmented with inner structures.

3 THE REGISTRATION CHAIN

To properly superimpose preoperative graphical data on images of the actual therapeutic site, it is necessary to establish a correspondence between the two coordinate frames via a registration chain consisting of six transformations, as illustrated in Figure 2. We describe next how each transformation is obtained.

A one-time calibration process, described in the following section, determines the AR probe calibration internal video camera parameters T_{camera}^{image} and the video camera/tracking relationship, T_{ref}^{camera} . Since the video camera parameters do not change and the video camera and the reference plate are fixed to a rigid casing, the transformations do not change and thus only need to be computed once.

The transformations that determine the location of the surgical tool, the AR probe reference plate, and the actual therapeutic site, T_{tool}^{sensor} , T_{real}^{sensor} , and T_{sensor}^{ref} are directly provided by the position sensor itself. The remaining transformation T_{pre}^{sensor} , relating the preoperative data to the position sensor coordinate frame, is obtained from the same registration procedure that is routinely used in image-guided navigation systems. The registration can be fiducial-based, contact-based, surface-based, or image-based (fluoroscopic X-ray or ultrasound).

Based on these six transformations, the preoperative and surgical tool data can be properly superimposed on the video images as follows. For a point x in the graphical preoperative data, its projection on the video image plane, x^p is computed as follows:

$$x^p = T_{camera}^{image} T_{ref}^{camera} T_{sensor}^{ref} T_{pre}^{sensor} x$$

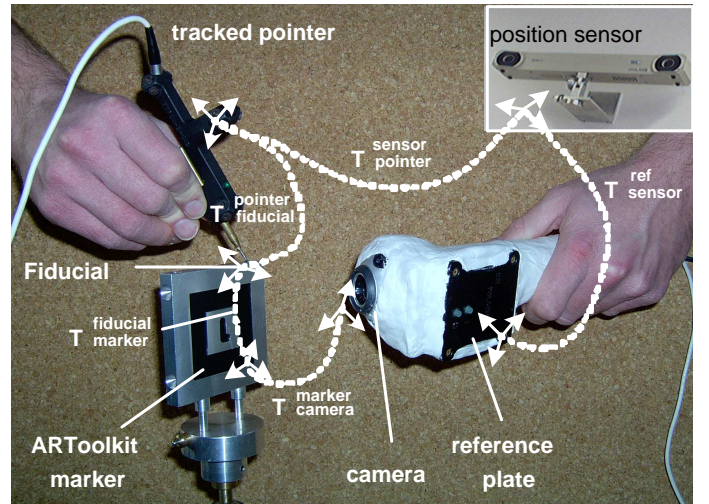


Figure 3: Photograph of the AR probe (right) and calibration jig (left) in the calibration setup. The AR probe is calibrated with an optical tracking system (top right insert).

Similarly, for a point x in the surgical tool model, its projection on the video image plane, x^p is computed as follows:

$$x^p = T_{camera}^{image} T_{ref}^{camera} T_{sensor}^{ref} T_{tool}^{sensor} x$$

4 AR PROBE CALIBRATION

The goal of the one-time AR probe calibration is to obtain the fixed transformation from the tracked reference plate coordinate system to the video camera image coordinate system. It is performed in two steps: intrinsic camera calibration and tracked reference plate to video camera calibration. The intrinsic camera calibration is performed with the Augmented Reality Toolkit (ARToolKit) [17].

The camera to tracked reference plate calibration is performed with the tracking system, a tracked pointer, and a custom-designed calibration jig (Fig. 3). The jig is a $75 \times 75 \times 10 \text{mm}^3$ aluminum plate with six cone-shaped fiducials machined on its sides for contact-based registration. It has an ARToolKit marker imprinted on one of its faces. The marker consists of an outer $50 \times 50 \text{mm}^2$ and inner $25 \times 25 \text{mm}^2$ black frame with the letter "L" engraved on it. It is used to determine the location of the jig with respect to the video camera.

To obtain the transformation, we first place the calibration jig close (15-25mm distance) and in front of the AR probe. From a video image of the calibration jig, we determine with the ARToolKit software the location of the ARToolKit marker, T_{camera}^{marker} . Since the jig was precisely manufactured according to our design, the transformation between the marker and a jig fiducial, $T_{marker}^{fiducial}$, is known in advance.

Next, we touch the jig fiducial with a tracked pointer. Since the tool was calibrated previously, the transformation $T_{fiducial}^{pointer}$ is known. Since the tool and the reference plate locations are tracked by the position sensor, their transformations with respect to it, $T_{pointer}^{sensor}$ and T_{sensor}^{ref} are known. The relation between the coordinates of a point x_i^{ref} in the reference plate coordinate system and its location on the camera coordinate system, x_i^{camera} is given by:

$$x_i^{ref} = T_{sensor}^{ref} T_{pointer}^{sensor} T_{fiducial}^{pointer} T_{marker}^{fiducial} T_{camera}^{marker} x_i^{camera}$$

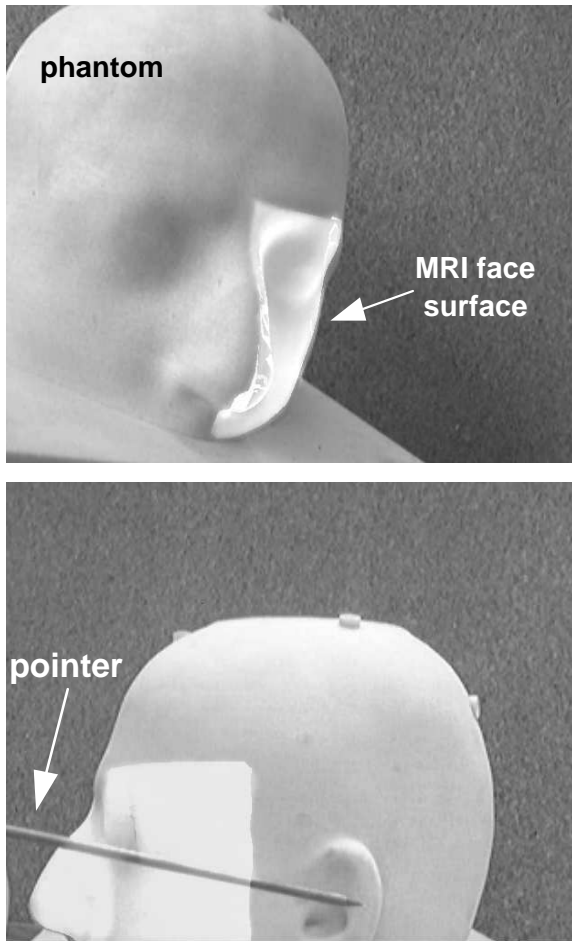


Figure 4: AR images from two viewpoints showing a real phantom with the virtual face surface from its MRI scan. The top image shows a real pointer near the phantom and the virtual surface to illustrate our treatment of transparency.

Then, we compute the transformation from the tracked reference plate coordinate system to the video camera image coordinate system using Horn’s closed form rigid registration solution [16] on the pairs $\{x_i^{ref}, x_i^{camera}\}_{i=1}^N$.

5 THE AR MODULE

The AR module inputs the preoperative plan, the AR probe and surgical tools locations, and the video camera images of the surgical site. It outputs video images with the graphical objects aligned and superimposed on it (Fig. 4).

The AR module is implemented with the Visualization Tool Kit (VTK) [18], the ARToolKit [17], and custom software. VTK is used to robustly process complex geometric objects. ARToolKit is used to capture video images and to transform the coordinate system of the geometric objects to the camera coordinate system. The custom software projects the graphical objects onto the video images. The user-defined opacity projection is computed so that the graphical objects do not occlude the view of the surgical site, thus providing better safety, better sense of depth, and more realistic, multi-object visualization.

6 EXPERIMENTAL RESULTS

We have implemented a complete hardware and software prototype of the system and designed three experiments to test its accuracy. The first two experiments quantify the accuracy of the AR probe calibration and of the contact-based registration on a phantom with an optical tracking system. The third experiment quantifies the overall targeting accuracy of the tracking system under AR probe guidance. In all experiments, we used the Polaris (Northern Digital, Toronto, Canada) optical tracking system and reference plate with RMS accuracy of 0.3mm, a Traxtal (Toronto, Canada) tracked pointer, an off-the-shelf QuickCam Pro 4000 webcam (Logitech), and a 2.4 Ghz Pentium 4 PC.

In the first experiment, the AR probe was first calibrated following the method described in Section 4. To quantify the accuracy of the calibration, the calibration jig was placed in different locations. For each location, we touched with the tracked pointer one of the fiducials on the jig, and recorded its location in the reference plate coordinates. We also determined from the video image the location of the ARToolKit marker and computed the location of the same fiducial in the camera coordinate system. We obtained the fiducial location on the reference plate coordinate system by applying the calibration transformation to the fiducial location in the camera coordinate system. The distance between the two computed fiducial locations is the calibration error. We repeated the procedure 10 times at 20 jig locations, for a total of 200 samples. The average distance error is 0.45 mm with standard deviation of 0.19 mm.

For the second experiment, we used a precise stereolithographic phantom replica of the outer head surface of a volunteer from an MRI scan (Fig. 5a) [19]. The phantom includes fiducials and targets at known locations. We performed contact-based registration between the phantom and its model by touching four fiducials on the phantom with the tracked pointer. Next, we touched several fiducial targets on the phantom, recorded their locations, and compared them to the predicted locations on the phantom model after registration. We repeated the procedure 15 times with six fiducials, for a total of 90 samples. The average registration error was 0.62 mm with standard deviation of 0.18 mm.

In the third experiment, we quantified the targeting accuracy of the tracking system under AR probe guidance. First, the AR probe was calibrated, and the phantom was registered to its model as described above. Next, we defined new targets on the phantom model as 0.3mm virtual spheres (Fig. 5b). Then, for each target, we placed the AR probe at an appropriate viewpoint (20-35mm distance from the phantom) so that the target is clearly seen on the AR phantom image. Based on the AR images (Fig. 5c), we guided the tracked pointer so that its tip coincides with the virtual target (Fig. 5d). We recorded the tip position and compared it to the location of the target in the model (both in the position sensor coordinate system). We repeated this procedure 12 times for four targets in different locations of the head surface, for a total of 48 samples. The average error was 1.9mm with standard deviation of 0.45mm. The average refresh rate is 8.5 frames/second, which is adequate for the applications considered.

From the experiments, we conclude that AR probe calibration accuracy of 0.45mm (std=0.19mm) is very good, given that the tracker accuracy is 0.3mm (std=0.15mm). The accuracy of the contact-based registration (avg=0.62mm, std=0.18 mm) is similar to that reported in the literature. It is mostly determined by the accuracy of the tracked pointer tip, which is about 0.4mm. The accuracy of targeting under AR probe guidance is similar to the results reported in [10]. This includes both the system and user errors. The system error consists of the AR probe calibration error, the contact-based registration error, and the optical tracking error. The user error stems from the user targeting performed based on the AR images.

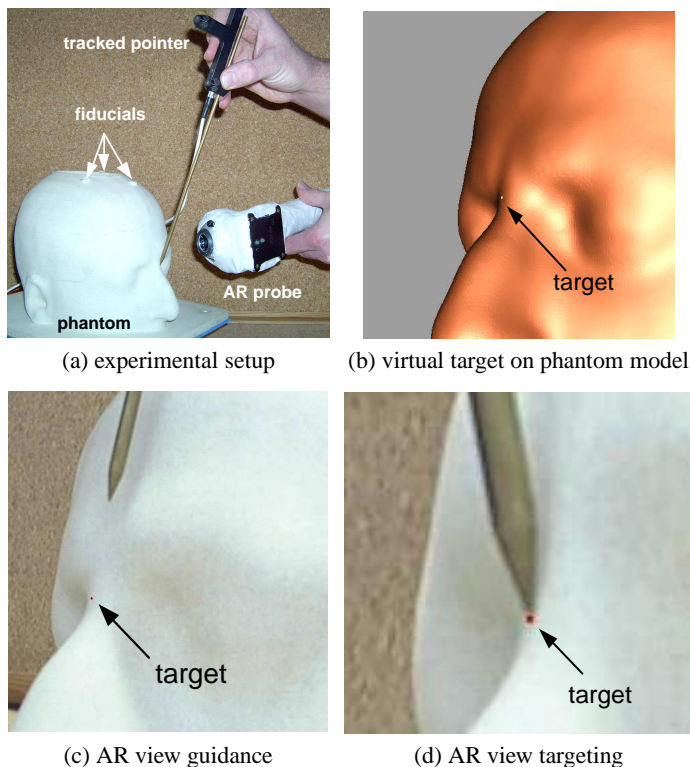


Figure 5: Experimental setup, and virtual and AR views.

7 CONCLUSION AND FUTURE WORK

This paper presents a novel AR probe and method for use with image-guided surgical navigation systems. Its purpose is to enhance the capabilities of these systems by providing a video image of the therapeutic site augmented with relevant structures defined preoperatively by the user. The AR probe consists of a video camera and an optically tracked reference plate mounted on a lightweight ergonomic casing which can be hand-held or fixed. It is directly connected to the optical tracking system and automatically updates the displayed image to match the AR probe viewpoint. Its advantages are that it is simple to use, as no additional on-site calibration or registration is required, that it adapts to varying viewpoints, that it is close to the current clinical practice, and that it is low cost. Our in-vitro experiments show that the accuracy of targeting under AR probe guidance is on average 1.9 mm (std=0.45mm).

These advantages and accuracy suggest that this navigation addition can be useful in a wide variety of treatments. Unlike other augmented optical devices, such as a microscope or an endoscope, the AR probe provides an external view of the surgical site. This view adds realism to the navigation virtual reality image by providing an outside view of the surgical site augmented with inner structures. It can be useful to determine more accurately the location of incisions in open surgery, or the entry point in minimally invasive surgery and keyhole surgery.

Our next step is to conduct targeting experiments with novice and experienced surgeons to evaluate the practical added value of the AR probe. We plan to compare the accuracy and required time for a variety of navigated targeting tasks with and without the AR probe. To estimate its possible acceptance, we plan to obtain feedback on its spatial localization and hand/eye coordination capabilities. We also plan to adapt the probe for magnetic tracking and investigate the use of a high-quality video camera with zooming capabilities.

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