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MARIN: an Open Source Mobile Augmented Reality Interactive Neuronavigation System

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Abstract Purpose: Neuronavigation systems making use of augmented reality (AR) have been the focus of much research in the last couple of decades. In recent years, there has been considerable interest in using mobile devices for AR in the operating room (OR). We propose a complete system that performs real-time AR video augmentation on a mobile device in the context of image-guided neurosurgery.
Methods: MARIN (Mobile Augmented Reality Interactive Neuronavigation) improves upon the state-of-the-art in terms of performance, allowing real-time augmentation, and interactivity by allowing users to interact with the displayed data. The system was tested in a user study with 17 subjects for qualitative and quantitative evaluation in the context of target localization and brought into the OR for preliminary feasibility tests, where qualitative feedback from surgeons was obtained.
Results: The results of the user study showed that MARIN performs significantly better both in terms of time ($p < 0.0004$) and accuracy ($p < 0.04$) for the task of target localization in comparison to a traditional image-guided neurosurgery (IGNS) navigation system. Further, MARIN AR visualization was found to be more intuitive and allowed users to estimate target depth more easily.
Conclusion: MARIN improves upon previously proposed mobile AR neuronavigation systems with its real-time performance, higher accuracy, full integration in the normal workflow and greater interactivity and customizability of the displayed information. The improvement in efficiency and usability over previous systems will facilitate bringing AR into the OR.

Keywords Image Guided Intervention · Mobile · Augmented Reality · Neuronavigation · Interactive

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1 Introduction

Neuronavigation has historically been at the forefront of surgical technological development due to the unique constraints of neurosurgery, which on the one hand require maximum resection of the disease and on the other hand requires minimum damage to healthy or eloquent tissue [7]. Owing to this, accuracy is of paramount importance, and therefore neurosurgery has often inspired new innovations that attempt to refine guidance accuracy, allow for distinguishing between healthy and diseased tissue, and improve the intuitiveness of guidance visualization, in order to improve surgical outcomes. A historical review of neuronavigation was presented by Galloway and Peters [8].

One solution proposed to facilitate neurosurgical guidance has been augmented reality (AR). The first use of AR for neurosurgical guidance dates back to the late 80s [16]. More recently, with the advent of smart mobile devices, new means of displaying intraoperative AR views, through the AR window paradigm have been explored (*e.g.,* [20,2]) for instance. The use of mobile devices for AR display in the clinical context has many advantages over other *in situ* AR setups. First, these devices offer an easy means to not only display information but also interact with it using the touchscreen. Thus, there is much more potential for interactivity than projector-based AR systems for instance. Second, these devices are small and wireless, which make them easy to move around and explore the anatomy from different perspectives, allowing for easier planning and teaching [11]. Third, it is much more versatile than head-mounted displays (HMDs), which can be bulky and disruptive. Indeed, current HMDs have been shown to be poorly suited for surgical tasks [1]. Additionally, contrary to HMDs, mobile devices can be draped in sterile bags, allowing for continuous use throughout a procedure. Mobile devices can be stowed away and brought back in a matter of seconds or clamped to the bed for hands-free continuous guidance. In this paper, we propose the MARIN (Mobile Augmented Reality Interactive Neuronavigation) system, which enables more intuitive and interactive visualization in image-guided neurosurgery (IGNS). The utility, usability, and performance of the developed system was evaluated in the lab and with feedback from surgeons.

2 Previous Work

A number of mobile AR systems have been proposed, implemented and/or tested in a clinical setting. Hou *et al.* [10] and Eftekhar *et al.* [5] both proposed phone apps that display the video feed of the camera overlaid with a previously selected slice of a preoperative CT or MRI. The system is set-up in the OR and the slice manually aligned with the patient intraoperatively, *i.e.,* the registration is done manually thus the accuracy relies on the operator. Owing to this the AR views are limited to be along a scan axes (*i.e.,* saggital, coronal or transverse), defined during preoperative planning. The systems from Deng *et al.* [2] and Watanabe *et al.* [20] consist of a tablet app showing presegmented structures overlaid on the live video feed. Contrary to previously mentioned systems, they make use of an external tracking system. This enables them to show the AR view from any angle around the patient, thus offering a significant improvement compared to previous work. At the same time these systems do not run in real-time, due to a large latency in

Fig. 1 Photos of the system, as was used in test study described in section 4. On the left: the iPad running MARIN mounted on an adjustable tripod, the phantom and the tracking system mounted an a larger immovable tripod at the back, behind the table. On the right: the iPad running MARIN and the tracked pointer.

image transfer. Watanabe *et al.*'s latency between tablet movement and updated AR information is about 400 ms. Deng *et al.* do not report latency, yet mention an alignment error caused by a certain degree of delay. This kind of latency, as shown by Sielhorst *et al.* [17], has a strong negative impact on task success. Even small discrepancies in time cause the impression of a larger discrepancy in space. Additionally, none of the current mobile AR systems take advantage of the touch screen of these devices to allow the user to interact with the displayed information.

In our previous work [13], we developed a mobile AR IGNS prototype that worked on an Android smartphone. Similar to the above mentioned works, this first prototype did not run in real-time and did not allow the user to interact with the system through the mobile device. This paper aims to address the limitations of our and previous systems. Namely, the main improvements over the state-of-the art is MARIN's real-time performance (80ms average latency), full integration into the surgical workflow, greater customizability and interactivity. In an effort to accelerate development in the field and enable faster improvements, with the publication of this paper we are making the software available under an open-source license. We strongly believe that development of better healthcare technologies will happen through sharing and collaboration of teams from around the world.

3 System Description

In the following section, the implementation details of the developed MARIN system are described.

3.1 Hardware

MARIN, being an open source project and in an effort to make it as widely available as possible, is compatible with a broad range of hardware. The required hardware components are a mobile device, a desktop computer, a tracking system and a wireless router. The mobile device can be either a phone or tablet, running iOS or Android. The desktop computer may run Linux, OS X or Windows, so long as it has networking capabilities and a graphics card. The router should support at least the 802.11n wireless standard and the WPA or WPA2 security protocol. The choice to include a dedicated router in our setup was made in order to ensure low latency, while still respecting security concerns. The router offers a private network on which only devices from our system are connected ensuring security. Thus additional encryption, which would unnecessarily increase transfer latency, is not required. Further, this allows MARIN to not rely on any external network. However, if the system was to be used in an environment with access to a trusted network, this component could be omitted. Finally the tracking system can be any of those supported by PLUS [12], which includes systems with very diverse specifications, including some small and cheap ones, as well as bigger and more precise ones, making it applicable in a broad range of applications, environments and setups. These hardware choices ensure the widest availability and portability, allowing MARIN to be used in as many different settings as possible.

For our tests, the following hardware was used: a FusionTrack500 Tracking System (Atracsys LLC, Puidoux, Switzerland), an iPad model A1893 running iOS 12.4.1 (Apple Inc., Cupertino, USA), an Archer A10 router (TP-Link USA Corporation, Brea, USA), a desktop computer with a i7-6850K 3.6GHz CPU, NVIDIA GTX 1080 GPU, Gigabyte GC-WB867D-I wireless PCI card, running Ubuntu 16.04 LTS. The iPad was outfitted with a passive tracker that is attached to a 3D printed attachment bracket (Figure 1).

3.2 Software

MARIN makes use of the IBIS Neuronav open-source platform for IGNS [4], which comes with plug-ins to integrate tracking, do patient-to-image registration, camera calibration, and the capability to do augmented reality visualization (by capturing a live video stream from a microscope or video camera and merging it with pre-operative images on the monitor of the system itself). In our work, we extended the IBIS Neuronav system to allow for augmenting an image on the screen of a mobile device that captures the surgical field of view. A custom built plugin (OpenIGTLinkSender) was contributed to the source code. The plugin enables images to be sent from the desktop computer running IBIS to MARIN, allowing for *in situ* AR visualization, through the AR window paradigm (not previously possible with IBIS). It should be noted that our system's usage isn't limited to interaction to IBIS. Our mobile application could work in conjunction with other systems offering similar functionalities, for example SlicerIGT [19]. This is due to the fact that MARIN uses OpenIGTLink [18], an open protocol and library for message transfer between devices, specifically made for the context of IGS. It thus enables any system that supports OpenIGTLink to communicate with MARIN. Choices about software used in the system were made with the

Fig. 2 Block diagram representing interactions between system components and data flow.

same goal in mind as for hardware support. We aimed at making the system as customizable and portable as possible. All libraries are open-source (PLUS [12], OpenIGTLink, OpenIGTLinkIO, libyuv and OpenH264), and can run on all common operating systems and hardware. The H264 codec used for image compression is also widely supported and has hardware acceleration on modern mobile devices, enabling shorter latency to be reached. MARIN's source code can be found at https://github.com/AppliedPerceptionLab/MARIN.

To make use of IBIS' existing functionality, the costly computations are handled on the desktop computer. In order to create the AR view, the mobile device camera is first calibrated. Calibration (intrinsic and extrinsic) is done using a modification of Zhang's camera calibration method[21], followed by a second optimization procedure to find the transform from the tracker to optical center of the camera (details are given in [4]). This calibration step takes about 10 to 15 minutes to perform. In our surgical workflow, calibration is done in the laboratory prior to bringing the system into the OR. Thus it does not add time to the procedure itself and does not require involvement from either the surgeon or OR staff. It does however need to be performed before every operation. Tracking information is sent from the tracker to IBIS through a PLUS server. The relevant transformations are computed in IBIS and renderings of the virtual objects made, from the camera's view point. Using the newly developed plugin the rendered virtual objects are compressed with the OpenH264 library and sent using OpenIGTLink through a UDP socket over the local area network to the tablet on which the virtual data is blended with the live video feed using OpenGL ES 3.0 and GLSL. Modifications were made to the OpenIGTLinkIO library to support transport over UDP sockets. The use of the UDP transport protocol, as well as video compression allows for shorter transfer latency. A block diagram of system components, their interactions and data flow is shown in Figure 2. In addition to image transfer from the desktop to the mobile device, other communication channels are opened between the two devices to send images from the device to the desktop and commands and status updates. These communication channels enable interactivity and more possible use cases. Since the camera view can also be sent from the mobile device to the desktop, it is possible to show the same AR view on the desktop, as well as on the mobile device, at the same time. This could be used for training and teaching as residents and other staff can see the same AR view as the surgeon, on the desktop screen. Channels for status and command transmission are also used to enable interaction with the AR view and see real-time information from tracking.

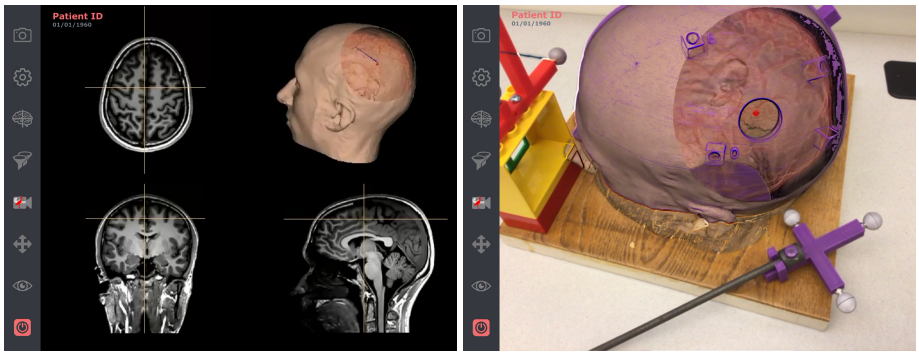

Fig. 3 On the left: screenshot of the system when used in standard IGNS mode; On the right: screenshot of the system when used in augmented reality mode.

3.3 MARIN Interface

MARIN offers an intuitive interface, letting the user easily customize what they want to be displayed on the AR view, in real-time, during the procedure. The view can be switched between camera-only, virtual only or AR. Users can pick only an area in which they have an AR view, potentially reducing clutter in cases where there is a lot of data needed by the surgeon. Different structures from the AR view can be switched on or off as desired, *e.g.,* skin, tumour, vessels, etc. Users can also choose from different navigation paradigms. They can switch between the standard IGNS view and AR view(see Figure 3) or show only the virtual view, showing only pre-segmented 3D models. MARIN also features a manual registration correction feature, which allows the user to realign the (virtual) patient pre-operative images with the real patient [14] using typical touchscreen gestures. All interactions with MARIN are done through simple gestures, making it intuitive and easy to operate, even if draped in a bag. Furthermore, MARIN can receive any type of image over the network through OpenIGTLink messages. This image could, for instance, be a static MR slice with highlighted structures, as was done by Hou *et al.* and Efthekar *et al.* MARIN can thus reproduce the behaviour of previously proposed systems, but also do much more. The interface was developed using the QT framework (version 5.9.8) which enables the application to be easily compiled for different devices.

4 User Study

To evaluate MARIN's performance and assess its usability and accuracy, we conducted a phantom study in the context of target localization. This task replicates some common surgical tasks such as electrode and port placement or ventriculostomy catheter insertion.

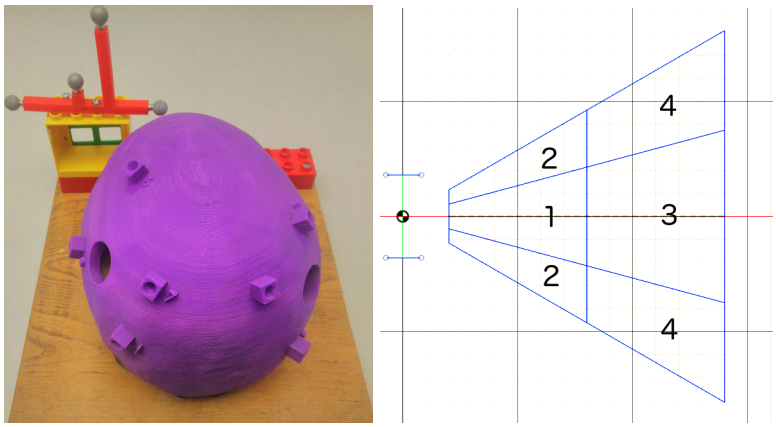

Fig. 4 Experimental phantom design. On the left: the phantom seen from the back, with craniotomies on either side, fiducials and the marker behind. On the right: a depiction of the four difficulty zones used in the experiment. The craniotomy is located between the two blue lines on the left and is centered on the dot. Then the four zones are: 1: 0-15°from normal, 1-4 cm deep; 2:15-30°, 1-4 cm; 3: 0-15°, 4-7 cm; 4: 15-30°, 4-7 cm.

4.1 Phantom Construction

A T1-weighted image of a healthy subject was segmented to extract the skin and cortical surfaces. The 3D model of the skin surface was used to represent a patient head and an 18 mm wide craniotomy on either side of the back of the head was added. Seven landmarks were added to the model for easy registration (inspired by those used by Drouin *et al.* [3]). The model was printed using PLA filament on a Replicator 5th Gen (MakerBot Industries, USA). The printed phantom was affixed to a rigid board to which a marker was attached (Figure 4).

A gelatin brain phantom was inserted into the cavity of the 3D printed head. Gelatin was chosen for its ease of use and because it is the most widely used material for brain phantom construction [15]. We used a 10% weight to weight ratio, heating the solution to 40°C, casting it into a hemispherical mold and letting it set for 12 hours at 4°C. We chose a concentration closer to human muscles than normal brain tissue in order to increase stiffness and make it more difficult for subjects to move the pointer sideways once insertion had begun. This was desired, to simulate the conditions of a surgical setting more closely; surgeons are required to plan an insertion path and follow it once they start inserting. Moving laterally would risk causing unnecessary damage to healthy tissue next to the insertion path.

4.2 Task Description

Participants were asked to reach target points within the phantom with a tracked pointer as precisely as possible. The task was performed under two different modes: traditional IGNS view (displayed on the tablet) and the AR view from MARIN. The IGNS navigation system served as a baseline to assess MARIN's performance.

Table 1 User study difficulty levels

	Level 1	Level 2	Level 3	Level 4
Target depth	$[1, 4]$ cm	$[1, 4]$ cm	$[4, 7]$ cm	$[4, 7]$ cm
Target angle with normal	$[0, 15]^\circ$	$[15, 30]^\circ$	$[0, 15]^\circ$	$[15, 30]^\circ$

Both systems were presented *in situ*, thus removing the potential confound of location of displayed information, since this has been previously shown to potentially affect task completion time [13].

When navigating using AR, subjects were shown the camera feed overlaid with a 3D model of the skin (opaque), the cortex (translucent), the target (red dot), the tip of the pointer (crosshair) and an extension to the pointer, extending 5cm downwards from its tip (blue line). This extension was meant as a guide to help subjects determine the best possible insertion angle, prior to inserting. When navigating using the traditional IGNS view, subjects were presented with a 3D model comprising of all the same parts, represented the same way, as in the AR view: skin, cortex, target, pointer tip and extension. Additionally, in this mode the standard cut planes of the MRI scan: coronal, transverse and saggital were displayed, see Figure 3. The target was also shown in the corresponding cut planes, as a red circled cross. When in IGNS mode, subjects could switch to see the 3D models in full screen, thus removing MR slices from the view. While they couldn't move the 3D model themselves, they could ask the experimenter to rotate or zoom in. This replicates how a surgeon would typically have to ask a technician to interact with the system, once they are sterile.

For each system, subjects completed four trials of varying difficulty, resulting in a total of eight tool insertions. For each trial the target to reach was randomly generated, but placed within a zone corresponding to the difficulty level. The generation zones were toroidal regions directly beneath the craniotomy location. A table summarizing the difficulty levels is shown in Table 1 and a view of the four regions is shown in Figure 4. This target generation method was chosen in order to have targets sampling the whole space so as to reduce location bias, while at the same time ensuring a broad range of depths and angles.

4.3 Experimental Procedure

Before commencing the study, a power analysis was performed using G*Power 3.1 [6] to assess the sample size needed. Given an expected intermediate effect, a sample size of 17 was used. All subjects were briefed on the study, the task and both systems. They were then shown the working of one of the system set-ups and given as much time as they wanted to practice using it and get comfortable with it. Once they felt ready, they completed the first four trials on that system. Next, they were trained on the second system and completed the four last trials on it. Both the order in which the systems were used, as well as the order in which the levels were performed on each system was randomized. To end each trial, subjects were instructed to tell the experimenter when they thought they had reached the

target, at which point the trial was ended by the experimenter. After completion of the study, participants were asked to fill in a questionnaire comprising of demographic, prior experience questions, questions on usability and further feedback. They were also asked to fill out the NASA TLX [9] for each systems. A copy of the questionnaire can be found at https://forms.gle/k18XJ4ZTmfRdTGXu6.

5 User Study Results

The study was run with 8 males and 9 females, aged between 18 and 67, with a median age of 26. Subjects were novices or intermediately experienced users: 35% had prior experience with using IGNS systems, 76% had prior experience with using augmented reality and 59% had experience with reading scans or looking at anatomical data.

System accuracy measurements were taken during the study. The average camera calibration reprojection error was 0.84 mm ranging between 0.6 mm and 1.02 mm. Registration RMS error was 1.32 mm. Pointer tip calibration was performed using fCal, from the PLUS toolkit [12]. The pointer tip calibration error was between 0.15 mm and 0.26 mm. The latency in augmentation display, which varies depending on the complexity of rendered structures and the resolution of the images sent, was estimated to be 50 ms. This estimate was calculated with images of typical complexity for navigation purposes (800×600 pixels, see right side of Figure 3). The latency was computed by synchronizing both devices to a common NTP server and comparing timestamps.

5.1 Quantitative Measurements

All data analysis was performed using MATLAB 2018b (The MathWorks, Inc., Natick, USA). First, to check for potential errors in the data, MATLAB's built-in function for outlier detection was run. This was run independently for all time measurements and all distance to target measurements for each condition. It was found that three individual trials were more than three standard deviations away from the mean for time taken and another trial was more than three standard deviations away from the mean for final distance to target. While we do not know specifically what happened during those trials, we posit that an event occurred during the experiment, resulting in this unusually large difference. These four individual trials were thus removed from further analysis, but only that relating to the affected variable.

To ensure validity of the acquired results, all time to completion measurements and final distance to target measurements were compared group-wise on the basis of difficulty level, trial number, subject ID and prior experience level. No subject was significantly different from any other; subject performance was within a similar range and thus comparable. Prior experience level didn't affect performance significantly. However, since our sample size wasn't evenly distributed relative to prior experience, it is possible that our sample size was not sufficient to show statistical significance. It was found that the time to completion of the hardest difficulty level was worse than all other trials. Specifically, a one way ANOVA revealed a significant effect ($F(3, 131)$, $p < 0.0006$)). This difficulty level was the

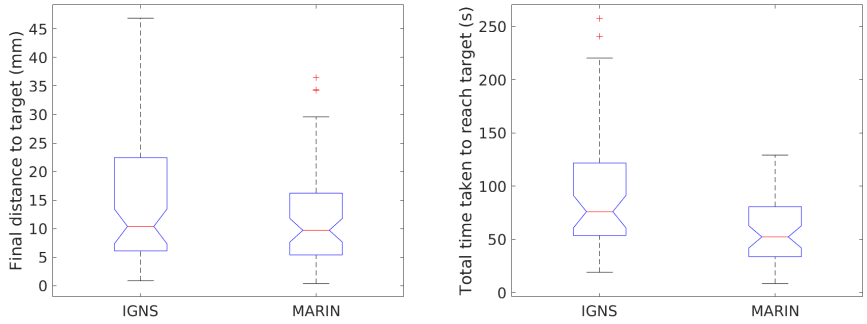

Fig. 5 On the left: Boxplots showing distribution of final distance to target, compared per system; On the right: Boxplots showing distribution of total time taken to reach target, compared per system.

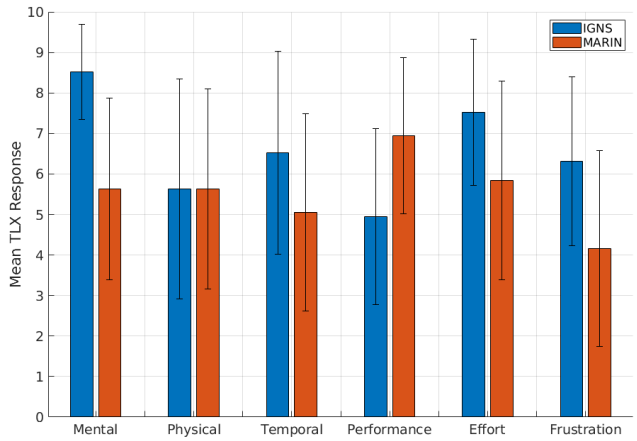

Fig. 6 All TLX scales, compared per system, where error bars correspond to standard deviation.

least realistic, being deep and at a strong angle with the craniotomy normal. For both of these reasons, it was removed from further analysis involving completion time.

Since there was some jitter in the pointer tip position, the final distance to target was computed as the minimum distance between tip position and target in the last two seconds of a trial. The three main outcomes of the validation procedure were time taken to reach target, final distance to target and the results from the NASA TLX. Boxplots of final distance to target for all trials and of total time taken to reach targets are shown in Figure 5. Comparative results of the TLX are shown in Figure 6.

For both measures, it was found that MARIN was statistically lower (better) than the standard IGNS guidance view. Specifically, a one-way repeated measures ANOVA showed that there was a significant effect of system type on the final

distance to target ($F(1, 136),\ p < 0.04$). For time taken to reach the target, a one-way repeated measures ANOVA showed that there was a significant effect of system type on the completion time ($F(1, 99),\ p < 0.0004$).

Subject's accuracy was found to be uncorrelated to either target depth or target angle from normal. Although, it was found that time to completion was weakly correlated with both target depth ($p = 0.026$) and angle with normal ($p = 0.045$).

5.2 Qualitative Feedback

In addition to filling out the NASA TLX for both systems, users were also asked which system they found most intuitive to use, which they felt most comfortable using and which they preferred. 100% of subjects found MARIN to be more intuitive to use. 82% felt more comfortable using MARIN, 12% felt more comfortable using the standard IGNS and 6% didn't have any preference. 94% preferred MARIN overall, while the remaining 6% didn't have any preference.

6 Expert Feedback

In addition to the user study, feedback was provided by senior neurosurgeons who tested the system both in the lab, as well as in the OR in clinical cases (Figure 7). Although the system is yet to be rigorously tested in the operating room, we have had continuous feedback from senior neurosurgeons during the development process. Although all found the system to have great potential, opinions differed as to how they would like to use it. Some said they would like it to be clamped to the bed, between them and the operating field and work from above it, using it throughout the operation. Others preferred to use it at the beginning of surgery, looking at the patient from different angles to give them a good sense of the anatomy to better plan their procedure. They would then give it to the nurse when operating to have both hands free, but said they might take it back later on during the procedure for more guidance. They also said they thought it might prove particularly useful for harder cases or those with more intricate anatomy.

7 Discussion

The main advantages of our system over previously published mobile AR systems are improved usability of the prototype, improved responsiveness, increased versatility, customizability, interactivity and wider possibility for adoption. MARIN can run on most hardware and OSes and is entirely open source. It allows users to manipulate data and interact with the AR view through intuitive gestures. The latency in image transfer with MARIN is roughly eight times lower than the lowest latency reported for previously proposed systems. As shown by Sielhorst *et al.* [17], the latency of previous systems severely hindered their usability. Our system on the other hand is in the range they recommend to increase performance of subjects using it. This gain in performance is attributable to how we transmit augmentation images to the mobile device. Our architecture, similar to that of Watanabe *et al.*'s [20] system, consists of a desktop, a mobile device, a tracking system and a

Fig. 7 Initial tests of MARIN in a clinical setting.

router. To alleviate the problem of delay, MARIN incorporates a modern video encoder, greatly reducing network load and allowing for shorter latency. Even though time for encoding and decoding is added, the gain in compression much more than compensates for it. The compression ratio depends on the complexity of images sent, but for a typical scene, compression was between 97% and 99%. Even for more complex scenes, this ratio wouldn't be much lower and should remain above 94%, thus still being relevant for all use cases. The remaining latency observed with MARIN is attributable to network transfer, as well as encoding and decoding of the images.

Other IGNS system performance metrics, (*i.e.,* camera calibration reprojection, registration RMS and pointer tip calibration error) place our system in the same range as previously proposed AR navigation setups. In our user study, MARIN outperformed the traditional navigation system, which served as our baseline for comparison, both in terms of time to reach the target, as well as accuracy with which users were able to reach the target. Unfortunately, a direct comparison with other mobile AR systems can't be made since no similar quantitative user accuracy assessment were done for any of them. Although, considering findings from Silehorst *et al.* [17], it can be hypothesized that thanks to MARIN's improved performance, users would perform better with it than with previously proposed ones.

Qualitative feedback unequivocally showed that MARIN outperforms standard IGNS views in terms of usability, comfort and ease of use. Subjects agreed that MARIN was more comfortable, easier to use and overall preferred it. The TLX results confirm these findings, as MARIN received better ratings on all scales.

An interesting point is how subjects made use of the two different systems. While navigation using the AR view was more or less constant across the sample, navigation using the standard IGNS system varied wildly. Some subjects looked mostly at the slices for guidance, finding the location of the target in all three planes and mentally mapping the location before making an insertion, while others looked almost only at the virtual view and tried to match the pointer extension with the target in that view. Thus individual differences in guidance system usage are present dependant on background and prior familiarity with certain tools,

views or concepts. We believe that this highlights one of the greatest strengths of MARIN: it lets the user decide, through an intuitive interface, what they want to see, enabling them to switch between AR, VR or standard IGNS views and also easily control through gestures what is displayed and how it is displayed in the AR view.

MARIN can integrate seamlessly into the typical surgical workflow. It can easily be draped in a sterile bag in the OR. It is less cumbersome than some other types of AR setups, such as HMDs, which can be bulky and disruptive, as well as not well-adapted for surgery [1]. A mobile device, on the other hand, can be stowed away in a matter of seconds and brought back if needed. Additionally the gestures used for interaction are familiar to anyone who has used a mobile device. Thus interaction is more natural and intuitive than that of other devices such as, for example, the HoloLens^{TM}. A mobile device can also be moved freely around the patient, allowing the view of the anatomy from a wide range of angles, thus providing a good sense of depth through the parallax effect. Further, this allows the surgeon to explain the approach and anatomy to residents and students in the operating room.

8 Conclusion

Mobile devices offer new untapped potential still to be harnessed in the surgical domain. MARIN is a step in this direction. With the release of MARIN as an open source project, we hope to pave the way for others wishing to build mobile AR setups for surgical guidance. MARIN can be used in conjunction with a broad range of hardware and software making it easy to integrate in an array of systems. The results presented here show that it has strong potential to make guidance more intuitive, easier and more comfortable to use. The evidence gathered here suggests that mobile AR may also enable shorter operation time and more accurate navigation. Although, to confirm this, quantitative measurements will need to be made with surgeons in a clinical setting. MARIN also enables other potential future research directions, including, integrating additional data sources provided by mobile devices (*e.g.,* accelerometer, gyroscope, etc.) to improve tracking accuracy or even explore the possibility of making an affordable and compact IGNS system by relying on mobile device trackers rather than an external tracking system. These are future avenues of research we are working on.

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Ethical approval, Informed Consent and Conflict of Interest

All procedures performed in studies involving human participants were in accordance with the ethical standards of the University Human Research Ethics Committee (Certification Number: 30007443). Informed consent was obtained from all participants included in the study. The authors declare that they have no conflict of interest.

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