Augmented Visual Instruction for Surgical Practice and Training

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Abstract

This paper presents two positions about the use of augmented reality (AR) in healthcare scenarios, informed by the authors' experience as an interdisciplinary team of academics and medical practicioners who have been researching, implementing, and validating an AR surgical telementoring system. First, AR has the potential to greatly improve the areas of surgical telementoring and of medical training on patient simulators. In austere environments, surgical telementoring that connects surgeons with remote experts can be enhanced with the use of AR annotations visualized directly in the surgeon's field of view. Patient simulators can gain additional value for medical training by overlaying the current and future steps of procedures as AR imagery onto a physical simulator. Second, AR annotations for telementoring and for simulator-based training can be delivered either by video see-through tablet displays or by AR head-mounted displays (HMDs). The paper discusses the two AR approaches by looking at accuracy, depth perception, visualization continuity, visualization latency, and user encumbrance. Specific advantages and disadvantages to each approach mean that the choice of one display method or another must be carefully tailored to the healthcare application in which it is being used.

Index Terms: Human-centered computing—Mixed / augmented reality; Applied computing—Health care information systems

1 Introduction

Augmented reality (AR) overlays contextual information directly onto a user's view of real-world objects and scenes, which removes the need for users to shift focus between multiple contexts. Without AR, a user would need to look away from an object to a separate display or information source, memorize the relevant information, and then mentally map the remembered information onto the scene, which can be slow and error-prone. AR provides a direct and implicit mapping of contextual information onto objects of interests, which reduces the cognitive load a user would experience from attempting to mentally remap information between different contexts [4].

Because of this reduction in focus shifting, AR is valuable to many aspects of society in which precise communication of contextual visual information is important. For this reason, AR holds great promise in the world of healthcare, which contains many use cases that require high levels of concentration and memorization. For example, trauma surgery requires the immediate availability of specialized surgical knowledge to provide necessary life-saving care. In another example, medical education using physical patient simulators becomes more efficient when guidance is integrated into the learner's view of the simulator.

We are a large interdisciplinary team of computer science and industrial engineering researchers, of practicing and teaching orthopaedic and general trauma surgeons, and of medical educators, who have been researching, implementing, and validating an AR surgical telementoring system. In this paper we present two positions that are based on our experience and findings from our multiyear project:

1. *AR has the potential to revolutionize surgical telementoring and medical training on patient simulators.* In particular, in austere environments, such as combat zones, and in rural and developing areas without specialized surgical care, AR can bridge geographic distances and provide guidance from a remote expert to improve patient outcomes. Medical training on patient simulators can be enhanced with AR interfaces that illustrate current and also future steps of a procedure directly in the context of the simulator.
2. *In healthcare, the AR interface can be implemented with a head-mounted display (HMD) worn by the healthcare provider, or with a video see-through tablet display interposed between the healthcare provider and the patient, each with important advantages and disadvantages.* In particular, HMDs have the advantages of depth perception and of lack of workspace encumbrance, but have the disadvantages of limited annotation accuracy and of head encumbrance. Video see-through displays offer increased accuracy at the cost of reduced depth perception and of workspace encumbrance. AR applications in healthcare must carefully consider the specific use case to choose the most suitable AR interface.

2 AR in Surgical Telementoring

Surgery has made considerable advances which led to surgeon specialization in narrow subfields, but the availability of subspecialty surgical expertise remains limited [3]. For example, in austere environments such as combat areas, rural locations, or developing countries, it may be logistically infeasible to evacuate or transport a patient needing urgent care to a more developed or urban environment to receive subspecialized surgical care [8]. Combat trauma injuries are particularly prone to this issue because such injuries often affect multiple organs and thus demand a wide array of specialized expertise. In such cases, a general surgeon could benefit from the partnership with remote experts brought in using telementoring [12]. Even outside the time-critical situation of a real operation, geographic distance similarly affects the ability of a surgeon to disseminate a novel surgical procedure they developed.

Augmented reality can help bridge the distance between surgical expertise and the patient where it is needed by enhancing the quality of the communication between the remote expert and the surgeon. Given a view of the operating field, the expert provides step-by-step instructions that are integrated into the surgeon's field of view. These augmented annotations give the trainee guidance without the need to shift focus away from the operating field, which reduces delays and potential errors.

Researchers have begun to realize AR's potential in surgical telementoring. Typically, a mentor and a surgeon are connected via a video stream which transmits imagery of the operating field from the surgery site to a remote mentor. In one system the surgeon views the operating field through a tablet-based video see-through display

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Figure 1: The surgeon follows an incision line drawn by the remote expert and delivered through the tablet interface.

suspended above the patient's body. The mentor receives imagery from the operating field and uses a touch-screen interface to author instructional annotations. The annotation data is transmitted back to the trainee site, where it is superimposed onto the trainee's view of the operating field (Fig. 1). In this way, the surgeon can follow step-by-step instructions from an expert mentor in order to complete the necessary procedure. When compared to a conventional telestrator system where the surgeon has to switch focus to a nearby monitor to view the mentor's annotations, the AR system had the advantage of 57% smaller surgical port and instrument placement errors (Fig. 2), and of 65% fewer focus shifts [1]. In an alternate configuration, the surgeon views the operating field while wearing an AR HMD (Fig. 3). In one system, an AR HMD was investigated in telemedicine for both ambulatorial and surgical applications and its technical robustness was verified for networking and visualization, but clinical studies to validate improved patient outcomes are still forthcoming [5].

3 AR in Medical Training on Patient Simulators

Medical simulator training, in which a trainee practices surgical procedures on a physical patient simulator (e.g. mannequin), is a common and growing part of medical education. However, the use of such simulators is currently constrained to practice sessions performed after initial lessons, usually from an expert mentor who is physically present with the trainees. This is because effective simulator training requires that trainees receive feedback on how to correct or optimize their actions [9]. Due to the relatively low numbers of such trained professionals this poses a bottleneck in the medical training process. The methodologies for using AR in live surgery, as described earlier, can be similarly applied to simulator training in order to reduce this bottleneck. One mentor could be networked with multiple trainees in an educational context, where they can oversee multiple simultaneous simulated procedures and virtually step in to provide guidance via AR annotations.

AR can also enhance this process by allowing trainees to use medical simulators without the need for real-life mentors, by providing guidance through artificial intelligence (AI) mentors. An AI mentoring system can display instructions to a trainee and test their knowledge and accuracy as each step of a procedure is performed. The instructions can vary in complexity, from simple virtual incision lines to rich video footage of an expert surgeon performing the operation. Fig. 4 illustrates how AR can help practice on a patient simulator. Compared to the surgical telementoring scenario discussed above, supporting practice on patient simulators is less challenging, as the procedure and the patient simulator geometry are known, which allows for a straightforward prerecording and mapping of guiding annotations.

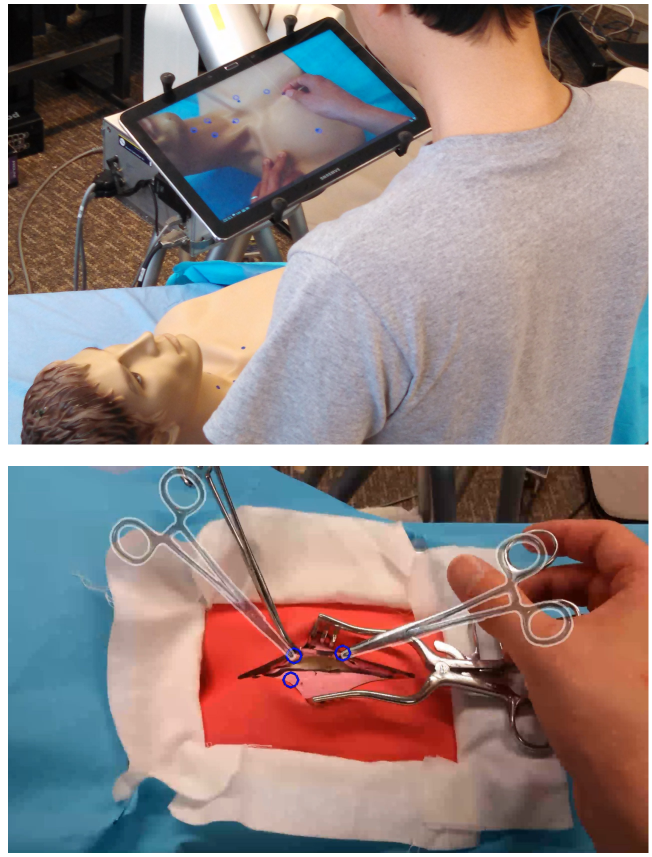

Figure 2: Surgical port placement (top) and surgical instrument (bottom) placement tasks in user study validating the tablet display AR surgical telementoring system.

4 Tablets vs. HMD AR Interfaces for Healthcare Applications

In this section we discuss the tradeoffs between a tablet display and an HMD AR interface in the context of the healthcare applications mentioned above, i.e. surgical telementoring and training on physical patient simulators. The comparison is performed along dimensions that include annotation accuracy, depth perception, visualization continuity, latency, and encumbrance.

4.1 Annotation Accuracy

In order for AR content to provide the benefits of in-context instruction to a user without the need for focus shifts, AR annotations must appear anchored to the real-world objects they describe. Surgical telementoring is a scenario where improperly aligned instructions could lead to delays or costly errors. For example, if an AR incision line for a fasciotomy is misaligned, a surgeon following the provided guidance could sever a blood vessel or a nerve. Even in the less-urgent scenario of medical training on patient simulators, poor annotation anchoring could adversely affect training.

Tablet displays possess some advantages over HMDs because it either remains in a fixed position with respect to the operating field, or it is moved infrequently. Annotations on such displays are made in the coordinate system of the tablet's camera and do not need to be remapped to a different coordinate system. For example, given a tablet horizontal resolution of 2,000 pixels, and a tablet camera horizontal field of view of 45 degrees, a annotation placement accuracy of 1pixel translates to a spatial accuracy of 0.2mm, assuming the tablet is placed 0.5m above the operating field.

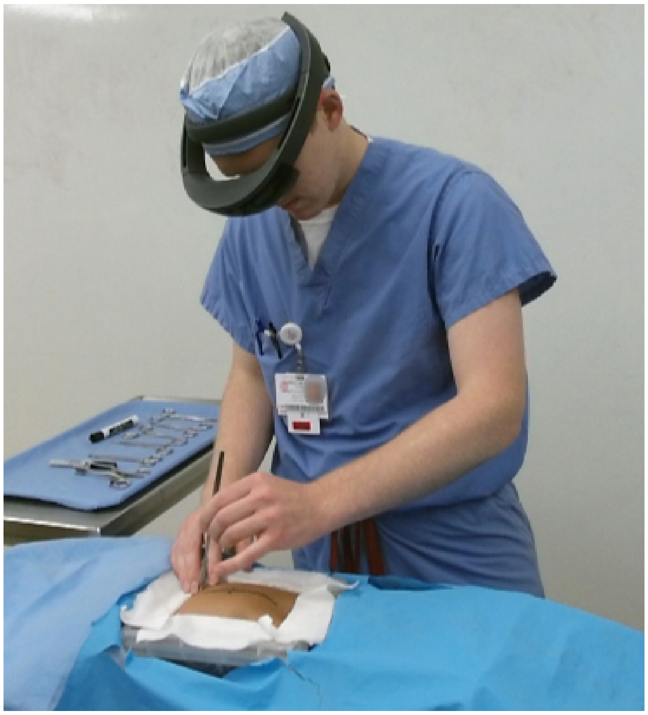

Figure 3: A trainee surgeon performing a simulated abdominal incision through telementored guidance, provided by an AR HMD.

In contrast, the viewpoint of an HMD changes constantly due to head motions, which requires more robust tracking to ensure that annotations are in a valid frame of reference. Furthermore, the correct placement of the annotation in 3D requires a high fidelity knowledge of the operating field geometry. Consequently, annotation placement accuracy in the case of AR HMDs can be orders of magnitude worse than in the case of a video see-through display.

The difficulty of robust anchoring is more acute in the scenario of telementoring than in the scenario of simulator-based training. Skin, organs and internal tissues are dynamic, complex, and non-rigid shapes, and also appear specular under the bright lights of an operating table, all of which hinder robust tracking. In contrast, the geometry of a physical patient simulator can be known in advance.

4.2 Depth Perception

AR HMDs provide the user with a stereo view of the real world, either optically or through dual video cameras. Therefore, surgeons retain depth perception and hand-eye coordination. In contrast, a video see-through display uses a tablet screen to display the operating field to a user, which reduces depth perception. In one study it was found that the use of tablet displays in a telementoring scenario led to increased task completion times, partially because participants slowly moved their hands into alignment in the ”z” direction due to the lack of depth perception [1].

4.3 Visualization Continuity

A well-known issue in AR is the ”dual-view problem,” where parts of the scene inside the borders of a tablet screen appear misaligned, incorrectly scaled, and redundant with respect to parts of the scene outside the borders of the tablet [6]. Such discontinuities can lead to incorrect estimates of scale or position of real-world objects that are viewed through conventional video see-through tablet displays. In the case of telementoring and medical training, these misalignments could lead to delays or errors in care or education. However, this issue can be mitigated by integrating user-perspective rendering with

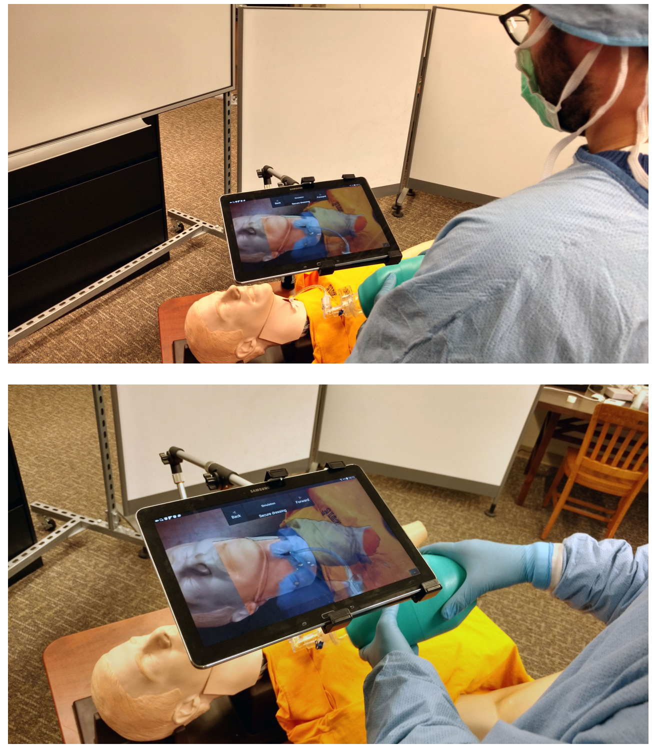

Figure 4: AR guidance in a simulated cricothyrotomy procedure. Prerecorded footage of an exemplary procedure is overlaid onto the trainee’s view of the patient simulator.

real-time scene geometry acquisition and viewpoint tracking (Fig. 5), neither of which is a trivial problem [2]. Furthermore, reprojecting the viewpoint from the tablet camera to the surgeon viewpoint suffers from disocclusion errors, which can, in theory, be mitigated with acquisition from additional viewpoints. It is possible that, given sufficient time and training, trainees could adapt to these perceptual errors, but more research is needed in this area. In contrast, see-through AR HMDs do not suffer from these discontinuities because AR content is rendered to seamlessly overlay onto a user’s normal view of the real world.

Longer term, it is conceivable that truly transparent displays will become available and simulating transparency using camera will not be needed anymore. The current transparent display prototypes [10] suffer from low transmission rates, which demand that the scene of interest be illuminated with very bright lights, and from the fact that they need to be tethered to nearby workstations, forfeiting the advantage of the compact form factor of tablets. Furthermore, even when an adequate see-through transparent display is developed, providing a stereoscopic view of the annotations produced on the display surface will require enhancing the display with a parallax barrier.

4.4 Latency

Video see-through displays that use tablet screens suffer from display latency of approximately 100ms, i.e the time between a change in the real-world scene and when that change can be made visible onto the tablet screen. This is due to the fact that the live preview of video is meant as a viewfinder and not as an AR platform. As tablet and smartphone manufacturers move towards native support for AR, this issue will be addressed. AR HMDs that offer a direct view of the operating field do not incur this display latency, which may make AR HMDs more suitable for urgent-care situations like

Figure 5: A video see-through tablet display without (top) and with (bottom) visualization continuity between display and surrounding scene. Visualization continuity is achieved by tracking the user viewpoint and by acquiring scene geometry, and by using this data to reproject the tablet camera frame to the user viewpoint.

surgical telementoring. In training scenarios on patient simulators, display latency may be less important.

However, some additional latency will always be present with AR annotations themselves due to the costs of tracking and rendering AR content. Video see-through displays can keep the real-world imagery and AR imagery temporally coupled on a frame-by-frame basis. However, optical AR HMDs show a direct view of the real world which can become decoupled from the alignment of AR annotations as the head moves, leading to increased inaccuracy.

4.5 Display of AR Annotations

Current optical AR HMDs only have the ability to render annotations by adding light to the user's view of the operating field; an annotation cannot be made darker than the real-world object in the background. Under the bright lights of an operating room, AR annotations can easily appear washed out or faint in an AR HMD. This is mostly a disadvantage in the surgical telementoring scenario; training on patient simulators can sometimes be accomplished in low-light conditions. AR annotations also appear semitransparent when viewed through an AR HMD, which limits the types of annotations that can be created; for example, a simulated 3D model of internal organs superimposed on a patient's body would always visually conflict with the real world visual state of the patient's body.

In contrast, a video see-through display offers complex per-pixel control of what imagery is displayed to a healthcare provider. Annotations can be made as light or dark as is desired, and entire segments of the display can be overwritten with opaque AR annotations.

4.6 Encumbrance

Current AR HMDs are bulky and heavy on the surgeon's head. Fatigue brought on by extended use of AR HMDs could adversely affect performance. However, the operating workspace is left free for unobstructed movement of hands and arms.

Video see-through displays relieve head encumbrance at the cost of additional workspace encumbrance. The presence of a large tablet above the operating field is bulky and cumbersome, and it may interfere with the natural arm movements of a user. In the case of live surgery, this interference could lead to delays that could affect patient outcomes. Training and simulation scenarios may allow for the use of tablet-based displays in a lower-risk environment, but it remains to be seen if a surgeon trained using such an encumbering device will encounter adverse effects when performing in real surgery. Special care must also be taken to ensure sterility when placing a tablet so close to an operating field of a real patient. A practical way of dealing with workspace encumbrance is for the display to be deployed and retracted as needed, the same way semi-portable X-ray machines are now used intraoperatively.

5 Conclusion and Future Work

We take the position that AR is on the verge of transforming surgical telementoring and of medical training on patient simulators. We foresee that at least for the near future the tablet display and the HMD AR interfaces will coexist since each have important unique advantages.

To concretize this potential, work needs to be done to answer questions about the effectiveness of specific implementation choices of AR healthcare applications. For example, the ideal form factor for the mentor side of a telementoring system is still an open question; a conventional desktop, a tablet, a full-size interaction table, or even a VR interface are all plausible approaches for the mentor to receive operating field information and to augment it with graphical annotations.

Another area where additional research is needed is around the question of AR annotation complexity. Annotations can be as simple as a dot from a mentor-controlled laser pointer to indicate a point of interest [7], or as complex as freeform lines and icons of surgical instruments [1] or fully-animated videos or 3D renderings that are superimposed over regions of the operating field [11]. It is important to find a balance where annotations offer sufficient information and yet are quick and easy to create.

So far, the golden standard for AR telementoring has been to enable communication between a remote expert and a surgeon that is at par with the natural communication that occurs when the expert is physically present in the operating room. As the AR interfaces advance, it will become time to move the goal for AR-enabled communication from matching to exceeding conventional in-person communication, further increasing the amount of good AR can contribute in healthcare.

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