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Augmented Reality as a Medium for Improved Telementoring

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ABSTRACT Combat trauma injuries require urgent and specialized care. When patient evacuation is infeasible, critical life-saving care must be given at the point of injury in real-time and under austere conditions associated to forward operating bases. Surgical telementoring allows local generalists to receive remote instruction from specialists thousands of miles away. However, current telementoring systems have limited annotation capabilities and lack of direct visualization of the future result of the surgical actions by the specialist. The System for Telementoring with Augmented Reality (STAR) is a surgical telementoring platform that improves the transfer of medical expertise by integrating a full-size interaction table for mentors to create graphical annotations, with augmented reality (AR) devices to display surgical annotations directly onto the generalist's field of view. Along with the explanation of the system's features, this paper provides results of user studies that validate STAR as a comprehensive AR surgical telementoring platform. In addition, potential future applications of STAR are discussed, which are desired features that state-of-the-art AR medical telementoring platforms should have when combat trauma scenarios are in the spotlight of such technologies.

INTRODUCTION

Combat trauma injuries require urgent and specialized care. When patient evacuation is infeasible, critical life-saving care must be given at the Point of Injury (POI) in real-time and under an austere environment. Telementoring has been one of the preferred approaches through the years to assist in these scenarios.[1–4]

Consider the following vignette of the use of such systems. Corporal Johnson, a combat medic situated in the frontlines of Afghanistan, needs to perform a lower limb fasciotomy on Private Smith, who was injured by an improvised explosive device. Given the severity of the wound, Corporal Johnson is unsure how best to perform the fasciotomy. Nonetheless, Corporal Johnson carries a portable telementoring system that allows her to connect with Dr Grover, an attending in Trauma Surgery located at Walter Reed Medical Center. After connecting through the telementoring system, Dr Grover guides Corporal Johnson through the procedure, saving Private Smith's leg.

However, current telementoring systems are not ready to fulfill the described scenario: they lack key capabilities for prompt remote instruction under uncontrolled conditions. Currently, mentor's interaction modalities are restricted to audio and telestrator-based guidance (annotations consisting of lines superimposed over patient's imagery shown in a nearby display), limiting the ability to describe complex instructions.[5–7] In addition, generalists must shift focus repeatedly between the operating field and the telestrator, adding complexity and increasing cognitive load.[8,9] Moreover, mentees lack a direct contextual visualization of the future result of their surgical actions, impairing their ability to follow the mentor's instructions in case of delays or communication disruptions.

The System for Telementoring with Augmented Reality (STAR)[10] is a surgical telementoring platform that improves the transfer of medical expertise. STAR achieves this by integrating a full-size interaction table that mentors use to create graphical annotations, with augmented reality (AR) devices that display surgical annotations directly onto the mentee's field of view (FOV). This paper summarizes the new findings and features enhancing STAR's telementoring capabilities. The paper is divided in two main sections. The first section provides an overview of STAR and its components, covering previous works as well as recent additions to the system. This section also describes experiments conducted to validate these recent features. The second section discusses potential end applications afforded by the STAR platform.

SYSTEM FOR TELEMENTORING WITH AR

STAR is a surgical telementoring platform that transfers medical knowledge from a remotely located specialist to a local generalist. Using AR, mentors can author guidance in the form of annotations that appears directly onto the local mentee's FOV. This AR guidance can be used to transmit surgical information such as locations and lengths of incisions, tools to employ, landmarks to avoid, among others. For example, consider a patient in a Role 2 care facility requiring a thoracic surgery. STAR could help the caregiver in charge to administer spinal anesthesia by leveraging AR guidance to identify nerve roots and targets for injection.

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The caregiver can then follow this guidance, without shifting focus from the operating field.

Two subsystems compose STAR: The Trainee System, which broadcasts live video from the operating field to the mentor, and receives the instructions sent by the mentor; and the Mentor System, used by the mentor to annotate the live video of the operating field and send surgical guidance to the mentee. Further explanation of these subsystems is provided in this section.

Mentor System

The Mentor System is comprised of a large-scale multi-touch screen where a remote specialist annotates video images from the distant operating field. The mentor interacts with this screen to create and edit medical-based annotations that range from line annotations to surgical instruments icons. This large-scale device provides: (1) a larger region to both display and annotate the imagery sent by the mentee; and (2) a space that supports an intuitive collaboration model: multiple specialists can work together to aid the generalist.[11,12] Through intuitive multi-touch interactions, the remote specialist can create meaningful surgical instructions to guide the generalist through an entire surgical procedure. Figure 1 illustrates the Mentor System's interface, as well as a surgical instruction created with it.

Trainee System

The Trainee System is the AR platform used by the local mentee to receive and visualize instructions sent by the remote mentor. This AR device is responsible for: (1) acquiring live video images from the operating field and broadcasting them to the Mentor System; and (2) displaying the surgical annotations sent by the mentor. The main advantage of the Trainee System is its see-through nature: by positioning the system between the mentee and the patient, mentees can observe annotations and actionable information directly in their view of the operating field, without requiring additional focus shifts that can hinder performance.[9] Currently, the Trainee System is implemented with two different AR devices: tablet and wearable device, each suited for different types of scenarios. Such devices are described in this subsection.

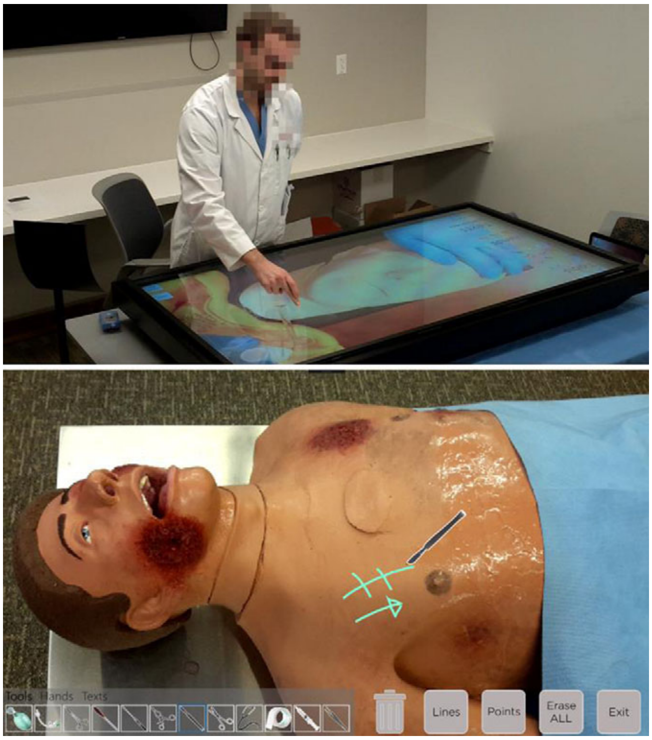

FIGURE 1. The STAR Mentor System interface. Top: The surgical specialist receives a video from the operating field and annotates it accordingly. Bottom: Surgical instruction created via multi-touch interactions with the Mentor System.

Tablet Trainee System

The first iteration of the Trainee System runs in a tablet device held in place between patient and mentee via a mechanical arm. Works as those of Vera et al and Shenai et al have proved the effectiveness of tablets as telementoring devices.[13,14] STAR's tablet-based system joins this list and reaffirms the potential tablet devices have in surgical telementoring. Nonetheless, the Trainee System differs from other tablet-based state-of-the-art devices in two extra features it provides: a simulated transparent effect on its display, and the ability to visualize future steps of the procedure that is being performed. Figure 2 presents the setup of the tablet-based Trainee System, as well as an example of the augmented imagery it generates.

Simulated transparent display. A simulated transparent effect means that the image perceived by the mentee must be the same as the one that would be perceived in the absence of the device. The Trainee System achieves this simulated transparent effect by tracking the mentee's head position and acquiring depth data from the environment.[15] The result is a view of the tablet's camera imagery that appears aligned with the rest of the elements in the mentee's view. This feature is useful to achieve both a proper hand-eye coordination, crucial when performing dexterous tasks;[16] and to resolve the dual-view perceptual issue, present in situations where the user of a device has to switch between both its user-perspective view of the scene and the device-perspective generated by the display.[17] Figure 3 portraits the simulated transparent effect in use.

Visualization of future steps. Another problem that needs to be considered is network unreliability: network communication between mentor and mentee may suffer delays, gaps or even become corrupted in an austere setting. A fallback mechanism should exist at the mentee site to deal with faulty communication scenarios, as mentees may not have enough procedural knowledge to continue the emergency procedure in the absence of the mentor. STAR's future steps visualization (FSV) feature is a simulation that allows mentees to visualize the previous and next steps of specific surgical procedures. By superimposing pre-recorded videos of the procedure's steps onto the mentee's FOV, the mentee can access

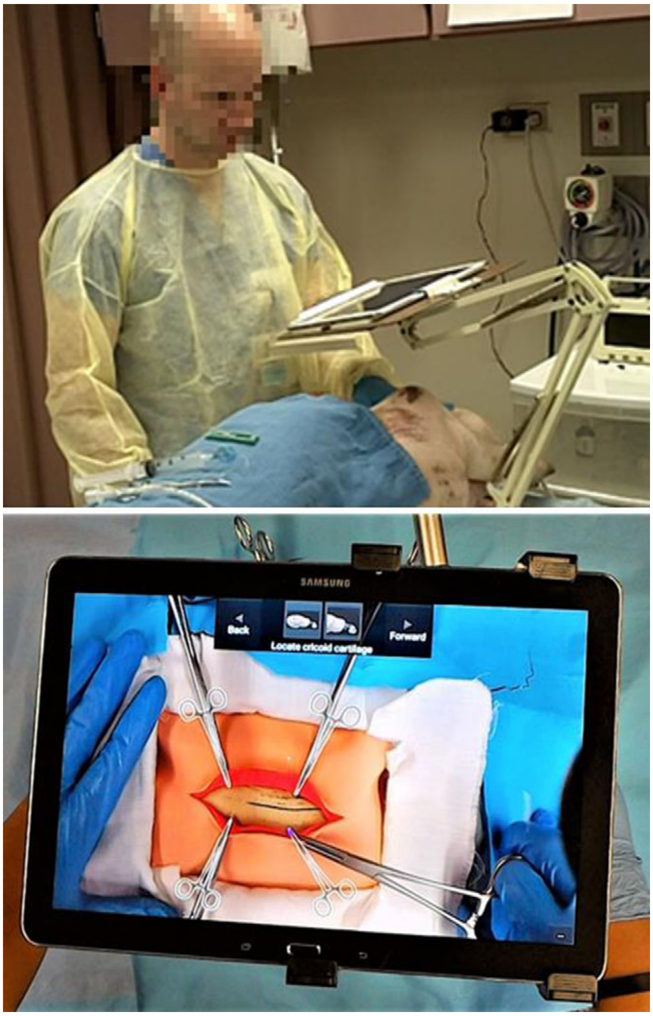

FIGURE 2. The STAR Tablet Trainee System interface. Top: A tablet device is held in place between the patient's body and the mentee. Bottom: Surgical instructions from a remote specialist are overlaid onto the mentee's field of view.

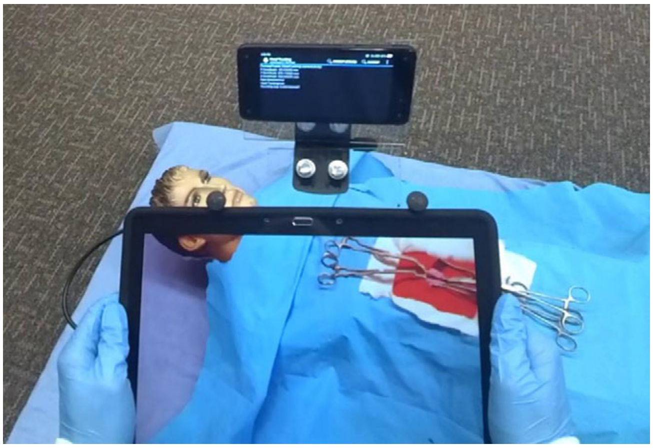

FIGURE 3. STAR tablet's simulated transparency effect. The user is able to see-through the tablet's screen as if it was a transparent window.

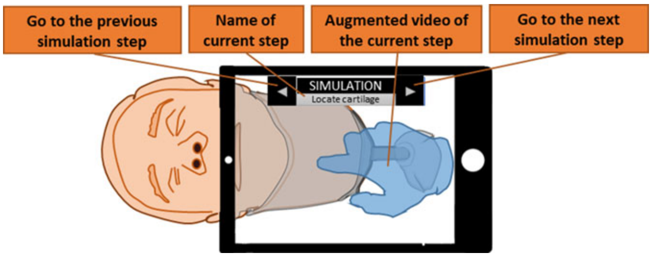

FIGURE 4. Schematic of the STAR tablet's visualization of future steps feature. The user can interact with the tablet to observe previous and future steps a specific surgical procedure, overlaid directly onto the user's field of view.

guidance even if the connection with the mentor becomes unstable. Figure 4 presents a schematic of the FSV feature.

A user study was performed to validate the effectiveness of this feature. In this study, the communication between mentor and mentees was intentionally hindered: the connection's bandwidth was automatically limited at pseudo-random intervals, resulting in drops of the connection's audiovisual quality. Twenty participants with no prior medical expertise performed a cricothyroidotomy procedure on a patient simulator under telementored guidance. Guidance was provided by a remotely located team member trained in the procedure by surgeons from Indiana University School of Medicine (IUSM). Participants were divided into two conditions: STAR with FSV and telestrator (with no FSV capabilities). The analyzed metrics were idle time ratio (ratio between the total time mentees remained idle and the total time taken to complete the procedure), recall error (how well participants could remember the procedure's steps after the experiment), and a performance score of how well the procedure was performed (rated by another team member trained in the procedure).

Participants using the STAR condition had 48% less idle time ($p < 0.001$), 26% less recall error ($p = 0.042$) and their performance score was 10% better ($p = 0.009$) than those in the telestrator condition. These results indicate that surgical telementoring with future steps instruction excelled when compared to conventional telestrator-based telementoring, highlighting the value a FSV feature has as a fallback solution to unreliable communication during telementoring.

Head-Mounted Display Trainee System

Initial development has been done towards implementing a Trainee System using an AR head-mounted display (ARHMD). This system leverages the ARHMD's capacity to display 3D annotations directly in the mentee's FOV, overcoming 2D annotations issues such as occlusion and binocular depth cues degradation.[18] Using a Microsoft HoloLens AR device, the Trainee System can construct a virtual representation of the space it is in, and anchor virtual annotations to this space, visible only to the mentee wearing the device. Figure 5 presents the setup of the ARHMD

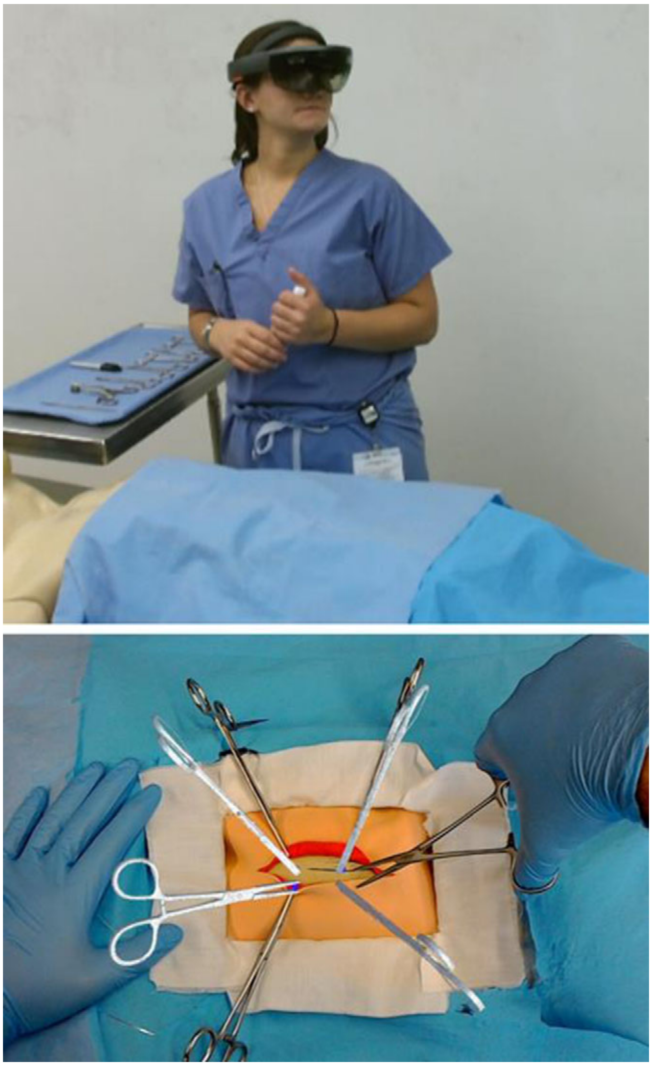

FIGURE 5. The STAR Head-Mounted Display (HMD) Trainee System interface. Top: A mentee is wearing the HMD device. Encumbrance is reduced, as the HMD does not require extra artifacts to be held in place between the mentee and the patient. Bottom: Mentees can receive 3D surgical instructions directly onto their field of view.

system, as well as an example of the augmented imagery it generates. A study that provides insights regarding applications of ARHMD devices in surgical telementoring for combat trauma scenarios is described in the following section.

APPLICATIONS OF THE STAR PLATFORM

The STAR platform's versatility affords a wide variety of potential applications. This section introduces some of the applications in which STAR has proven to be effective, as well as insights regarding how to extend these approaches to become more reliable and impactful.

The Ultimate Patient Simulator User Manual

Healthcare has greatly benefitted from the use of patient simulators. Whereas in the initial stages of a novice nurse training,[19] practice of emergency procedures,[20] or as a tool to develop management skills in trauma residents,[21] patient simulators have shown to be efficient in medical skills refinement and improvement. However, patient simulators companies either assume that medical knowledge is directly transferable to the simulators regardless of the technical interface, or require extensive training sessions for users to become familiar with the simulators' features.[22]

A step towards next-generation patient simulators is for them to be self-contained: end users should be able to use the simulator's features without requiring extensive training. For this purpose, AR systems can used along with patient simulators to provide a detailed and comprehensive guide through the simulator features: every patient simulator should communicate with an AR device that depicts its capabilities. The authors envision a scenario in which medical students or institutions can use AR devices to familiarize themselves with the procedures afforded by patient simulators.

This idea's viability requires a low-cost AR setup that is easy to deploy and requires no prior technical expertise to be used. STAR's Tablet version satisfies both necessities: a self-contained, low-cost tablet device could be shipped together with the patient simulator for an out-of-the-box operation. While an out-of-the-box solution tablet-based device cannot outperform features offered by other AR devices (e.g., 3D environment acquisition), significant increases in task performance can still be achieved through their use.

To assess the effectiveness of the STAR tablet to transfer guidance, a user study was conducted where users with no prior medical knowledge marked regions in the neck of a surgical dummy.[23] Participants received guidance by looking at either a nearby monitor or at the STAR tablet, superimposed over the dummy's body. Participants were evaluated in terms of marker placement error (in pixels), number of focus shifts during the procedure, and time taken to complete the task.

Participants in the STAR condition presented 46% less ($p = 0.013$) placement error (μ, 32.04px; σ_x, 19.19px) than those in the nearby monitor condition (μ, 59.60px; σ_x, 16.86px); and 52% less ($p < 0.001$) focus shifts (μ, 6.56; σ_x, 3.97) than those in the nearby monitor condition (μ, 13.76; σ_x, 4.48). Nonetheless, participants using STAR performed the tasks slower (μ, 53.44 s; σ_x, 15.51 s) when compared to those using a nearby monitor (μ, 41.31 s; σ_x, 14.66 s), which was 23% faster ($p < 0.001$).

These results favor the use of low-cost AR devices to receive and follow instructions: information can be followed more accurately, resulting in increased performance. If patient simulators were to come with AR devices like the STAR's tablet-based system, even users with no prior medical expertise could follow instructions more easily. In addition, STAR's previously described VFS feature can further improve the information transfer: the AR device could come with pre-loaded step-by-step simulations of how to perform each of the simulator's procedures. Further studies should be conducted to prove the viability of this approach, but overall the STAR platform opens the door of low-cost AR devices as powerful additions to the state-of-the-art patient simulators used to improve healthcare.

Enhancing Healthcare Education

Consider a scenario in which a medical specialist needs to instruct several residents on a recently developed surgical technique. Normally, residents would first observe video recordings of the procedure, and then participate in one-to-many live demonstrations led by the medical specialist.[24,25] However, tradeoffs between time and quality of training exist: training sessions with a reduced number of residents (often in a ratio of 1 specialist to 4–5 residents)[26] achieve higher learning ratios, but the time a medical specialist can dedicate to instruct is often limited, making small training sessions not as viable.

Reznick and MacRae presented surgical simulation (e.g patient simulators and virtual reality (VR) devices) as a feasible technique to cope with the high demand of surgical training.[24] However, the small number of "technical" applications patient simulators offer and the inaccurate simulation of a three-dimensional space in VR environments can result in inadequate training sessions. Medical training can be improved using AR devices: a higher number of techniques can be instructed, and VR's simulation of the three-dimensional space is not required because AR augments the operating field instead of replacing it. With STAR, one specialist could monitor a larger number of residents and provide them with instructions accordingly, even without requiring them to be co-located.

A user study was conducted to demonstrate STAR's potential as a surgical telementoring tool.[27] Twenty pre-medical and medical students performed two simulated telementored tasks on a patient simulator: anatomical marking (Task 1) and a multi-step abdominal incision (Task 2). Participants were randomly distributed between two telementoring conditions: telestrator and the STAR tablet device. The metrics consisted of placement error (in pixels), number of focus shifts, and task completion time taken. The experiment evaluated health practitioners' performance while being mentored with STAR through simple medical tasks, stressing its viability as a healthcare education device. Results following a non-normal distribution are reported with median and interquartile range (IQR) instead of the usual mean and standard deviation notation.

For Task 1, participants using STAR reported 59% less ($p < 0.001$) placement error (median, 23.73px; IQR, 13.28px) than those using the telestrator (median, 57.55px; IQR, 32.80px); and performed less ($p < 0.001$) focus shifts (median, 0; IQR, 0.5) than those using the telestrator (median, 13; IQR, 3.75). Nonetheless, participants using STAR performed the tasks slower (μ, 48.0 s; σ_x, 15.5 s) when compared to those using the telestrator (μ, 40.4 s; σ_x, 16.6 s), which was 16% faster ($p < 0.001$).

For Task 2, participants using STAR reported 68% less ($p < 0.001$) placement error (μ, 23.1px; σ_x, 8.4px) than those using telestrator (μ, 72.6px; σ_x, 16.9px); and 44% less ($p = 0.003$) focus shifts (μ, 11.61; σ_x, 10.46) than those using the telestrator (μ, 20.68; σ_x, 5.78). Regarding task completion time, no significant difference ($p = 0.165$) was found between participants using STAR (μ, 274.9; σ_x, 86.9 s) and those using the telestrator (μ, 231.1 s; σ_x, 63.4 s).

These results emphasize STAR's capabilities has as a healthcare education tool: medical students with no prior telementoring experience showed significant increases in performance when guided with the STAR platform. Teaching programs in medical facilities could be enhanced through the addition of AR devices such as STAR, which can cope with current problems in large-scale trainings and surgical simulation.

Immediate Assistance in Austere Environments

So far, the described STAR applications assumed that there exists a room where the STAR platform is installed. This matches more closely a Role 2 care scenario, in which basic primary care needs can be provided, surgical capabilities are given, and Prolonged Field Care can be administered. Nonetheless, this is likely to not be the case in an austere scenario (e.g., battlefield), where emergency situations demand POI assistance. Role 1 scenarios like this require a medium to provide immediate assistance to stabilize the patient before translating it to a medical treatment facility.[28] These scenarios call for a portable, easy-to-deploy AR system that can be used without requiring additional artifacts to be placed.

Tablet-based systems require a setup in which the tablet is either held by the user or positioned in a fixed location.[10,13,14] This introduces additional encumbrance that is likely to affect the motions performed by the health providers: medics would need to alter their natural movements to avoid collisions with the devices. This additional encumbrance is undesirable: medics in emergency scenarios should have total freedom of movement to perform the procedures efficiently.

STAR's ARHMD-based system is an easy-to-deploy, Role 1 care-targeted device that addresses these concerns by displaying medical guidance directly in the user's FOV without constraining its workspace. This ARHMD system will allow Combat Lifesavers to provide POI care, while providing the same telementoring capabilities as STAR's tablet device (e.g., indicate incision lengths, identify nerve roots and targets for injection for anesthesia, among others). To validate the system's potential, medical students participated in a user study that replicated those conducted with the tablet device.[29] Twenty medical students with no prior telementoring experience performed a marker placement task and an abdominal incision task under two telementoring conditions: ARHMD and telestrator. Figure 6 illustrates both telementoring conditions. Prior to the participants' arrival, the 3D position that the tablet device

FIGURE 6. Experimental setup used to validate Augmented Reality Head-Mounted Displays (ARHMD) as surgical telementoring devices. Participants received surgical instruction from either the STAR ARHMD Trainee System (top) or a nearby monitor (bottom).

would have occupied in the workspace was obtained with a depth camera. During the experiment, participants' limb movements were tracked in 3D using the same depth camera. As a post-experiment metric, workspace efficiency was measured as the amount of times and for how long participants would have had to alter their motions had a tablet being present in their workspace. Such data were captured by analyzing the 3D positions of participants' arms compared with the 3D position of the tablet had it been present.

Participants using the ARHMD condition performed the marker placement task 45% better ($p < 0.001$) than those in the telestrator condition. The same is true for the abdominal incision task, were participants in the ARHMD condition performed the task 14% better ($p = 0.01$). In terms of focus shifts, participants in the ARHMD condition performed 93% less ($p < 0.001$) focus shifts in the marker placement and 88% less ($p = 0.013$) in the abdominal incision task than those in the telestrator condition. Furthermore, participants in the ARHMD condition performed the marker placement task 31% slower ($p < 0.001$) and the abdominal incision 24% slower ($p = 0.013$) than those in the telestrator condition. For the workspace efficiency analysis, the ARHMD helped to avoid an average of 4.8 collisions for the marker placement task (lasting 3.2 s in average) and of 3.8 collisions for the abdominal incision (lasting 1.3 s in average). For the first task, collision time meant 51% of the total task completion time.

This study demonstrates that ARHMDs are viable devices to transfer medical guidance. This is a first step towards the adoption of ARHMD devices in austere environments. STAR's ARHMD-based platform successfully offloads the medic's workspace while performing a procedure, which is a valuable feature when providing Role 1 care. Further studies will be conducted in a less controlled environment to provide a higher ecological validity regarding the use of this type of systems in austere conditions.

Potential Future Applications

STAR has a high potential for future work and applications. Some of the most prominent avenues for future research are described below.

Robustness to Strict Firewall Configurations

STAR communicates surgical instructions through the network. However, the current protocol assumes that the network has no firewalls or extra security measurements that prevent the transmission of information. In an ideal scenario, the system should be able to exchange information regardless of the type of network to which it is connected. Preliminary work has begun regarding the implementation of WebRTC, a web socket communication protocol that adaptively changes bitrate and resolution to ensure that the video has as low latency as possible. Through this feature, the system would be able to exchange information regardless of firewalls and other constraints that the network could cause, making it more robust and deployable in a broader range of conditions.

Assistance to Rural Regions

Another venue that is being explored is the deployment of the system in rural and remote access regions, in which transport of bulky equipment is cumbersome or infeasible. For this purpose, an approach consisting of a drone-mounted camera to broadcast live video to the STAR platform is being explored. This approach would allow a specialist to receive a top-down view of the patient, annotate the view, and sent back those annotations to the medic assisting the patient in the rural environment. Figure 7 presents the envisioned scenario for assistance in rural locations via a drone-mounted camera.

X-Ray Mode: Superposition of Patient Imagery

Given the 3D rendering capabilities the STAR ARHMD platform offers, the system could be used to show not only surgical instructions, but also to provide detailed information regarding the inner anatomy of a patient. Consider a scenario in which an abdominal aortic aneurysm is detected on a

FIGURE 7. STAR's envisioned scenario for remote medical assistance in rural areas. A drone-mounted camera captures the view of the operating field, which will be sent to the remote specialist. The mentee located in the rural area will then receive surgical instructions from the specialist via the STAR Augmented Reality Head-Mounted Display.

patient. Computed tomography (CT) scans are used to diagnose and provide medical specialists with information about the patient.[30] However, this requires the surgeons to shift focus away from the patient's body to observe the scans as they operate. A more natural approach would be to overlay this imagery directly onto the patient's body as the specialists operate. Given the 3D nature of a CT scan, a 3D reconstruction can be built from it and exported to the ARHMD system. Once the system loaded the model, it could be overlaid onto the patient's body prior or during surgery, providing the surgeons with more detailed information during operation. Figure 8 illustrates how the X-ray mode could be used to explore the inner anatomical structures of a patient.

ARHMD System Development

Further development and studies proving the usefulness of the STAR ARHMD platform are yet to be done. Development has been done towards implementing computer vision routines to position the 2D-based annotations sent by the Mentor System into the 3D-based environment of the ARHMD. These routines are indispensable to the correct performance of the system.

Once these routines are done, a user study will be performed at IUSM. The selected task is to perform a lower limb fasciotomy on cadaveric legs. Mentee participants will perform the fasciotomies under two different conditions: STAR-mentored or instruction book-mentored, randomly selected. Specialist surgeons of the team will act as mentors for the mentees in the STAR condition. These specialists will also evaluate the performance of the procedure after each participants' attempt. This evaluation will be performed for both conditions, ensuring that the mentor and the evaluator are different individuals (for the STAR-mentored scenario). This experiment will provide a starting point for the use of ARHMD telementoring devices in real-life settings.

FIGURE 8. STAR's X-ray mode capability. The user will observe internal anatomical structures of a patient, overlaid directly onto its field of view.

CONCLUSIONS

An overview of the STAR platform was presented along with results that explore its capabilities in applications that range from medical education to emergency assistance; STAR's capability to superimpose medical guidance directly into the user's FOV has proved to be effective in increasing performance during telementored tasks. New features of the system include a wearable see-through display that affords a more efficient workspace; and a mechanism to simulate the future steps of a procedure as a fallback method against faulty network communication. Using the STAR system, medics in the frontlines will be provided with a channel to receive reliable surgical assistance amidst complex trauma scenarios. Furthermore, promising future applications such as a simulated X-ray mode to visualize internal anatomy of a patient, and a drone-mounted camera for video broadcasting in rural regions keep positioning STAR as one of the state-of-the-art AR medical telementoring platforms to be used during combat trauma scenarios.

PRESENTATIONS

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