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An Augmented Reality-Based Approach for Surgical Telementoring in Austere Environments

Dan Andersen, MS*; Voicu Popescu, PhD*; Maria Eugenia Cabrera, MS†; Aditya Shanghavi, MS†; CDR Brian Mullis, MC USN (Ret.)‡; Sherri Marley, BSN, RN‡; Gerardo Gomez, MD‡; Juan P. Wachs, PhD†

ABSTRACT Telementoring can improve treatment of combat trauma injuries by connecting remote experienced surgeons with local less-experienced surgeons in an austere environment. Current surgical telementoring systems force the local surgeon to regularly shift focus away from the operating field to receive expert guidance, which can lead to surgery delays or even errors. The System for Telementoring with Augmented Reality (STAR) integrates expert-created annotations directly into the local surgeon's field of view. The local surgeon views the operating field by looking at a tablet display suspended between the patient and the surgeon that captures video of the surgical field. The remote surgeon remotely adds graphical annotations to the video. The annotations are sent back and displayed to the local surgeon while being automatically anchored to the operating field elements they describe. A technical evaluation demonstrates that STAR robustly anchors annotations despite tablet repositioning and occlusions. In a user study, participants used either STAR or a conventional telementoring system to precisely mark locations on a surgical simulator under a remote surgeon's guidance. Participants who used STAR completed the task with fewer focus shifts and with greater accuracy. The STAR reduces the local surgeon's need to shift attention during surgery, allowing him or her to continuously work while looking "through" the tablet screen.

INTRODUCTION

Treating combat trauma injuries effectively and rapidly is currently a key challenge in the military. Such injuries are often complex and affect multiple organs (polytrauma). For example, trauma resulting from blast or fragmentation injuries in the thorax is the main cause of mortality in 25% of military victims, and a contributing factor in an additional 25% of trauma-related deaths.[1] Such trauma is difficult to treat, requiring appropriate care from specialized surgical experts. Most combat deaths occur before the injured soldier can reach a medical facility,[2] but approximately one in four battlefield fatalities have been deemed potentially survivable; reducing the time interval between the point of injury and a surgical operation can significantly improve outcomes for such patients.[3] Kotwal et al. found that an institutional mandate to reduce the time between injury and receiving of care improved patient outcomes, which emphasizes the importance of targeting the "golden hour" in treatment of combat injuries.[4] However, evacuation of soldiers with such injuries to a hospital may not always be logistically possible. Even in such cases where transport is possible, the required time of transport (more than 30 minutes) can reduce the likelihood of patient survival. As a result, combat trauma injuries may be restricted to an austere environment, such as a Role 2 Forward Surgical Team, where the necessary expert surgeons are not physically present. Improving the outcomes for these patients requires solving the problem of providing diverse, specialized, and expert care in such austere environments. Providing adequate care during the "golden hour" in future military scenarios (such as prolonged field care and long-distance evacuation) will require an emphasis on surgical measures that can be carried out regardless of patient location.[5]

One promising approach to reducing the number of combat deaths due to complex trauma injuries is to bring the specialized expertise of a surgeon into an austere environment where that surgeon is not physically present, using information technology. For example, surgical telementoring is a method of providing a remote expert surgeon's expertise to a local, less-experienced surgeon in real time, during a surgical operation itself.[2] In such a method, the remote surgeon receives information about the operating field, and then provides real-time instruction or guidance to the local surgeon on how best to proceed with the surgery. It should be noted that, in the austere environments targeted by such a telementoring system, there is an assumption and requirement of basic medical skills on the part of the local surgeon, which can be augmented by remote expert assistance.[6]

The goal of surgical telementoring is to improve patient outcomes by bringing the expertise and mentoring abilities of a remote surgeon into the operating room. Providing the surgeons with a sense of co-presence, where both the remote

*Department of Computer Science, Purdue University, 305 North University Street, West Lafayette, IN 47907.

†School of Industrial Engineering, Purdue University, 315 North Grant Street, West Lafayette, IN 47907.

‡Indiana University School of Medicine, 340 West 10th Street, Suite 6200, Indianapolis, IN 46202.

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and local surgeons are able to interact as if the other were physically co-located, has the potential to enhance the effectiveness of telementoring. As the level of communication and visualization between the surgeons increases, the level of co-presence increases, which moves the telementored experience toward two objectives: (1) that the remote surgeon receives all relevant information as if he or she were present in the operating room and (2) that the local surgeon receives the remote surgeon's guidance as if he or she were physically present.

While current telementoring systems have demonstrated the usefulness and potential of telementoring, the interaction between surgeons is constrained by the limitations of communication and visualization in these systems. For example, current approaches allow an expert surgeon to draw visual annotations overlaid on an image of the operating field in a process called telestration, but the local surgeon can only view these annotations by looking at a nearby computer monitor.[7] As a result, the local surgeon is forced to repeatedly shift focus between the monitor and the operating field during the course of the procedure. Such focus shifts can be distracting and reduce the sense of co-presence. Further, it requires the local surgeon to mentally transform the annotated view to his or her direct view of the operating field. This could lead to delays or errors in medical treatment.[8]

In this article, the STAR system is described and it is shown how it can improve the sense of co-presence by using augmented reality (AR). Such a system removes the need for distracting impediments such as focus shifts from the surgical telementoring process. The technique of AR overlays relevant virtual information onto imagery of a real-world scene. The STAR overlays the remote surgeon's textual and graphical annotations onto imagery of the operating field, as with current telementoring systems, but it also overcomes the focus shift limitation by placing this augmented imagery directly into the field of view of the local surgeon. The augmented imagery appears to the local surgeon using a tablet suspended between the operating field and the local surgeon's head, which allows for continuous viewing of both the operating field and the remote surgeon's instructions in a form factor that avoids bulky eyewear or headwear. By improving the sense of co-presence in this way, telementoring becomes more of a feasible solution for the problem of combat trauma injuries, allowing experts to provide more assistance closer to the point of injury within the "golden hour" where intervention can improve patient outcomes.

This article first provides a general overview of STAR and how each of its components interacts to provide surgical telementoring without the need for focus shifts. Second, it describes formative evaluation of a prototype version of our system. Third, it describes two experiments that were conducted to evaluate the system from a technical perspective and from a user validation perspective.

MATERIALS AND METHODS

Overview of STAR

STAR is divided into two general components: the remote subsystem and the local subsystem. The remote subsystem's function is to display real-time imagery of the local surgeon's operating field to the remote expert surgeon, and to provide the remote surgeon with a touch-based user interface to annotate the imagery of the operating field. The local subsystem's function is to capture imagery of the operating field at the local site, and to display the remote expert surgeon's annotations directly in the local surgeon's field of view.

In a typical workflow using STAR, each surgeon can communicate verbally with each other using an audio channel. The remote surgeon views live images of the operating field, and then creates and transmits a relevant annotation of the next step of the operation to the local surgeon. After the local surgeon has either followed the instruction or indicated an understanding of the next step, the remote surgeon can erase the annotation if desired and illustrate the next step of the operation.

Figure 1 shows the local subsystem. The local subsystem is an off-the-shelf tablet that is positioned between the operating field and the local surgeon's head. It should be noted that the form factor of a tablet is lightweight, portable, and suitable for prolonged field care missions where space is a planning constraint and heavy or bulky equipment would be suboptimal.[9] The tablet captures and displays a live video feed of the operating field using its on-board camera. As a result, the local surgeon is always able to view the operating field by looking at the tablet display, as if the display were a transparent window. The captured video feed of the operating field is wirelessly sent to the remote subsystem.

Figure 2 shows the remote subsystem. The remote subsystem contains a display that allows a remote expert surgeon to view the operating field in real time. Because the

FIGURE 1. The STAR local subsystem, as seen from the local surgeon's perspective.

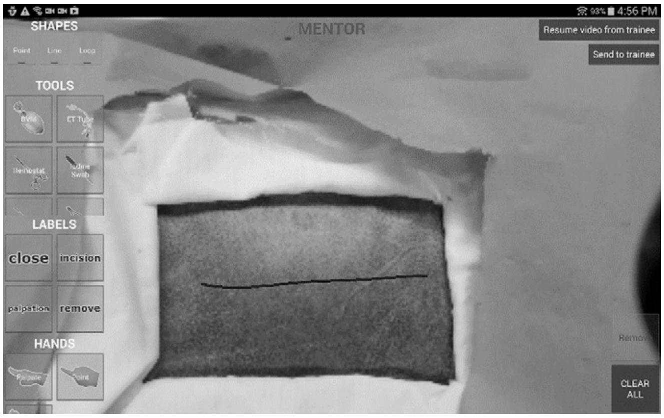

FIGURE 2. The STAR remote subsystem. An annotation representing an incision (dark line in operating field) has been drawn by the remote user.

position of the local subsystem's camera is similar to the local surgeon's viewpoint, the remote surgeon is able to view the operating field from approximately the same perspective as the local surgeon. The remote subsystem also contains a touch-based user interface, which allows the remote surgeon to draw annotation on top of the surgical view. These annotations include instructional visuals (e.g., lines and shapes), and icons of surgical instruments or predefined textual labels. The annotations are actionable physical knowledge conveyed to the local surgeon. These placed annotations can be moved, rotated, or scaled by the remote surgeon. Once the remote surgeon has finished creating a set of annotations of the current operating field imagery, the annotations are wirelessly transmitted to the local subsystem.

Once the local subsystem receives the remote surgeon's annotations, it overlays the annotations (e.g., a polygon representing an incision region) onto the live imagery of the operating field. In this way, the local surgeon is able to view the operating field with relevant expert-provided annotations without ever needing to shift focus.

In the implementation of STAR described in this article, wireless communication was achieved using a Wi-Fi Direct connection to create an ad-hoc local area network between the two subsystems. Video frames from the local subsystem to the remote subsystem were delivered as low-resolution (320 × 200) PNG images at approximately 20fps. Annotation data from the remote subsystem to the local subsystem was in the form of text strings ranging between 1 and 100 KB depending on the complexity of the drawn annotation. Data were sent over a TCP connection for increased reliability.

During surgery, regions of the operating field move with respect to each other as the tissue is deformed as a result of the intervention. If the expert-provided annotations were static and unchanging in their appearance over time, then the operating field may shift underneath an annotation. This could result in an incorrect instruction, increased cognitive load for the less-experienced local surgeon who must mentally remap the now-invalid instruction to its correct location, and increased cognitive load for a remote surgeon who must recognize when an annotation has become invalid. To solve this, the local subsystem uses a series of computer vision algorithms to perform minor repositioning of the expert-provided annotations, such that the annotations appear anchored to the operating field elements that they describe. This annotation anchoring process allows the annotations to remain valid and useful even if the local subsystem is repositioned or if elements of the operating field change their relative position. To accomplish this annotation anchoring, the system first extracts data about salient features of the operating field near the location where the annotation was first created. Areas of high contrast, such as edges and corners, are automatically selected as salient features. In subsequent video frames, the local subsystem detects matching salient features, and, if these features have moved relative to the video frame, the annotation's position is moved with it.

To validate that the STAR approach to telementoring was viable, an early STAR prototype underwent formative evaluation by surgeons during an Advanced Trauma Operative Management course at the Indiana University School of Medicine. A trauma surgery faculty operated the STAR remote subsystem in order to provide remote telementored guidance to a resident surgeon who was performing a fasciotomy on a euthanized porcine model (Figures 3 and 4). The resident surgeon was able to use the drawn annotations, as viewed through the local subsystem, to complete the operation.

Subsequent development incorporated the formative feedback provided by the surgeons after the conclusion of the test operation. For example, the mechanical assembly holding the local subsystem over the operating field was redesigned to be more stable. In addition, the remote expert surgeon reported that more free-form drawing tools like lines and circles were favored as annotations over more complex placement of icons. This suggests that the value of

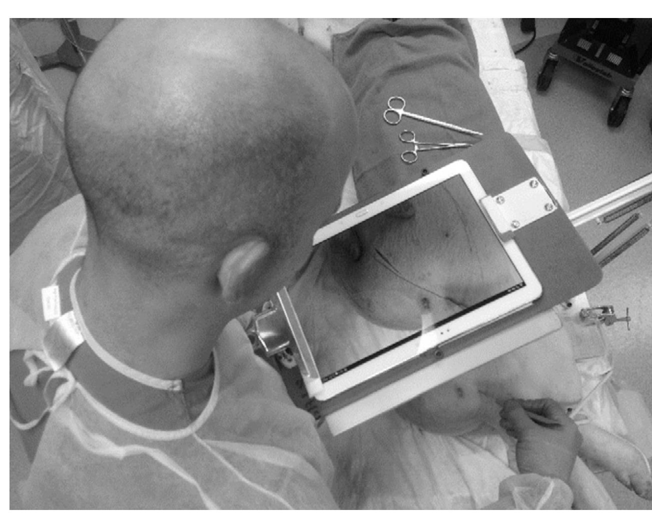

FIGURE 3. A resident surgeon at an Advanced Trauma Operative Management course uses the STAR remote subsystem to complete a fasciotomy on a euthanized porcine model under telementored guidance

FIGURE 4. A remote surgeon provides guidance using STAR to provide telementored guidance to a local surgeon. Annotations (dark arrows) were drawn by the remote user and transmitted to the local surgeon's view of the operating field.

telementored annotation was in quick arrow-like indications, rather than a more detailed but slower construction of a more photorealistic illustration.

During the development of the current STAR prototype, two experiments were conducted, to validate the quality of the STAR system's implementation,[10] and to compare user performance of tasks between STAR and a traditional telementoring approach.[11] This section provides an overview of each experiment.

Experiment 1: Accuracy of Annotation Anchoring

When an annotation sent from the remote subsystem is received by the local subsystem, it should be drawn at a location on the tablet screen that matches the operating field region at which it was first created. To evaluate the annotation anchoring algorithms used, pregenerated annotations were overlaid onto captured video frames of a simulated operating field (represented by either an anatomical print or a surgical simulator). In the video frames, the position of the simulated operating field was translated, rotated, and zoomed relative to the local subsystem. In the case of the surgical simulator, the operating field was also occluded and deformed.

Given these video frames as the input to the annotation anchoring algorithm, the local subsystem updated the positions of the pregenerated annotations each frame. The resulting annotation positions were compared against a ground truth position in each frame, and the distance between the positions was the annotation error. Errors above a particular threshold (20 pixels) were considered an anchoring failure, and errors below the threshold were considered an anchoring success.

Experiment 2: User Validation

To compare STAR with a traditional telementoring approach which relies on telestration (i.e., where annotations are provided on a monitor outside the local surgeon's field of view), a user study was conducted. Twenty premedical and medical students performed two simulated surgical tasks under telementored guidance. The first task was to place a set of adhesives, representing the location of incision ports, onto the neck region of a patient simulator. The second task was to perform a multi-step abdominal incision on a patient simulator using several surgical instruments to be placed at precise locations. One half of the test subjects used STAR, while the other half used a telementoring approach that displayed each step of the operation on a nearby screen. Figure 5 shows the abdominal incision task for the STAR condition, where a series of icons of surgical instruments were displayed to guide the local surgeon to place real-life surgical instruments in the correct locations on the patient simulator. The independent variable was the choice of telementoring system, and the dependent variables were task completion time, placement error, and the number of times the subject shifted focus away from the operating field. Placement error was defined as the physical distance between the location on the operating field where the remote surgeon instructed the local surgeon to place a surgical instrument, and the location on the operating field where the local surgeon actually placed the surgical instrument.

RESULTS

In this section, results are provided for each of the 2 experiments, described earlier, that were conducted to validate the current STAR prototype from a technical perspective and from a user task performance perspective.

Experiment 1: Accuracy of Annotation Anchoring

Annotation anchoring was robust to translation, minor occlusion, and zooming out, succeeding in approximately 90 to 100% of the frames. However, major occlusion, in which large portions of the operating field were occluded by the local surgeon's hands, succeeded only 60 to 74% of the time.

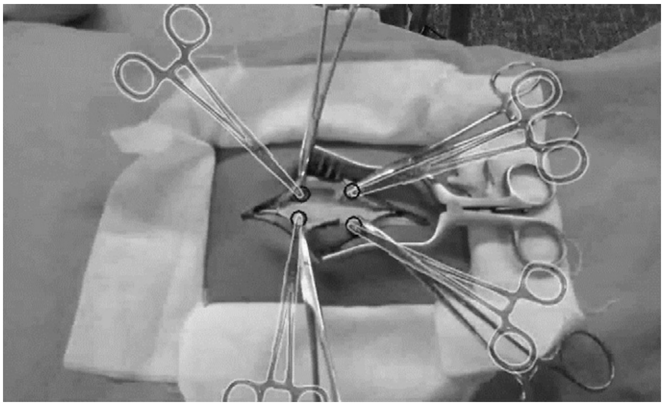

FIGURE 5. The local STAR subsystem's view of the operating field during a simulated abdominal incision task. Annotations from the remote expert (translucent icons of surgical instruments) augment the operating field to provide instruction.

Deformation of the surgical field also led to lower success rates (15–63%), an expected result as the current anchoring approach assumes a rigid, planar operating field. Zooming in tended to result in more anchoring failures than zooming out; this is because when the operating field is zoomed in, there is less of the original operating field that is visible. As a result, the annotation anchoring algorithms have fewer salient features in the image with which to track the operating field elements relative to their original location.

Experiment 2: User Validation

For the two tasks (adhesive placement and abdominal incision) performed by the participants in the study, the subjects using STAR had lower placement error (45 and 68%, $p = 0.003$), and also shifted focus away from the operating field less often (86 and 44%, $p = 0.0003$) than the subjects who used the telestrator system. Those who used STAR also were 19% slower on average for each task, but this result was not statistically significant ($p = 0.165$).

DISCUSSION

The initial results from user studies are promising, indicating that an AR transparent display approach to surgical telementoring can improve the quality of telementoring by improving surgeon accuracy and decreasing focus shifts. However, some limitations of the current STAR prototype exist: the remote surgeon is constrained to a small tablet-based system, the network connection between the subsystems is suboptimal in its bandwidth efficiency, and the local tablet's display only gives an approximate sense of transparency to the local surgeon.

One limitation is that the STAR remote subsystem is currently constrained to a small tablet form factor, which reduces the ability of the remote surgeon to view the operating field in the context of the entire patient's body. In future work, the remote subsystem will be adapted to a larger patient-sized interaction table, which will enhance the sense of co-presence for the remote surgeon by placing the operating field in its proper context.

There are some limitations in the described implementation of STAR regarding the network connection between remote and local subsystems. The use of lossless video frame encoding increases the bandwidth needed for transmitting video frames from the local site to the remote site. Future work will integrate more robust video streaming solutions for guaranteed delivery of video and annotation data in the austere environments that STAR would be used in. A surgical telementoring system for use in forward operating bases would require a robust solution to connectivity so that latency does not impede the ability for the local surgeon to receive adequate guidance. In addition, data transmitted between the subsystems should be encrypted for security reasons in a fully deployed system. However, it should be noted that any surgical telementoring system would need to address these issues, and that STAR's approach to telementoring is not unique in this regard.

The STAR local subsystem acts as a window through which the local surgeon views the operating field, but currently it only gives an approximate window-like appearance. The captured video frames of the operating field are directly shown on the tablet display, and does not change based on the local surgeon's current viewpoint. As a result, objects in the operating field may appear with a position or size that is different from what the local surgeon would see if the tablet were not present. Work is ongoing into investigating simulating a transparent display by capturing the 3D geometry of the operating field, and tracking the local surgeon's head position with cameras, to generate a real-time image on the tablet display that appears transparent to a particular viewpoint. Integrating such simulated transparent display technology into the STAR telementoring approach will result in a system that enhances the co-presence perceived by the local surgeon.

It is also valuable to consider the wider application of STAR's approach to surgical telementoring. Beyond military medicine, STAR also has potential applications for public and rural health care, where trauma patients at hospitals that lack specialized expert surgeons may receive urgent, life-saving care by a local general surgeon receiving telementored guidance.[6] Outside the context of urgent trauma care, STAR has the potential to enhance teleproctoring by allowing a small number of expert surgeons to oversee and interact with a large number of remote students of surgery. By increasing access to specialized training, improved telementoring systems can act as a force multiplier for the limited resource of expert surgeons in the world.

Additional work will involve enhancing the remote surgeon's experience by providing a large interaction platform, complete with hand gesture controls, to allow the remote surgeon to perform more intuitive actions in the course of guiding a less-experienced surgeon through a surgical procedure. Furthermore, the annotation anchoring capabilities of the local subsystem will be enhanced to better support the occlusion and deformation of the operating field that frequently occurs during an operation. Finally, as the field of AR continue to improve, STAR will serve as a robust sandbox platform for further testing and validation of new AR technologies, such as Google Glass and Microsoft HoloLens, which may prove to be useful tools for enhancing the ability of the remote and local surgeons to interact as if they were physically co-located.

CONCLUSIONS

STAR improves on traditional telementoring systems by reducing the need for less-experienced local surgeons to shift focus away from the operating field, and by anchoring virtual expert annotations to the operating field elements that they describe. Initial user studies indicate that STAR can improve a less-experienced provider's accuracy when performing surgical tasks. These benefits promise to improve the care provided to soldiers who receive traumatic combat injuries by increasing the level of co-presence between local and remote surgeons in a telementored operation in the austere environment of a forward operating base.

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