The Application of Augmented Reality for Immersive TC3 Training

Alyssa Tanaka, PhD, Jeffrey Craighead, PhD, Glenn Taylor
Soar Technology, Inc.
alyssa.tanaka@soartech.com, jcraighead@soartech.com, glenn@soartech.com

ABSTRACT

Military medical personnel are the first responders of the battlefield, where they are tasked with maintaining tactical objectives and making critical decisions for care that may determine if a casualty lives. Having providers engage in realistic Tactical Combat Casualty Care (TC3) scenarios can optimize the leadership, teamwork, tactical, and medical skills required to succeed in the challenging situations they may encounter. An issue that instructors face when attempting to create engaging TC3 training scenarios is effectively simulating battlefield injuries on the standardized patients imitating casualties. While medical moulage offers a static visual portrayal of a wound, instructors often have to provide supplemental content to the scenario using verbal prompts about the patient's injuries. Augmented Reality (AR), especially the recent boom in wearable AR headsets, has the potential to revolutionize how TC3 training happens today. AR can provide a unique mix of immersive simulation within the real environment by overlaying dynamic virtual injuries on simulated patients. The AR field has seen billions of dollars invested for development and deployment of hardware and software, which has been leveraged into many fields. While AR offers many opportunities for training improvement within the TC3 training, several challenges for integrating these technologies still exist. TC3 scenarios present complex environments for AR tracking and projection due to the many dynamics of the scenario. This paper will explore the technical challenges encountered during development of a TC3 AR capability and discuss both hardware and software solutions for addressing these limitations.

ABOUT THE AUTHORS

Dr. Alyssa Tanaka has earned a Ph.D. and M.S. in Modeling and Simulation, Graduate Certificates in Instructional Design and Training Simulations, and a B.S. in Psychology and Cognitive Sciences from the University of Central Florida. She also holds a diploma in robotic surgery from the Department of Surgery, University of Nancy, France. Dr. Tanaka currently works at Soar Technology as a Research Scientist. She leads several programs aimed at developing medical training technology and applications by leveraging artificial intelligence and machine learning. Prior to joining SoarTech, she led research initiatives directly related to improving the training and education of robotic surgeons through simulation as a Senior Research Scientist at Florida Hospital Nicholson Center.

Dr. Jeff Craighead is a Research Scientist and technical lead in SoarTech's intelligent training business area where his research is focused on AR- and VR-based training tools, stealth assessment systems, machine learning, and knowledge representation. He has spent the last 15 years in both private and government sectors publishing research on robotics, mobile sensor systems, RFID, and adaptive, game-based training as well as leading the development of commercial, cloud-based software. He earned his Ph.D. in Computer Science from the University of South Florida in 2009.

Glenn Taylor is a Senior Scientist at SoarTech in the autonomous platforms business area. Glenn's work has included developing multi-modal interfaces (speech, gesture, sketch) for human-robot interaction, computational human behavior/communication models of air traffic controllers, fighter pilots, helicopter pilots, fire direction centers, and numerous models of social/cultural/political systems. He has extensive experience in knowledge elicitation and knowledge engineering, and has published widely in the areas of intelligent agents, agent-based systems, and intelligent system design. Mr. Taylor has a M.S. in Computer Science and Engineering from the University of Michigan, Ann Arbor.

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INTRODUCTION AND RELATED WORK

In this paper we discuss the issues encountered during the development of an augmented reality (AR) tool to improve tactical casualty combat care (TC3) training. The goal of this system is to reduce costs and add realism to the training experience. Today, this experience relies primarily on live casualties and mannequins that do not have the wounds that the trainees are being trained on. Additionally, the mannequins generally lack the realism needed for effective training. Current approaches primarily rely on static moulage that offers a tactile experience, but does not portray the dynamics associated with the wound or the casualty physiology.

The challenges presented by live training exercises in the field are substantial - the range of injuries and other related physiological and mental sequelae, the range of treatments and instruments used during treatment, the different environment conditions under which TC3 occurs, and the range of feedback and guidance that happens as part of instruction all contribute to a very complex use case. This is complicated by the fact that commercial-off-the-shelf (COTS) technologies for augmented reality and haptic feedback are very new and are in many ways still under development. An ideal hardware solution would probably include a fully self-contained AR headset that allowed for a full field of view, had sufficient computing on-board to keep up with a moving medic, and enough outward-looking sensors on the device to fully recognize and track the casualty and treatments. Our approach has been a practical one - using COTS tools as possible to develop an end-to-end system that may not have all the technology components that are desired in a full solution, but one that enables deployment of near-term training aids while also identifying technology gaps that can be addressed with longer-term R&D efforts.

Section 2 will outline various challenges faced when implementing an AR medical training system; challenges such as the tracking and registration of holograms on live, moving casualties. Section 3 will discuss potential solutions to these problems, some of which have been tested, others are proposed based on inadequacies found in existing solutions. The remainder of this section outlines current TC3 training environments and procedures. Figure 1 shows the concept of how an AR system would be used for live TC3 training.

State of the Practice at Medic Training Facilities

Medic training facilities, such as the Medical Battalion Training Site (MBTS) at the Army National Guard facility at Fort Indiantown Gap, PA, have a primary mission to teach the 68W MOS Transition course. As part of an earlier investigation we visited this training facility to observe current instruction practices and identify opportunities for using AR and enhanced moulage. A trainee starts the 8-week 68W MOS Transition course knowing absolutely nothing about medical care and graduates as a certified medic, ready to join a unit. The first two weeks are an intense EMT course, followed by Army medic training. The facility has large classroom space, hands-on lab space, and indoor mockup environments for scenario-based training - an alleyway for training care under fire, a section of a house for training room clearing as well as EMT skills, and an evacuation room for training skills for triage and loading and unloading casualties in and out of medical evacuation (MEDEVAC) vehicles.

As part of the final weeks of the course, the trainees go through intense scenario training which includes a simulated Battalion Aid Station (BAS) with a building for triage and another for treat-

Figure 1: *Combat casualty care augmented reality training system conceptual architecture.*

ment and holding prior to evacuation. Casualties from the field arrive in a MEDEVAC truck and have to be treated before being evacuated to another facility. The scenarios also include dismounted and military operations in urban terrain (MOUT) patrols where one or two medics are part of small squads that are given missions to find, care for, and evacuate casualties, often under fire from simulated opposing forces (OPFOR). These also include convoy operations where a MEDEVAC truck is escorted to the dismounted or MOUT units to pick up casualties and, and trainees on-board can treat them on their way to the BAS. (In a few cases, airborne MEDEVAC was available from the nearby airfield, and trainees were able to practice loading onto a helicopter.) The BAS training is collective, with multiple trainees working on one or more casualties at each stage of the process. The dismounted and MOUT patrols and the convoy operations are more focused on individual training, with one trainee working on one or more casualties (one in the dismounted patrol and MOUT, two in the convoy scenarios inside the MEDEVAC vehicle).

The MBTS facility uses a mix of mannequins and live volunteers to serve as casualties. MBTS uses an array of different types of mannequins during training. They have at least one instrumented medical mannequins that are controlled via computer, and which can bleed, provide blood pressure and respiration, and can speak using prerecorded utterances that the instructor can select. However, these are expensive and require extra equipment, which means the instructors are disinclined to take this out into field training. Most of the mannequins are instead not instrumented, ranging from very simple lightweight mannequins with replaceable limbs, to mannequins with built-in injuries such as burns or amputations, to mannequins that can be injected with IVs (though they do not bleed), can have cricothyroidotomies performed on them, and which can show respiration if they are ventilated. Where injuries are not built into the mannequin, the instructors use moulage to add injuries such as gunshot wounds or blast injuries. (MBTS uses purchased moulage kits and also has some staff members with special effects training who can build custom moulage on site.) They also use live volunteers to play the role of casualties, adding moulage for the wounds, with the added benefit that the volunteers can provide more realism such as screaming or responding to verbal prompts. The trade-off is that, for ethical reasons, the live volunteers cannot receive the full range of treatments that a mannequin can receive. In addition to moulage, they use some specialize part task trainers - one in particular we saw was a block of plastic representing some of the upper chest including the sternum so trainees could practice intra-osseous IV insertion, which could not be done on most of the mannequins and certainly not on the live volunteers.

Dismounted and MOUT missions are typically are framed as needing to find someone who has been reported as wounded or they come upon someone who is wounded. This is in contrast to the injury happening as part of their patrol - e.g., the unit comes under attack and one of their teammates is injured. The primary reason for this is that setting up the casualty with moulage takes a considerable amount of time, and cannot be done immediately for an attack on the unit. (Scenarios where an attack happens on the medic's own unit might happen at other facilities such as the National Training Center (NTC) or Joint Readiness Training Center (JRTC). Instructors at MBTS mentioned that they do not use the Multiple Integrated Laser Engagement System (MILES) at this facility as part of dismounted or MOUT training, in part because of the complexity in setting it up. However, these instructors also liked to be able to script out a scenario ahead of time for instructional purposes. On the other hand, JRTC and NTC instructors prefer using MILES because it is less scripted - no one knows ahead of time who is going to get shot.)

Roles of the Instructor

The role of the TC3 instructor is multi-faceted. Classroom instruction is certainly part of their role, but the instructors endeavor to get the trainees as much hands-on experience as possible, including the scenario-based training we observed. Because what we observed was practice rather than a test, the instructors were still providing instruction as part of the exercise, though sometimes in indirect ways. Instructors may question the trainees about why they're using a particular instrument or treatment, making suggestions or giving hints, or even reminding them of the steps in a procedure (or more directly ordering them if need be). The instructor will also facilitate after-action review (AAR) sessions with the trainees as a group or individually, depending on the particular scenario. In addition to providing traditional instruction, the instructor also plays other roles during training, at least as observed at Fort Indiantown Gap.

During live training, MBTS maintains at most a 6-1 ratio of trainees to instructors. In the BAS exercises, groups of 6 medics would rotate from station to station, while the instructors would stay at each station. In the dismounted patrol, MOUT, and convoy exercises, there was a ratio of one instructor for each active trainee: in a group of 6 trainees, 2 would be the medic of the group, and each would have an instructor; the other trainees would play other roles in the unit.

Simulating and Reporting the Condition of the Casualty

Because the casualties - as simple mannequins or live volunteers - do not have actual injuries, and also do not have the physiological conditions and do not exhibit the cues associated with those conditions, the instructors have to provide those cues verbally. For example, a trainee might verbalize a task such as taking a pulse: "Taking pulse for 30 seconds." A few seconds later, the instructor would verbalize the pulse that the trainee would have felt: "27 in 30 seconds" or even "no radial pulse." From that, the trainee can proceed with the next assessment or treatment. These dialogues happen for vital signs like blood pressure, respiration rate, but also other cues, such as when the trainee presses along the chest to check for internal injuries, or when doing a blood sweep along the backs of arms and legs. To simulate arterial blood loss, the instructor will also squirt moulage blood onto the wound to give the trainee both the visual of the presence of blood, some dynamics associated with the wound, as well as the slippery feel of blood. This helps provide the trainee with additional cues about the casualty's condition beyond just the verbal reports from the instructors. However, the blood squirt bottle is one of the few physical elements available to the instructor to make the training more realistic. We observed a number of cues provided by the instructor, many of which can potentially be replaced using AR:

- injury description if not obvious from moulage
- squirting fake blood onto wound to simulate arterial bleeding (though sometimes oozing blood as well)

- reporting vitals - pulse, blood pressure, breathing rate, pupil dilation
- casualty verbalization - “patient is moaning”
- results of responsiveness tests - “casualty is in and out of consciousness” . . . “patient is non-responsive”
- injury state: “injury continues to bleed,” “injury begins bleeding again through bandages”
- CPR / defibrillator results (or other equipment)
- other cues that might indicate a specific condition: presence of bodily fluids, condition of veins (e.g., distended jugular), skin coloration, etc.

This aspect of the instructor’s job is especially important because the trainee has few sensory cues as to the condition of the casualty. Some wounds might be visible as moulage, but the dynamic condition of the wound is not something the trainee can observe as they perform interventions. The instructor may have to keep reminding the trainee of a particular condition simply because there is nothing for the trainee to observe, and so no outward cue to serve as a reminder. Where the moulage is not of high quality, and the type of injury is not obvious, the instructor may have to explain what the wound is before the trainee knows how to respond.

In performing this job, the instructor has to keep in mind the casualty’s overall condition, the current physiology based on treatments by the trainee, and the instructional goals including for the trainee, along with adjusting this internal mental model according to whatever interventions the trainee administers. This gets more complicated in some training situations, for example in the *Evacuation* stage of a BAS where the training area may have four or more casualties that are being treated, one instructor has to keep these straight throughout the duration of the training, which may last a couple of hours.

Observation, Assessment and Adjustment

One of the instructor’s roles is to observe the interventions by the trainees, partly as an assessment of their skill, but also as a way to update the internal model of they casualty the instructor maintains. The instructor constantly moves around the trainee and casualty to get a view of what the trainee is doing to answer a few questions - What treatment is being administered? What instruments are being used? Are they being used in the right way?

The instructors may adjust on the fly the level of difficulty of the scenario. This might be by injecting new conditions as the treatment progresses to challenge the trainees, or to add additional stress to the situation, such as by manipulating the amount of time available for treatment. This role can augmented or replaced by an adaptive training system, assuming the AR device and application can accurately assess what the trainee is doing. At a minimum, the casualty model can be offloaded to a computer-based simulation and the instructor can record objective assessments using a mobile device or tablet.

Role-Playing Radio Protocol

As part of field training, where there is a medic as part of a dismounted squad on patrol (for example), the medic or squad leader would have to call for a MEDEVAC. The instructor plays the role of the dispatch unit on the other end of the radio, listening and responding to the 9-line MEDEVAC request. Where the trainee is not doing this properly, the role-playing instructor may ask questions to clarify or play dumb and wait for the trainee to get it right. This is also a way for the instructors to inject changes to the scenario - for example, changing the time at which the MEDEVAC would arrive to add stress or give more time for more deliberate field care.

AR CHALLENGES IN TC3

Given the training procedures discussed in Section 1 we have been developing a prototype AR training system to address some of the shortcomings in live training with mannequins and static moulage pieces encountered by trainees. As we have investigated AR solutions we have identified technology issues that must be addressed to successfully implement a fieldable training tool for LVC training. This section discusses how these issues affect AR training while Section 3 identifies possible solutions to these problems.

Moving Patients (tracking and registration)

When using live participants as casualties for practice it is guaranteed that the person will move, possibly frequently, while a trainee is practicing a procedure. For AR systems that depend on world-space feature tracking (Engel, Schöps, & Cremers, 2014; Davison, Reid, Molton, & Stasse, 2007) or fiducial markers (Fiala, 2005; Garrido-Jurado, Munoz-Salinas, Madrid-Cuevas, & Medina-Carnicer, 2016) placed in the environment to register hologram locations, this is a breaking condition. Any movement from the initial calibrated location will cause a misalignment in the projected hologram. For systems that simply present floating informational text and images a small misalignment is tolerable, however for a system that is projecting a wound consistent alignment with the casualty's body is critical otherwise the would will appear to float in space. Additionally, by keeping the AR wound registered to the body of the casualty, scenarios that require treatment while the casualty is in motion (for instance transporting to a vehicle or to another room) become possible.

A more robust solution to hologram registration is to use markers on the body, specifically, near the target wound such that the fiducial moves when the casualty moves. By keeping the hologram in the same position relative to the marker the trainee will be able to continue treating the wound as the casualty is moved or shifts in place. This approach has its own limitations, however. The marker must be exposed to the AR system and large enough to be detected at a reasonable distance. This detracts from the realism when used in Live exercises that use MILES or the Instrumented Tactical Engagement Simulation System (ITESS). Markers could be placed on top of clothing or integrated into the uniform, however, many procedures require removal of clothing; this makes markers on top of or integrated into clothing a poor choice. Markers worn under the clothing eliminate this problem, however introduce the need to have all trainees participating in the exercise wear some kind of stick-on markers under their clothing. This is less than ideal from the standpoint of rapid engagement and cost. Finally, all marker-based registration is limited by the need for the marker to remain visible to the AR hardware to maintain accurate registration.

Tactile Feedback (physical vs virtual moulage)

Many diagnostic procedures rely on touch to provide information to the treating medic. While using augmented reality enables a system to provide more dynamic visuals and a greater variety of wounds, it completely eliminates the tactile sensations a trainee might be looking for. Addressing this problem is an area of ongoing research, with academic and industry researchers attempting to solve the problem of tactile sensation in both augmented and virtual reality (Bau & Poupyrev, 2012; Lugtenberg et al., 2018; Meli et al., 2018). One option is to use mannequins and cut suits to provide tactile feedback while using the augmented visuals to enhance the dynamics of the wound (Kobayashi, Zhang, Collins, Karim, & Merck, 2018), however this again limits the type of injury to one supported by the moulage, mannequin, or cut suit.

Wound Occlusion

Occlusion problems can be broken into two categories, full occlusion and partial occlusion. Full occlusion occurs when the wound is covered by a bandage, for example. In this case the AR system should stop drawing the hologram. This case is relatively manageable when using fiducial markers as the of covering or loss of a marker is generally reported by all tracking systems. A more complicated and interesting problem is that of partial occlusion. Partial occlusion occurs when only part of the hologram should be covered, by a few fingers or part of a tool. Covering a fiducial is typically a binary operation, either enough of the marker is visible to be detected or it is not, information about which parts are occluded is not provided in COTS tracking systems. A limited solution would be to use a multi-marker approach in which each marker corresponds to a segment of the hologram. Segments could be individually activated based on full occlusion as mentioned above, however this runs into issues with fiducial size and that individual segments can still be partially occluded and drawn incorrectly. Figure 2 shows a mockup of an AR knife wound with blood rendered on top of an image of a hybrid moulage piece. Without handling partial occlusion, the wound and blood will be drawn on top of the trainees hand when they interact with the simulated patient.

Figure 2: Mockup of wound moulage worn in a spandex sleeve with AR wound and blood projected into view.

Physiology Simulation (what is needed)

As mentioned in Section 1 the state of the practice in TC3 training is for the instructor to act as the physiology simulator, calling out changes in status and vitals to the trainee. This type of instructor-based control could still be leveraged using an AR system by giving the instructor a tablet that gives the instructor live control over the wound and other vital statistics information displayed to the student. Ideally the AR system would make use of a physiology simulation to reduce the burden on the instructor, possibly giving them time to monitor several students at once.

Multi-participant Live Training

A common problem faced by all branches of the military (and educators in general) is the student-teacher ratio. While classroom-based training can easily support many trainees learning from a single instructor, live training exercises present a problem. Trainees are typically dispersed in the field taking on different roles in the exercise or are divided into small groups in which each trainee can take on every role over several training exercises. In the dispersed case, there may be instructors observing and making notes for use in an after action review; in small groups case, there is one instructor needed per group making notes and providing help where necessary. This costs associated with this type of training could be reduced significantly if the instructor-to-trainee ratio for the small group case could be reduced such that a single instructor could manage and observe multiple groups simultaneously with the aid of intelligent tutors and automated assessments built into the AR system.

POSSIBLE SOLUTIONS

Markerless Body Tracking

A potentially more robust alternative to fiducial markers is a computer vision based system that identifies body parts and pose positions from video (Runz, Buffier, & Agapito, 2018; Zhang, Han, & Hui, 2018; Mahmoud et al., 2017). However existing markerless tracking systems have their own issues. Hardware and software solutions that are specific to hand tracking, such as LeapMotion and ManoMotion, are by nature limited to hand tracking. While this could be useful for identifying how the trainee interacts with real and virtual objects, it does not help with registering the body position to project a virtual wound. Full body software frameworks such as the open source OpenPose and the commerical wrnch.ai, provide reasonably stable pose estimation that can be used for wound projection. However, in our limited testing with these frameworks, the entire body had to be visible to maintain a stable pose estimate. This mean that as the trainee approaches the patient, tracking will be lost. As video-based markerless tracking technology evolves, a pose estimation framework trained on both full body and partial body images would be ideal for medical training purposes.

Hybrid Moulage

A hybrid, instrumented moulage consists of a physical piece of silicone moulage that is marked or instrumented in order for an AR system to provide additional visual elements that can enhance the realism of the wound. We have tested silicone moulage pieces that contain sensors and fiducial markers. The fiducial markers enable an AR system such as the Microsoft HoloLens to track the wound directly without needed to determine the relationship to the rest of the body. The embedded sensors provide acceleration and rotation data that can be fused with the visual tracking information to provide a more stable position estimation for the AR holograms. Figure 3 shows a hybrid moulage concept mockup. A hybrid moulage could be create using 3D printed molds and poured silicone (Smooth-On makes many silicone products that are suitable, for example).

Hand and Object Tracking for Occlusion Handling

As mentioned in Section 3.1, hand tracking is needed for realistic interaction with virtual objects. Interacting with virtual objects requires hand pose estimation not only to enable a user to pick up or touch a virtual object, but to also change how that object is displayed. Lighting, shadows, and partial occlusion are all problems that must be addressed to enable seamless integration of virtual AR objects into real world training. Recent research has shown that a robust occlusion estimate can be derived from a combination of RBG video and a LeapMotion hand tracking system. (Feng, Shum, & Morishima, 2018) We have yet to test a similar implementation, but believe that this will be an important factor in creating realistic AR training tools.

An alternative approach may be possible using a combination of hand pose estimation software, an infrared camera, and a hybrid moulage piece that either is highly reflective in the IR range or has IR emitters embedded in an IR transparent material. The intense IR emitted or reflected from the moulage should make it relatively easy to segment and identify the boundary of the piece in

Figure 3: Mockup of the hybrid moulage concept.

the IR video stream. Objects occluding the moulage, such as a hand or tool, should produce a significant decrease in the intensity of the occluded pixels. This information can then be used to mask the occluded portion of the AR holograms that are rendered on top of the physical moulage.

Pulse Physiology Engine

Kitware's Pulse Physiology Engine (Bray et al., 2019) provides simulation of many human body system using parameterized models. These models have been validated against medical literature and should be accurate enough to drive training simulations that only need high level simulation of body systems. For example we have tested the cardiovascular simulation capabilities of Pulse by integrating it with a prototype AR gun shot wound simulation. The Pulse engine provides heart rate, blood flow, blood volume, oxygenation, and more. Using these parameters we could control the virtual wound and blood animations. At this time, Pulse only supports modeling blood flow between major compartments, such as left arm and torso; finer grained modeling must be handled by the application developer. However, we found that even the high level modeling was suitable for driving our AR training prototypes.

Shared, Synchronized View

In order to facilitate a more natural interaction between the instructor and trainee, while using AR training systems, we propose a shared, synchronized view. In this situation multiple users (trainees and instructors) would interact with the same virtual objects and see the same animations. The shared AR environment is not too difficult to implement on a theoretical level. The same data synchronization and distribution methods used for current multi-player video games will suffice. A multi-user AR system also provides an opportunity to explore how a shared AR environment could provide enhanced tracking of real-world objects and users through a fusion of SLAM and oject tracking data from multiple AR devices.

SUMMARY AND FUTURE WORK

In this paper we have discussed how AR can be used to enhance TC3 training, identified several problems with current AR technology, and discussed several possible solutions to these problems. Some of these solutions can be readily implemented using off the shelf hardware and open source software. Other problems, such as partial occlusion, however, have no simple solution and are still actively being researched by many university and private sector scientists. The US Army has recently committed nearly $500M to purchasing hardened HoloLens 2 devices from Microsoft. Many of those devices will be used for training purposes and should provide enhanced capability beyond what is currently available in the current HoloLens and MagicLeap AR systems. This has the potential to revolutionize training for TC3 and medical training in general, but widespread adoption will require significant improvements in the usability and capabilities of AR hardware and software systems. Beyond the basic tracking and rendering capabilities, training software developers targeting AR will still need to consider how to best provide training that leverages the advantages of AR and not simply develop eye candy that makes a compelling demo, but lacks pedagogical rigor.

REFERENCES

Bau, O., & Poupyrev, I. (2012). Revel: tactile feedback technology for augmented reality. *ACM Transactions on Graphics (TOG)*, *31*(4), 89.

Bray, A., Webb, J. B., Enquobahrie, A., Vicory, J., Heneghan, J., Hubal, R., . . . Clipp, R. B. (2019). Pulse physiology engine: an open-source software platform for computational modeling of human medical simulation. *SN Comprehensive Clinical Medicine*, 1–16.

Davison, A. J., Reid, I. D., Molton, N. D., & Stasse, O. (2007). Monoslam: Real-time single camera slam. *IEEE Transactions on Pattern Analysis & Machine Intelligence*(6), 1052–1067.

Engel, J., Schöps, T., & Cremers, D. (2014). Lsd-slam: Large-scale direct monocular slam. In *European conference on computer vision* (pp. 834–849).

Feng, Q., Shum, H., & Morishima, S. (2018). *Occlusion for 3d object manipulation with hands in augmented reality.* http://hubertshum.com/info/publications/miru2018/files/miru2018.pdf.

Fiala, M. (2005). Artag, a fiducial marker system using digital techniques. In *2005 ieee computer society conference on computer vision and pattern recognition (cvpr'05)* (Vol. 2, pp. 590–596).

Garrido-Jurado, S., Munoz-Salinas, R., Madrid-Cuevas, F. J., & Medina-Carnicer, R. (2016). Generation of fiducial marker dictionaries using mixed integer linear programming. *Pattern Recognition*, *51*, 481–491.

Kobayashi, L., Zhang, X. C., Collins, S. A., Karim, N., & Merck, D. L. (2018). Exploratory application of augmented reality/mixed reality devices for acute care procedure training. *Western Journal of Emergency Medicine*, *19*(1), 158.

Lugtenberg, G., Hürst, W., Rosa, N., Sandor, C., Plopski, A., Taketomi, T., & Kato, H. (2018). Multimodal augmented reality–augmenting auditory-tactile feedback to change the perception of thickness. In *International conference on multimedia modeling* (pp. 369–380).

Mahmoud, N., Grasa, Ó. G., Nicolau, S. A., Doignon, C., Soler, L., Marescaux, J., & Montiel, J. (2017). On-patient see-through augmented reality based on visual slam. *International journal of computer assisted radiology and surgery*, *12*(1), 1–11.

Meli, L., Pacchierotti, C., Salvietti, G., Chinello, F., Maisto, M., De Luca, A., & Prattichizzo, D. (2018). Combining wearable finger haptics and augmented reality: User evaluation using an external camera and the microsoft hololens. *IEEE Robotics and Automation Letters*, *3*(4), 4297–4304.

Runz, M., Buffier, M., & Agapito, L. (2018). Maskfusion: Real-time recognition, tracking and reconstruction of multiple moving objects. In *2018 ieee international symposium on mixed and augmented reality (ismar)* (pp. 10–20).

Zhang, W., Han, B., & Hui, P. (2018). Jaguar: Low latency mobile augmented reality with flexible tracking. In *2018 acm multimedia conference on multimedia conference* (pp. 355–363).