ARTEMIS-FlexTrack: Immersive Surgical Telementoring with Flexible Tool Tracking

Zhuoqun Robin Xu, Danilo Gasques

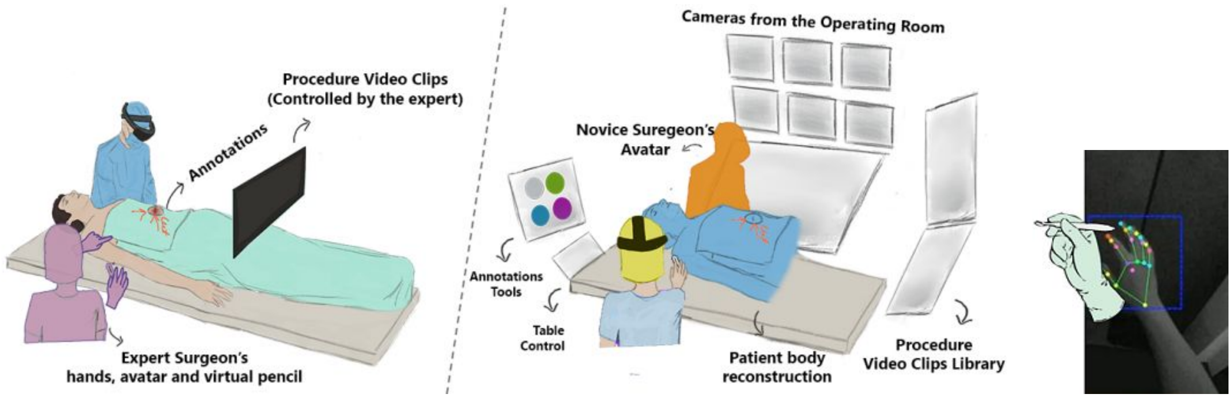

Figure 1. Artistic rendering of ARTEMIS and FlexTrack features. Left: Novice Surgeon in Mixed Reality receiving help from a remote expert. Middle: Remote Expert Surgeon in VR interacting with 3D point-cloud of patient, and engaging with the novice on a surgical procedure. Right: Surgeon use FlexTrack to project the actual tools virtually into the ARTEMIS with hand tracking

***Abstract*-** A novel system here in UC San Diego Health has been established to explore how Virtual/Mixed Reality (VR/MR) can improve collaboration in time-constrained environments such as surgery. Due to incompatibility between existing tracking adaptors and unconventional tools used in surgical space, FlexTrack, is a portable and low-power wireless accessory allowed: 6 Degree-of-Freedom (DoF) sensibility of location/orientation based on universal hand tracking system and high-fidelity IMU, and the flexible adaptability to mount on most surgical tools. It enables researchers to incorporate 3D annotations and gestures upon portable VR/MR devices with tools projected into the virtual operation while maintaining physical feedback. Benchmark shows that our system reaches x% accuracy of other tracking solutions while reducing y% time consumed in the preparation stage.

Index Terms- Virtual Reality; Mixed Reality; Tools Tracking; Interactive Visualization; Telementoring.

I. Introduction

Traumatic injuries often require urgent action, but medical expertise may not always be available nearby. In such situations, telemedicine has taken place around the world allowing the expert surgeons to guide novice to perform successful operations at different geographical locations. The golden hour following a traumatic injury holds the highest likelihood where surgical treatment may prevent mortality and morbidity. However, the increasing occurrence of large-scale disasters overwhelms local medical systems and patients often find themselves without timely access to medical expertises. Within the Military Health System, the operational medics also face similar challenges when caring for combat patients in the environment of the field [1].

To respond to this problem, medical care experts are actively exploring telemedicine, which typically attempts to use synchronous audiovisual communication. Unfortunately, most telemedicines until now were typically based on synchronous audiovisual communication, which restrained the ability of medical experts to collaborate efficiently and effectively in physical tasks, such as trauma care. Current telementorship is still based on pure video-based communication, while telementoring on surgery requires more than just 2D images that is typically provided by most telemedicine platforms [2]. Level of details is critical to meet the requirement of a successful operation. Surgical telementoring entails continuous and ad hoc support of remote surgeons in the operating room, and requires remote experts to get a situational awareness of the patients' condition to best understand how to help. In the traditional remote surgery, the remote experts typically have to map actions they would normally express with a combination of gestures, dialogues and actions, into video-based interactions and more verbalization. Novices operating on the real patient have an excessive burden to map instructions from a 2D screen to the actual operating field, with increased possibilities to make unwanted consequences in the process.

Virtual Reality (VR) and Mixed Reality (MR) have been popularized and demonstrated at scale through smartphone-based immersive experience (eg. Ingress, Pokemon Go) and consumer VR/MR headsets (e.g. Oculus Rift/Quest, HTC Vive, Microsoft HoloLens). These applications and devices offer immersive, multiplayer gaming experiences where signal latency and sustained real-time interaction under constrained bandwidth is critical. As a technology, they are now primed to revolutionize telementoring care capabilities, addressing the serious gaps in current healthcare emergency response for complex and challenging crises. With these recent advances and the increased availability of commodity VR and MR hardware, researchers have started exploring their use also in physical task collaborative problems. These technologies have the potential to improve collaboration as they can introduce new channels of communication and use contextual cues from spatial information.

Previous works showed that Mixed-Reality (MR) technology could help guide or teach physical activities. A novel system here in UC San Diego, ARTEMIS (Augmented Reality Technology-Enabled reMote Integrated Surgery), has been established to explore how MR can improve collaboration in time-constrained environments such as surgery. ARTEMIS enables skilled surgeons and novices to work together within the same immersive virtual space using a mixture of MR and VR technologies (Fig. 1). However, due to the nature of the varied and unconventional tools used in the surgical space, a tracking solution without the excessive outer sensor, as known as In-Side-Out tracking, is eagerly needed for the system. This paper introduces, a portable tracking solution, FlexTrack, which is designed to come with a minimal-size wireless tracker devices that enables multiple features:

1) 6 DoF sensibility of its location/orientation, and rough touch points where the user holds/grabs on it;

2) The communication ability through standard Bluetooth BLE services to link with different devices and report its sensor data in high frequency

3) the adaptability to mount on top of different surgical tools that provide realistic physics feedback and virtual presence in the challenging surgery situation.

The tracking system enables surgeons to create and incorporate 3D annotations and hand gestures, and can be projected into the surgical field for the mentor in Virtual Reality while showing visual aids to the mentee in Augmented Reality. Expert surgeons in remote sites use Virtual Reality to access a 3D reconstruction of a patient's body, and instruct novice surgeons on complex procedures using different tools projected as if they were demoing together in the operating room. Novice surgeons in the field can focus on saving the patient's life while being guided by the remote expert's holographic avatar and tools created by an intuitive Mixed Reality interface.

FlexTrack, along with the ARTEMIS project, critically improves on previous works in two ways. First, a human-centered approach to co-design a collaborative trauma care system with surgeons and medical residents (experts and novices) is ported into a relatively compact and portable system; it allows the researchers to understand and articulate the need for specific affordances in our system with convenient usage and fast interaction. Second, FlexTrack grants ARTEMIS, the first immersive VR/MR operating telementoring system with greater choices of visualization and interaction, where they can use most surgical tools dynamically visualized in the portable immersive experience and interact with a 3D reconstruction of the patient body to guide novice surgeons in Mixed Reality. ARTEMIS-FlexTrack allows local surgeons to focus on the patient and the tasks at hand, rather than having to interact with complicated AR interfaces.

2. Technical Overview

By going over iterative design and development work with the previous research logs and codes in the past month, the new ARTEMIS-FlexTrack system was successfully implemented together into the Microsoft Universal Windows Platform (UWP) and Oculus Mobile platform. ARTEMIS-FlexTrack enables skilled surgeons and novices to work together in the same virtual space and approaches the problem of remote collaboration through a hybrid interface: expert surgeons in remote sites use Virtual Reality to access a 3D reconstruction of a patient's body and instruct novice surgeons on complex procedures; novice surgeons in the field focus on saving the patient's life while being guided through an intuitive Augmented Reality interface.

From now on, the expert interface will be referred to as ARTEMIS VR and the novice interface as ARTEMIS AR. The novice bedside environment is equipped with a Microsoft HoloLens v1 [3] worn by the novice surgeon,1 5x depth-cameras to capture the 3D scene (1x Microsoft Azure Kinect [4] placed on top of the bed and attached to the surgical lamp, 2x Intel RealSense cameras [5] in the corners of the room, and 2x Intel RealSense cameras on wheels movable in the Operation Room), and an OptiTrack optical marker system [6] to track the movements of objects and people in the room (markers are attached to the HoloLens, the Kinect camera, and the surgical table).

The expert's remote environment is equipped with a portable Virtual Reality headset (Oculus Quest) which is completely untethered, hands and objects tracking for the expert surgeon based on Oculus Quest Hand Tracking Integration and FlexTrack API, and an single-board microcontrollers (arduino nano 33 IoT) used for reporting the tools accelerator and gyroscope data to FlexTrack API running in the platform. Figure 2 showcases the overview of ARTEMIS-FlexTrack communication and implementation.

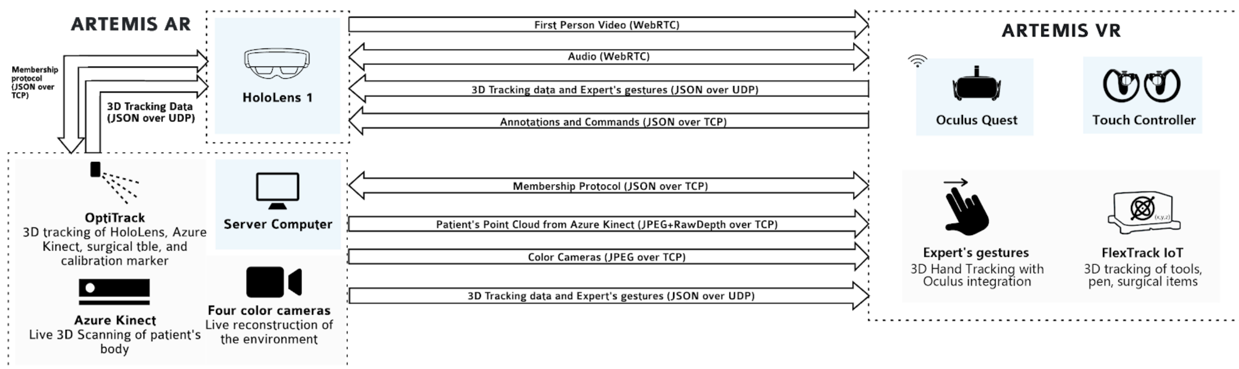

Figure 2. ARTEMIS is composed of two different environments: ARTEMIS AR and ARTEMIS VR . This diagram shows the origin and direction of data flowing and protocol usage from each environment

Novice Surgeon's Interface

The novice surgeon's main goal is to operate on the patient. To avoid distractions, the ARTEMIS AR interface components are passive, and by design the novice surgeon is not able to directly interact with the interface. All the features described here are authored and controlled remotely by the expert; for instance if the novices need to hide annotations or play a procedure clip, then they can request the expert surgeon to do so. This decision emerged directly from the previous research logwhere it became clear that novices were not able to directly interact with an AR application while operating on a patient. The hypothesis is that this resulting interface will not overwhelm the novice surgeons nor distract them from their operating tasks. With the FlexTrack, ARTEMIS AR would be able to visualize the tool categories and show specific information that will be needed for instruction.

The novice surgeons are able to see three main holographic representations in front of them (Fig. 3): (a) the expert's avatar, hands and tools, (b) a remote tool and 3D annotations, and (c) procedural video clips. In addition, the novice surgeon is able to provide direct views of the patient and the surgery to the remote expert, by manipulating the position of the Kinect camera and by directly attending to regions of interest with the HoloLens device's camera.

Expert's Avatar and Hands – The novice surgeon can see both the expert surgeon's location, their hands and tools on hand (Fig. 3a). This enables the expert surgeon to communicate through gestures and tools, for example, by pointing to a location on the patient body or by showing how to handle a surgical tool. The expert surgeon's avatar automatically disappears if the novice surgeon walks into their virtual location. This interaction allows the novice surgeon to repeat what the expert surgeon is gesturing in a more intuitive way as they are both doing it from the same point of view. In other words, the expert surgeon's hands can act as a second pair of hands that originate from the novice surgeon's body and guide the novice step-by-step.

3D Pen Tools and Annotations – 3D annotations (Fig. 3b) allow the expert surgeons to instruct the novice by 3D sketching over the patient body. Because these annotations are in 3D, they can directly communicate depth, length, and area, which are critical for surgical procedures such as incisions, tracheostomies, thoracotomies, etc. To allow for additional interaction space for the remote expert, 3D annotations can also happen in mid-air and are not limited to the patient body. To facilitate the novice surgeon's understanding of where the annotations will show up, if the remote surgeon is holding a pen, FlexTrack API will inform ARTEMIS AR to show a 3D model of a pen. This is the same 3D pen that expert surgeons see in their VR interface, and it is shown in the hands of the expert surgeon's avatar when in use.

Procedure video clips – Procedure clips are an additional resource used to support guidance during remote telementoring. They are instructional, short video clips of different steps of specific surgical procedures that are available for the expert to show to the novice when needed (Fig. 3c). These video clips show up as a floating screen on top of a surgical table (Fig. 1) and always face the novice surgeon. They keep repeating until disabled by the expert, and typically contain audio instructions that can be muted by the expert surgeon if needed. The instruction command can be also triggered by the FlexTrack system of showing the specific tool usage guide.

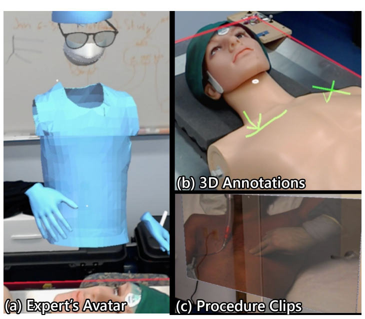

Fig. 3

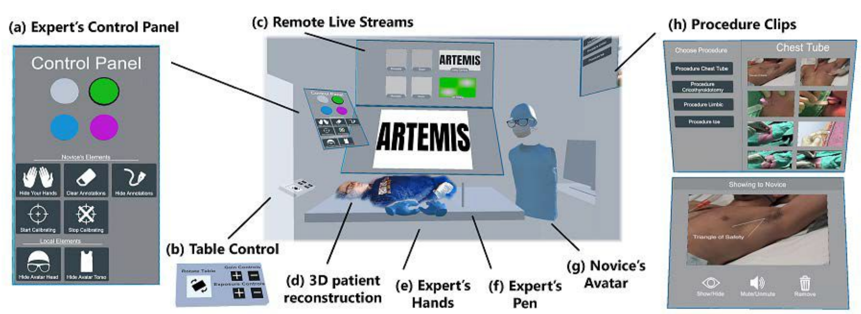

Fig. 4

Figure 3. ARTEMIS AR Interface - Novice surgeon's interface in Mixed Reality.

Figure 4. ARTEMIS VR - Expert surgeon's interface in Virtual Reality. At the center, the main view that the expert surgeon sees. (a) Expert's control panel with colors for 3D annotations and buttons to control novice's calibration and visibility of hands. (b) Table control to adjust orientation and camera exposure and gain. (c) Remote Live Streams with two moveable cameras (RealSense on wheels), two fixed cameras (RealSense), one patient focused camera (Kinect) and a first-person view from the novice's HMD (HoloLens). (d) Real-time 3D Patient Visualization. (e) Expert's Hands as seen in VR. (f) Expert's Pen Tool. (g) Novice's Avatar (when visible). (h) Expanded View of the Procedure Clips (the lower part is only visible when the expert is watching a procedure clip with the novice).

Expert Surgeon's Interface

The expert surgeon's Virtual Reality interface provides surgeons with a virtual operating room. In this operating room, the 3D reconstruction of the patient is at the center of the stage, surrounded by tools and VR camera views (from the Kinect, RealSense and HoloLens cameras in novice side), which is designed to make the expert surgeons' interaction with ARTEMIS more efficient, and enable the expert to successfully explain procedural and conceptual steps of the surgery being performed. Figure 4 shows the entire interface and highlights its key components. The expert surgeon interacts with the interface via a laser pointer, but unlike most VR experiences, this laser pointer is implemented through an actual physical pen, and not as a virtual tool they “grab” with VR controllers. ARTEMIS VR does not use regular VR controllers to facilitate the use of gestures and tools by an expert surgeon that is most likely new to VR experiences. Thus, instead of having users learn how to map controller buttons to actions or commands with non intuitive bulky controllers, the expert surgeons use their real hand in the designated Hand Tracking system (Oculus Hand Tracking API). Their surgical tool can be a pen-like tool that they can hold and feel with their hands, and can point, select, ordraw with different specific keys.

Control Panel – The expert’s control panel (Fig. 4a) provides four types of tools: (i) annotation controls and color palette,(ii) local space controls, (iii) novice surgeon’s interface controls,and (iv) calibration controls. Through the annotation controls and color palette, the expert surgeons can change the color of the pen before making a 3D annotation. They can also erase annotations on both their side and the novice surgeon's side. The local space controls allows experts to show and hide the novice’s head or torso. The Novice surgeon’s interface control allows experts to change the visibility of their hands and annotations on the novice surgeon’s space. Finally, the calibration controls allows experts to work with the novice surgeon to improve the alignment of annotations as seen from the novice surgeon’s side.

Table Control – This interface serves two purposes (Fig. 4b); the Rotate Table flips the orientation of the patient so that the expert surgeon can look at the surgical field from two different points of view; the Gain and Exposure controls allow the expert surgeon to control settings of the remote Kinect camera, adjusting the visibility of the patient as needed.

Remote Live Streams – This interface (Fig. 4c) shows six different live video streams to the expert surgeon in the top part. Two displays show cameras attached to rolling wheels that the novice surgeon can move around the operating room. Two displays show cameras located at opposite corners of the operating room. One display shows the internal camera of the head-mounted display, and the last display shows the patient as seen by the depth camera attached to the surgical lamp. The expert surgeon can use the pen as a laser pointer or designated keys defined in FlexTrack to select and display any of these six video streams in the bigger display at the bottom. The location and layout of these displays allow for the user to see both the patient reconstruction as well as the video displayed in the bigger screen without the need to switch focus or move their heads.

3D Patient Reconstruction – This is the central interface available to the expert surgeon to guide the novice through specific surgical procedures (Fig. 4d). Through a point-cloud view, the expert surgeon can see the patient in a three-dimensional rendering that keeps real-world proportions. The point cloud view is a real-world live representation of the patient and it is placed on top of an actual table in the remote expert’s environment. By looking at the point cloud the expert can see in real-time what is happening to the patient, and can interact with the patient representation by placing hands on particular parts of the body, and by annotating the body using 3D annotations. Both hand maneuvers and 3D annotations show up in real-time in the AR view of the novice.

Novice Surgeon’s Avatar – The novice’s avatar (Fig. 6f) shows the location of the novice surgeon with respect to the surgical table at all times. Experts use the avatar as a communication and interaction anchor when guiding the novice through their procedures.

Procedure Clips Control – This interface provides a video library containing a number of surgical procedure video clips for different procedures (Fig. 6h). By selecting one of the options, a series of video clips pop up on the right side of the interface (for instance the chest tube procedure); when the expert surgeon selects one of these video clips, it displays on the larger screen at the bottom of the interface, and it plays synchronously on both the expert side in VR, and as holographic representations on the novice surgeon’s side (Fig. 3c). The expert surgeon can show, hide, pause, mute, and remove this interface from both the expert’s and the novice’s side.

3. Implementation and Milestone

As introduced earlier, ARTEMIS consists of two separate spaces: ARTEMIS AR and ARTEMIS VR. ARTEMIS AR encompasses the novice surgeon's AR head-mounted display and the server that connects to the cameras and trackers in the operating room. ARTEMIS VR encompasses the tracking hardware including FlexTrack used for the expert surgeon. Each computing device (HoloLens, Server Computer, and Oculus Quest with Arduino IoT) runs applications developed with Unity 2019.3, Visual Studio Code and Arduino IDE. Figure 2 summarizes the ARTEMIS' hardwares and the streams/protocols of data.

ARTEMIS AR uses HoloLens v1 [4] as the AR headset and a standalone computer (Server Computer). HoloLens sends audio and video directly to ARTEMIS VR through WebRTC. It also receives tracking data and commands directly from the VR computer. We also use a separate computer, the Server Computer, to encode and stream data from the many cameras installed in the operating room. We use the Azure Kinect depth camera to create the patient's point-cloud at resolution of 1280x720, 30fps. The Server computer also encodes and streams frames from four Intel RealSense color cameras (2 on rolling wheels, 2 in the corners of the room) at a resolution of 800x600. Finally, we use five OptiTrack Prime 13 motion capture cameras to cover the entire surgical space. These cameras track HoloLens, the surgical table, the surgical lamp, and the calibration marker used to realign annotations. Tracking data from these cameras flow from OptiTrack's Motive to the Server Computer and then to both the HoloLens and the VR Computer through a custom protocol (Fig. 2, left).

ARTEMIS VR uses an untethered Oculus Quest as the VR headset. However rather than no-FlexTrack-implemented AR side, it does not require massive setups of OptiTrack motion capture cameras to track the headset. The head motion, the hand, the tools and a physical table that serves as a proxy to the surgical table (Fig. 8 shows the FlexTrack IoT sensors attached to the tools). The devices are hardware flashed with customized firmware that connect to the mobile VR headset through Bluetooth 4.1.

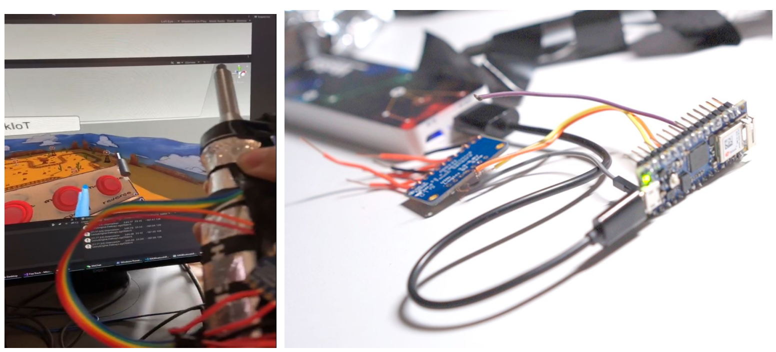

Figure 5. ARTEMIS VR Input Interfaces - FlexTrack IoT. Expert surgeons interact with the interface through hands and a physical object attached with FlexTrack sensors. Left: a Tools integrated into FlexTrack API; Right: FlexTrack Sensor, connected with 4000mAh power bank

There are two main objectives of ARTEMIS-FlexTrack achieved:

a. Remote Annotations/Sending Command ability – For better instruction and understanding to the novice surgeon on performing the correct operation procedure, the remote expert can now use the FlexTrack IoT sensors to attached on needed tools to click and make certain commands such as annotating the 3-dimensions (3D) patient representation in front of the surgeon. Telestration in 3D can be enabled by projecting the annotations in real-time as Mixed-Reality holograms in front of the novice who is wearing Microsoft HoloLens. In addition, FlexTrack has multiple customizable capacitive touch sensors to allow the surgeons to make other commands like change annotation colors or enable voice call etc.

b. Projection on the Surgical Field – Particular maneuvers around the patient body, as well as precise indication of specific parts of the body, require the projection of tools movements onto the surgical fields. FlexTrack enables different tools or objects to be tracked their position in the 3D space, and it does not require excessive tracking calibration and redundant diagnosis procedures like the previous versions.

c. Easy adaptability – compared to traditional VR controllers, the FlexTrack is smaller/lighter and doesn't take too much excessive weight to cause unwanted distraction when surgeons learn the tools with this attachment. With the limitation of non-exclusive design of power supply, the size of FlexTrack sensor can be further reduced with a customized on-boarded power management chip. But it clearly demos a relatively small design which is flexible and portable enough to fit on surgical tools.

The project successfully implemented the Oculus Mobile VR API which offers a great portability by its all-in-one design of relative good VR rendering speed and, most importantly, the hand tracking ability that allows hands and finger movements to be projected in the VR space without any external tracker. Combining the rough acceleration/orientation and the relative hand touch points reported by FlexTrack's IMU/capacitive sensor with the hand location, ARTEMIS can reverse deduce the tool's position and show the relative accurate presence of the tools. Novice surgeon is able to follow the specific indications of tools and hands figures moving by the remote expert, and mirror the indicated movement as necessary.

4. Challenges

In developing ARTEMIS, there are 3 key technical challenges: (1) Oculus Mobile VR platform limitations, (2) networking through wifi and bluetooth, (3) calibrating the different coordinate systems.

(1) Overcoming Oculus Mobile VR Limitations

Released to the public in the mid of 2019, Oculus Quest was one of most popular untethered 6DoF VR devices to use inside-out global sensor fusion for devices tracking. However, its capability to track itself in space, makes Oculus integration with external tracking systems like FlexTrack quite challenging. To check that devices are properly integrated and therefore ensure smooth user experience, an interface for the expert surgeon is created to verify that calibration of the Hand Tracking API to FlexTrack is accurate. In addition, as an untethered device, Oculus runs on a battery that lasts around 3-4 hours during continuous use, but previous study indicates that the surgeons were worried that some procedures could last longer than that. To allow surgeons to quickly switch to a new device, Multiple Oculus Quest will be connected to the Server that acts as a hub and advertises that a new MR/VR display is available which enables the devices exhausted their batteries to be quickly swapped without the interruption of the operation. With comparison, FlexTrack Sensors only take up to 30mA which grants over an whole day of regular usage with current power solution.

(2) networking through wifi and bluetooth

Unity has poor support for custom, high-throughput networking protocols. With all relevant data going and coming through the network, we implemented a networking library for Unity with support for Python, C++, and other platforms such as NodeJS. The Unity counterpart of the library provides a high-level interface to TCP clients and servers as well as UDP sockets. It also receives and decodes network packets in an external thread to avoid impacting rendering performance. Moreover, our networking library allows throttling network streams and dropping old packets that are not relevant anymore. With the exception of the WebRTC audio and video streams, we implemented all the network streams described in Figure 10 with this library. The networking library is available as an open source project at http://anonymized.com.

Unity also has poor bluetooth library support for mobile devices, especially Oculus Quest in customized Android platforms which require non-standard authentication of bluetooth usage. I implemented a customized UUID for peripheral devices using BLE services and specifically wrote the firmware that has later been flashed into the Arduino Nano 33 IoT boards. I also took the reference of the library code in github created by Victor Cheung. (https://github.com/thisisvictor/UnityBLE) I successfully implemented the bluetooth communication ability on Unity to recognize the FlexTrack devices and testing done using the Oculus Quest.

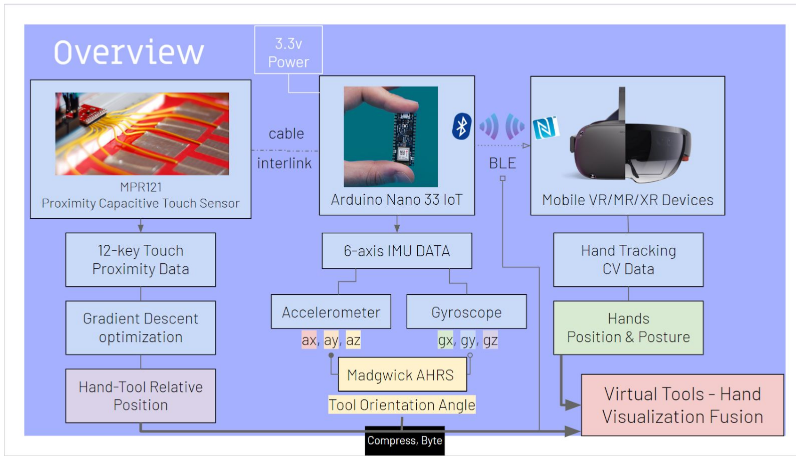

Figure 6. FlexTrack Network overview. The FlexTrack IoT calculates only the orientation fusion algorithm and mostly serves as the data reporter of IMU data and touch key info, due to the limited computing power and battery life.

(3) Calibrating Different Coordinate Systems

Showing tools location requires us to know their location with respect to the Oculus coordinate system. Unfortunately, Oculus is unable to track the tool directly. It relies on Oculus Hand Tracking API to track both hand position and tools coordinate in the Flextrack system with its internal IMU. The different coordinate systems and required transformations are summarized in Figure 6. Overall, there are two main transformations needed to establish a coordinate system for the tools. This requires a single, offline calibration between FlexTrack. So I created a reset button to allow the user to continue repositioning the tools by touching the reset button to find the perfect alignment of actual tools feedback and virtual presence in the calibration, which mostly worked as the purpose.

5. Group Member

Zhuoqun Xu - the ARTEMIS-Mobile and ARTEMIS-FlexTrack developer, researcher, paper writer

Danilo Gasques - the consultant and QA tester

6. Conclusion

This report introduced ARTEMIS, a Mixed-Reality system for immersive surgical telementoring. ARTEMIS ad-dresses the need of high-fidelity remote collaboration in time-critical environments, to allow on-site medical personnel that are not trained in specific surgical procedures to respond to an emergency, and perform complex surgeries on critical patients under direct guidance from remote experts. The immersive mixed-reality environments allows experts to work in the same virtual space, side-by-side with novices, and get access to crit-ical information in real-time and in 3D.

ARTEMIS contributes several novel aspects to research in HCI, specifically in terms of user interface software and technology for mixed reality. It shows the important design, and details how it allowed people to both understand design constraints in the setting of time-critical collaborative environments, and at the same time how it supported exploration of new technology and novel user interfaces for remote interaction in this space. It uses surgery as the use case, but the described interaction techniques are general and broad. Certainly the ARTEMIS system could be used to telementor any number of physical actions that require a high-degree of fi-delity and accuracy (down to millimeter scale). Finally FlexTrack is implemented as one of the interaction techniques enabled the creation of a unique system that brings together AR and VR within a novel interface for remote collaboration. The qualitative evaluation of ARTEMIS in a real-world surgery scenario out-lined a number of important aspects that will be key for the further development of immersive collaborative environments for time-critical applications also in the future.

While much can be achieved in the future with a system like ARTEMIS, I expect this study to allow us to understand if the hyperrealistic remote surgery platform could be used in future training, and also to evaluate other virtual health tools in the provision of emergency care. And it can also be able to prompt other usages in the many portable VR experiences such as remote office and general education purposes.

7. Reference

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