# A Distributed Collaborative Simulation Environment for Orthopedic Surgical Training


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*Abstract*— **The use of Virtual Reality (VR) simulators has increased rapidly in the field of medical surgery for training purposes. In this paper, the design and development of a Virtual Surgical Environment (VSE) for training residents in an orthopaedic surgical process called Less Invasive Stabilization System (LISS) surgery is discussed; LISS plating surgery is a process used to address fractures of the femur bone. The development of such virtual environments for educational and training purposes will accelerate and supplement existing training approaches enabling medical residents to be better prepared to serve the surgical needs of the general public. One of the important aspects of the VSE is that it is a network based simulator. Our approach explores the potential of emerging Next Generation Internet frameworks and technologies to support such distributed interaction contexts. A discussion of the validation activities is also presented, which highlights the effectiveness of the VSE for teaching medical residents and students.**



***Keywords— virtual reality, orthopaedic simulator, LISS plating.***


## I. Introduction

Current trends for medical/health related education include the use of simulations in a range of areas such as heart surgery, laparoscopic surgery and other domains. Recently, there has been a growing number of research efforts which have explored the use of Virtual Reality (VR) technology in developing simulation environments to facilitate training of residents and surgeons in various medical procedures, including surgery. In this paper, the focus is on the creation of a VR based simulation environment for orthopaedic surgery (specifically a process called LISS plating to address fractures of the femur); the creation of a virtual surgical environment will enable residents and budding surgeons to learn the appropriate way of managing various conditions with safety considerations to the residents and patients. It will also provide an avenue to study, propose and compare alternative ways to surgically respond to a specific medical condition. Such virtual environments are essential to educating/training young budding surgeons. The traditional way of surgical teaching involves residents first merely observing a 'live' surgery and then gradually progressing to assisting experienced surgeons. Developing such virtual environments for educational and training purposes will accelerate and supplement existing approaches used to train medical doctors. Better preparation and providing more surgical training opportunities are other benefits of adopting simulator based training approaches.

## II. Literature Review

This section provides a brief discussion on the literature relating to VR based environments for orthopaedic surgery and other surgical domains. A brief review of collaborative virtual simulators is also presented.

Qin et al. [2] developed a framework for simulating the soft tissue deformation in an orthopaedic surgery. The experimental results have shown the practicability of their model both in providing an interactive and realistic model of human tissue deformations. Delp and Loan [3] created a graphical software, called SIMM (Software for Interactive Musculoskeletal Modeling), which can be used to develop and analyze musculoskeletal models. Tsai et al [4] have developed a virtual reality orthopaedic simulator which can simulate different orthopaedic procedures including arthroplasty, corrective and open osteotomy, fusion, and open reduction. In [5-9], virtual reality based simulators for heart surgery are described. In [10], an interactive simulator is described for real-time and tactile catheter navigation. Modeling of drilling forces are described in [11, 12]. Sourina et al [13] developed a virtual orthopaedic surgery simulator, called Virtual Bone Setter, which can be used to train the surgery residents in correcting bone fractures. In [14], the development of a distributed virtual environment for orthopaedic surgery is detailed. An information model of the LISS surgical process was first developed by closely interacting and interviewing orthopaedic surgeons [15]. In [16], a virtual reality based training system for arthroscopic surgery is elaborated . Laparoscopic Surgery is another surgical field in which VR based simulators have been introduced [17 – 20]. Other papers have discussed the attitude of surgeons towards the role of VR-based simulators and their use as training and planning tools in surgeries [21, 22].

The role of expert surgeons as knowledge sources for understanding a given surgical process has not been emphasized in prior research efforts. In this research, the expert


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surgeons played a key role in understanding the complexities of the target surgical processes, which in turn was used as the basis to create an information centric model of the target surgical processes (namely, LISS plating surgery). This information centric model, in turn, has played a central role in facilitating a better understanding of the complexities of a surgical process and provided a the contextual basis for adopting a systems engineering approach to the design and development of the surgical simulator discussed in this paper; it should be noted that past research has not focused on such information centric models or adopting such systems engineering oriented approaches. In this research, the information centric model was developed after close interactions with an orthopedic surgeon (Dr. Pirela-Cruz). Dr. Cruz also played an important role during the development and validation of the VSE.

Collaborative virtual environments have been investigated by prior researchers to enable distributed Internet based interactions [35-37]; Morris et al. [32] proposed a collaborative VR based environment for temporal bone surgery. A collaborative surgical system with a haptic interface is discussed in [33]. Paiva et al. [34] described a cloud based collaborative virtual environment for surgical education for managing multiple virtual rooms for training residents. However, Next Generation Internet technologies, including Software Defined Networking (SDN), have not been explored by prior research. The networked based approach supporting distributed interaction discussed in this paper explores Software Defined Networking (SDN) emerging next generation Internet technologies including SDN as part of an initiative related to the Global Environment for Network Innovation (GENI) and US Ignite initiatives. Additional information about these initiatives is provided in section 6.

## III. Overview of the LISS Plating Surgical Process

The scope of training for the developed Virtual Surgical Environment (VSE) is a process involving the Less Invasive Stabilization System (LISS) which supports surgical procedures to address fractures of the femur bone. Before this surgery is carried out, pre-operative planning is performed. Subsequently, the required implant is chosen depending upon the type and the intensity of the fracture. Specific reduction methods are used to place the broken parts of the bone in their natural positions [25]. The LISS plate is then inserted into the appropriate position with the help of an insertion guide. The next and most important step of the surgery is screwing the LISS plate to the bone using different types of surgical screws. After the proper placement of the LISS plate over the femur, the insertion guide is detached. The last step is the closing of the surgical incisions.

## IV. The Process of Designing and Building the VSE

Information modeling based approaches to design and build complex simulation environments for various engineering applications has been reported for other process domains including manufacturing simulation as well as for designing software systems for various domains including manufacturing [26, 27], fixture design [39] and virtual teaming in the context of distributed collaboration [40]. In this research, the information centric model was built using the engineering Enterprise Modeling Language (eEML); as indicated earlier, this information centric model was used to design and build the VSE outlined in this paper. While the eEML modeling language has been used in our approach, other modeling languages (such as IDEF-0 or activity diagrams based on the Unified Modeling Language) can also be used in general to support the overall design and development of surgical simulators. In general, eEML was a modeling language primarily created to help model the process of creating software system for simulation applications, it lends itself to simulation applications [28]. Our earlier work in modeling this process highlighted the advantages of such an approach [27]. The information process model built for creating VSE focused on modeling the following facets: data and information needed to complete various tasks in each of the 5 phases (involved the design and development of the VSE), major constraints influencing the accomplishment of these various tasks, software and physical resources needed for these various tasks as well as final/intermediate outcomes within these five phases.

The Top level view of the information centric (eEML) model of the process of designing, building and validating the VSE is shown in Fig. 1. A multi-disciplinary team comprising of engineers, IT experts and surgeons was involved in the development of the VSE. In general, an eEML model comprises of functional entities and associated attributes vital to identified tasks. Each entity corresponds to a functional task; eg. Entity E1 in Fig. 1 is ‘Understand user requirements.’ For each entity or task, associated attributes were identified which included influencing criteria (IC), performing agents (PA) and decision objects (DO). The IC can be sub-grouped into constraints (CO), information inputs (II) and physical inputs (PI). Teams (T), physical resources (PR) and software resources (SO) are the sub-catagories of PA. The decision objects consist of information outputs (IO) and physical outputs (PO) [27].

A brief description of the five phases involved in building the VSE follows.

Phase 1: Understand user requirements (E1): The focus is to understand users’ preferences and requirements. The VSE project team (see E1, Fig. 1) discussed the requirements with the surgical experts (surgeons) along with their user interface preferences and specifications.

Phase 2: Understand the surgical (process) domain (E2): The VSE design/building team has to become familiar with the target surgical process by reading books, articles, watching videos of LISS plating surgeries and interviewing surgeons, among others. In E2, the output is the surgical domain understanding, which is reflected in eEML process models of LISS plating (this model has been discussed in [15]). Each of the top level processes (E1, etc.) have been decomposed but not included for brevity.

Phase 3: Design the VSE (E3): It involves designing the VSE’s architecture, identifying the major software and user interface modules as well as developing pseudo code of the various functions of the software elements in each module of the VSE.

Phase 4: Build the VSE (E4): The focus is building the VSE using various programming tools, software and VR hardware. Software tools identified in this phase include Unity 3D, Blender and hardware such as the VR Powerwall, haptic devices and computers.

Phase 5: Validate the VSE (E5): This task involves validating the developed VSE by interacting with expert surgeons. Feedback was provided to make changes to the VSE's contents and user interface. Additional details of the validation task is presented in section VII.

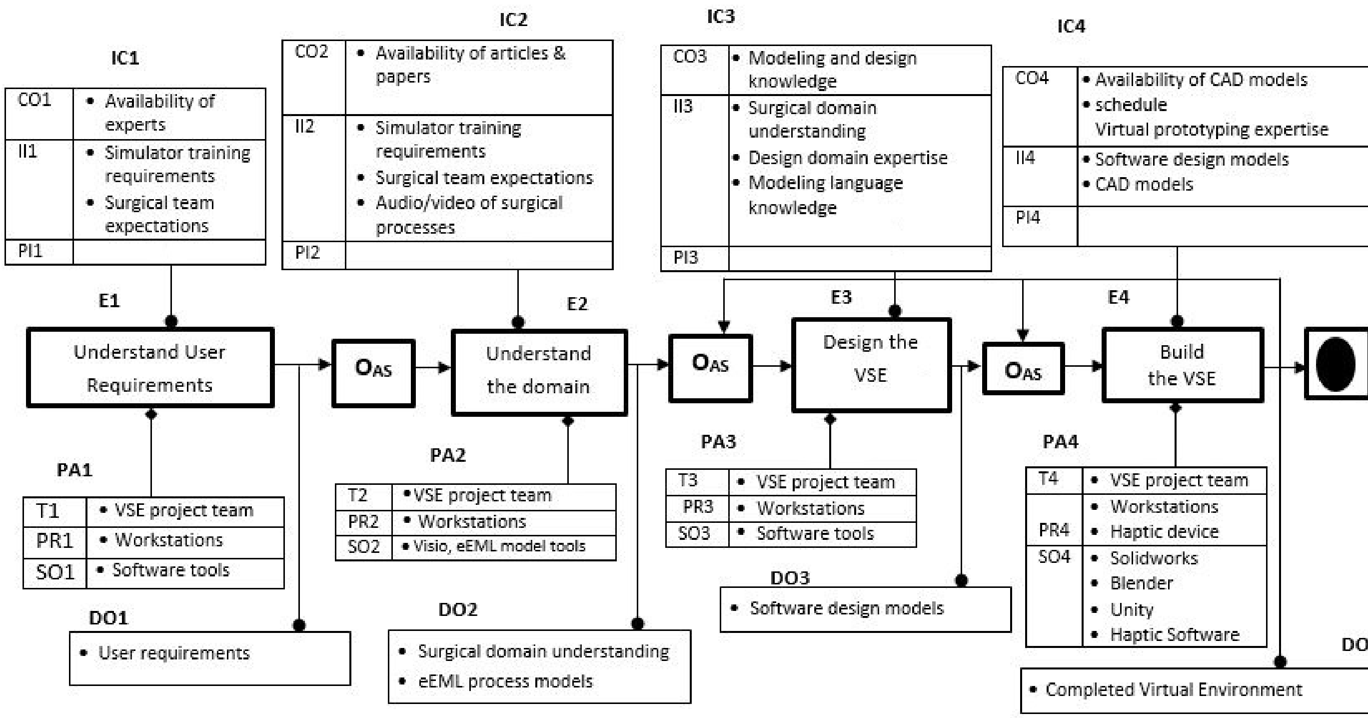


Fig. 1. eEML model showing the VSE development process

## V. The VSE Architecture

The VSE has two modes of training: (a) Automated and (b) Manual. The automated mode provides an overview of the surgical simulation in a step by step manner without much user interaction (except for starting, pausing and stopping a simulation activity).

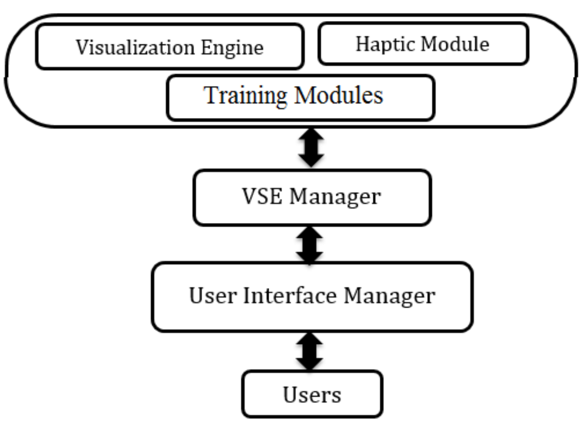


Fig. 2. Architecture of the VSE

A 3D Avatar (see Fig. 5) helps the residents with the training activities interactively (it provides both voice based guidance as well as text based descriptions). The manual mode allows the user to gain control and manually practice the various surgery steps using a haptic device.

The VSE manager is a software component that coordinates interactions between the various modules and the user. It interacts with an orthopaedic training scenario manager which 'loads' and manages the various training scenarios with the user. The VSE also interacts with the network access module which enables multiple users to interact from different locations (see section VI). The VSE has been built using the Unity game engine and C#/Java scripts on a Windows based platform. The Haptic interface has been incorporated to provide a very basic sense of touch and grasping during the practice sessions. The Geomagic Touch™ haptic device (Fig. 3) is used to support this function. In the developed system, accurate modeling of the forces coming into play has not been incorporated. Other researchers (for example) have modeled the magnitude of the drilling forces coming into play during a virtual drilling task [16]; in the VSE, the haptic interface primarily functions to give an intuitive 'feel' for various tasks (such as picking up various plates, placing them accurately in a certain location, etc.). A resident can pick up a tool or any other object by making 'virtual' contact with the object to be moved by pressing and holding the button on the stylus of the haptic device, and then moving the stylus to the desired position.

An overview of the key LISS plating training modules follows.

### A. *The LISS plating assembly module*

In all of the modules of the VSE, there are two modes (automated and manual) as indicated earlier.

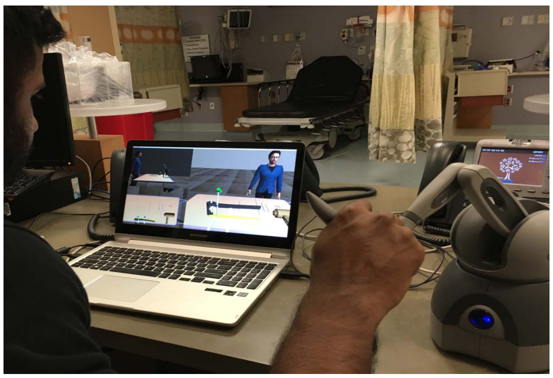

Fig. 3. Medical student practicing assembly of LISS components using the Geomagic Touch ™ haptic device

The objective of the LISS assembly module is to help the resident or budding surgeon to become familiar with assembling the LISS plate from the necessary components. This process is a sequence of key steps; during the design of the VSE, these key steps were identified as process entity elements in the eEML process model; the main simulation outcome that the VSE manager tracks and monitors after each training step is identified as a Decision Outcome. The elided eEML model view corresponding to the process "Assemble LISS plate" is shown in Fig. 4. Fig. 3 provides an image of a user interacting with one of the modules using the Geomagic Touch ™ haptic interface.

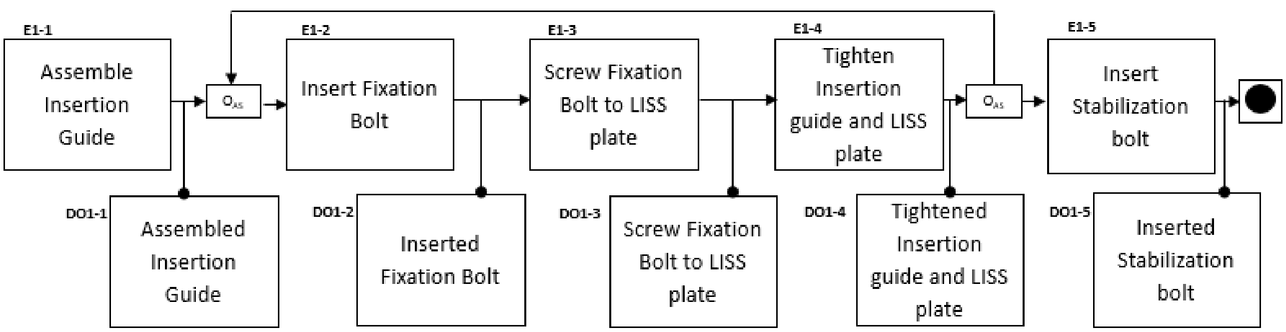


Fig. 4. Elided decompostion of LISS assembly module

### B. *The LISS Insertion Module*

In this module, the residents can learn and practice the insertion techniques in the context of the LISS plate based surgical process. The assembled plate is inserted between the vastus lateralis and the periosteum with the assistance of the LISS insertion guide.

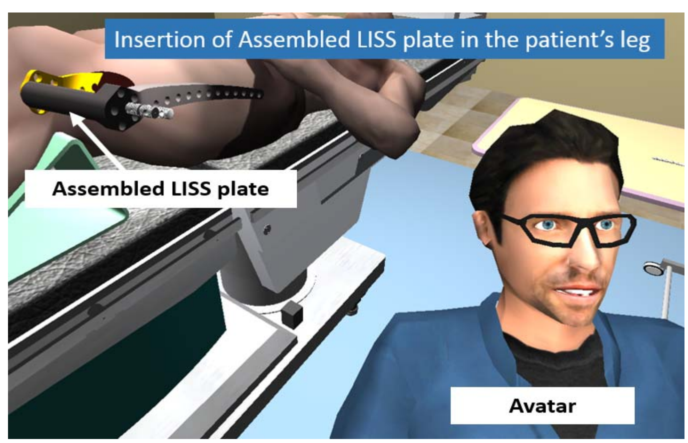


Fig. 5. LISS plate insertion

In the manual mode, the residents practice the various steps of the insertion module with the help of the haptic device (Fig.5)

### C. *Position Training Module*

The positioning of the plate in between the distal and proximal is an important step for fracture reduction of the femur. The position training module uses a red/green color indication scheme to support training activities involving placing the LISS plate in the proper position and orientation.


Fig. 6. Position Training module

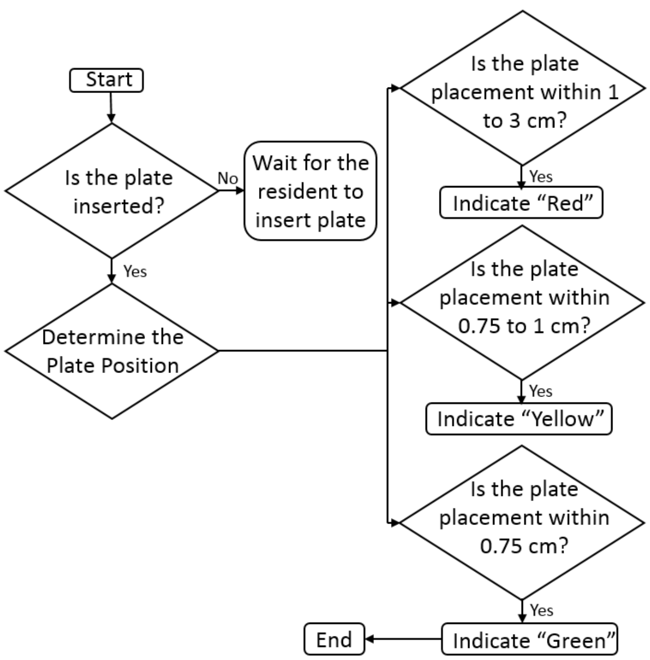


Fig. 7. Flowchart for designing the position training module

Residents use the haptic interface and practice placing the LISS plate in the correct position and orientation. The correct positioning zone is a small zone of 0.75cm in diameter. When the implant is in the recommended position, the color indicator turns green. When it is placed in the wrong position/orientation, a red light appears as shown in Fig 6. A detailed flowchart of the underlying approach is shown in Fig. 7.

### D. *Fracture Reduction Module*

The fracture reduction module demonstrates the reduction of fracture using several steps. Reduction is another important step in the overall process. The simulator highlights the preferred approach to resolve target fractures using K-wire and pull reduction instruments. Fig. 8 shows the view of the fracture reduction module in the VSE.

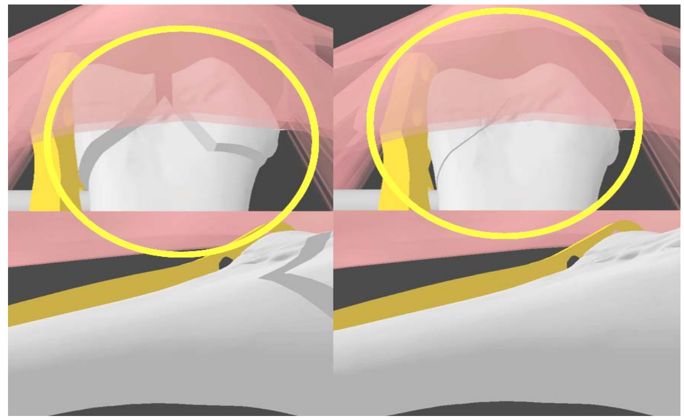

Fig. 8. Fracture views (a) left, before (b) right, after fracture reduction

## VI. NETWORK BASED SIMULATION ENVIRONMENT

The simulation environment developed uses Next Generation Internet technologies related to the GENI initiative in the US. The Global Environment for Network Innovations (GENI) [29, 31] initiative (under the auspices of the National Science Foundation NSF) is a national initiative focusing on the design of the Next Generation Internet technologies aimed at providing multi-gigabit bandwidth and low latency capabilities while also adopting software-defined networking (SDN) principles. SDN separates network control and forwarding functions which enables network control to be directly programmable (and ideal for today's dynamic low latency applications [38]). The development of this network based simulator was part of a GENI and US Ignite project. The US Ignite can be described as a national initiative dealing with deployment of next generation cyber applications in six areas of priority including health care, education, energy, transportation, manufacturing and public safety.

In our training approach, there are two modes of interacting with the VSE: (a) medical residents can access and learn directly with the VSE from remote locations, (b) the second mode involves collaborative learning and training involving an expert surgeon at one location and a medical student at another location. An overview of the next generation SDN based architecture and approach is provided in this section. The distributed surgical training application has been implemented using the 3D Unity platform. VSE uses a popular and easy-to-use platform for simulation and other gaming applications called Unity. In the Unity's multi-player architecture, participant can be a medical resident or expert surgeon and can be referred to as a simulation client (SC). The simulation server (SS) has several critical coordination roles in this architecture. A SC joins the simulation by first registering with the SS. If the simulation session is ongoing when a SC joins the SS, sequence of messages with the new SC to synchronize the state of the SC to that of the other SCs is initiated by the SS. There will be some latency due to communication delays in this architecture. As the Unity based architecture is susceptible to single point failure of the SS, if the SS fails and/or if network connection to the SS fails, the entire system fails and all SCs are deregistered and disconnected, which is not acceptable in the surgery context. The players are the surgeon and the trainees (students, residents and others) in the surgical training application context. They are referred to (for discussions) generically as telemedicine client (TMC)s in this section. To maintain consistency, only one TMC has a ``token'' at any given time that gives him/her the right to modify the state (e.g., perform a surgical step); the other TMCs can observe the changes being made by the "TMC with the token." A command interface allows a TMC with the token to 'pass the token' to any other TMC (such as from a surgeon to a trainee or another participant). Since Unity is not an open-source platform, it is not possible to modify its libraries to support resiliency against connection failures to the telemedicine server (TMS). Since such a support is important in telemedicine applications, using Software Defined Networking (SDN) helped in improving resiliency to TMS failures.

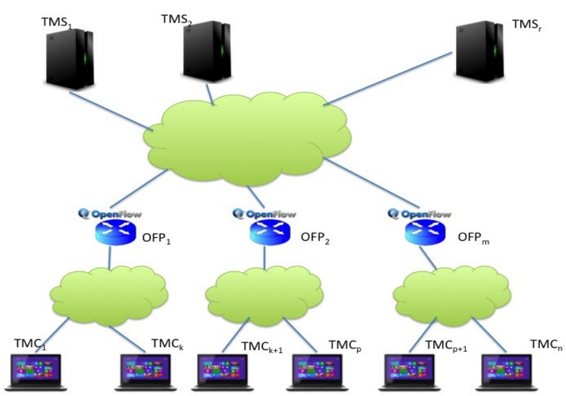


Fig. 9. Architecture for the telemedicine surgical application that supports resiliency to server and network failures. TMS is the telemedicine server, TMC(s) are telemedicine clients, and OFP(s) are OpenFlow switch based proxies.

Fig. 9 shows the SDN-integrated architecture of our surgical application. There are *r* redundant TMS in this architecture. Failure to connect to up to *r-1* TMS can be seamlessly tolerated in this architecture. To support this, the TMCs do not connect directly to a TMS. Each of the TMCs connect to the TMSs via proxies implemented by SDN switches (OFP) (realized through OpenFlow). If there are m OFPs, then the TMCs are partitioned into m groups; using one of the OFPs, each group connects to the TMSs. The OFPs play a crucial role in providing failure resiliency without introducing much latency. Using SDN principles helps increase the the resiliency to TMS failures.

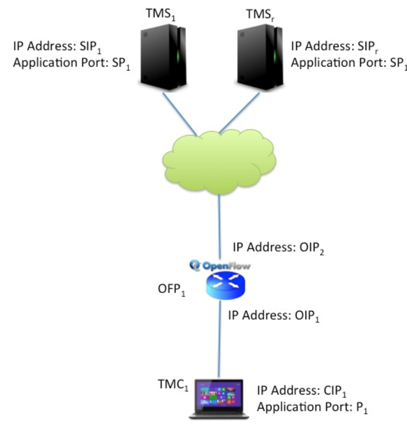


Fig. 10. Portion of the telemedicine surgical architecture corresponding to one TMC.

To understand the actions undertaken by an OFP, consider the part of the architecture corresponding to one TMC (such as $TMC_1$). Fig. 10 shows the relevant network related parameters necessary for the functioning of OFP. These include the Internet Protocol (IP) addresses of the host running the TMC, the application port of the TMC on this host, the two IP addresses of the $OFP_1$, and the IP addresses of the hosts running TMS and the publically known application port of TMS (Fig. 10).

In this implementation, the OpenFlow switch behaves like a proxy. However, unlike traditional proxies, such as the HTTP proxy, the packets at the OpenFlow switch do not have to travel up the protocol stack to the application layer. Instead, the forwarding rules at the OpenFlow switch can forward packets at line speed at the network layer. This is very important because the reduced latency is essential in telemedicine applications. Without the OpenFlow API, a proxy with small latency would not have been possible.

## VII. Validation Activities

The usefulness of the VSE was validated through a set of activities at the Paul Foster School of Medicine in El Paso, Texas. Dr M. Pirela-Cruz, who was then the department head of Orthopaedic Surgery coordinated these validation activities. Twenty orthopaedic residents and twelve medical students participated in this activity. The participants were first pre-tested on their knowledge/skills of the LISS plating process. Subsequently, they interacted and used the VSE to become familiar and knowledgeable about the LISS surgery. Then, the participants were evaluated through a post-test. Some of the questions used include the following: (a) Which portion of the plate is applied on the condyles of the femur? (b) What instrument or tool is used to apply the plate to the jig? (c) What device positions the extremity correctly on the operating room table? (d) Which portion of the plate is applied on the shaft of the femur? (e) How is the jig attached to the LISS plate?

The initial emphasis was in evaluating the capabilities of the stand-alone (non-networked VSE) to demonstrate it impact on student learning and understanding related to the LISS surgical process; results from the post-test and pre-tests conducted indicated that 27 out of 32 participants demonstrated significant improvements in their understanding of the LISS plating surgical process. The average score improvement in the participants after interacting with the VSE was 30 points. Nearly 80% of participants indicated that the use of the haptic interface in the VSE helped them gain better understanding of the LISS surgical process. 85% of the participants indicated that the teaching avatar helped them in interacting with the VSE. A comparison of the pre- and post-test results of the participants are shown in Fig. 11. Scores are indicated on the Y axis on a scale of 0 to 100 (corresponding to various participants indicated on the X Axis).

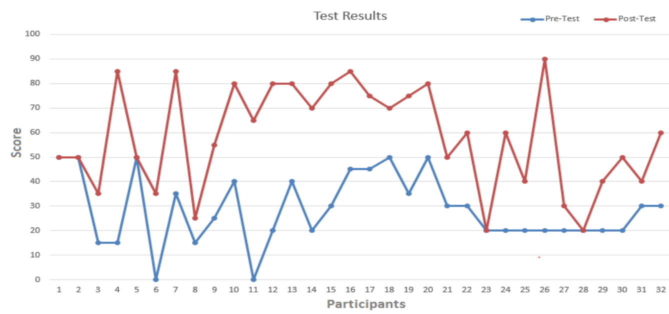


Fig. 11. Test results for pre-test and post-test

The second set of validation activities focused on the performance of the network in supporting distributed interactions (involving a surgeon and a trainee participant) using the approach discussed in section VI. In these activities, four sessions were conducted involving two participants interacting with the VSE from different locations. All the trainees showed significant improvement in their understanding of the LISS plating process as well. The average score improvement in the participants was noted to be 28 points.

The results from the validation activity underscore the impact of using VR based simulators to improve understanding of orthopaedic surgery procedures. Network latency performance was also studied involving interactions among 2, 3 and 5 users (Fig. 12 (a)). As can be seen from Fig. 12 (a), the latency is stable at around 46 milliseconds. Fig. 12 (b) shows the latency graph involving interactions among 2 users. These initial experiments indicate the feasibility of the overall GENI based networking approach to support distributed interactions involving the VR based simulator discussed in this paper. Experiments are continuing to compare the network traffic and bandwidth involving a larger number of multiple interactive modes.

| Users | Latency (ms) | | |
|---|---|---|---|
| | Max | Min | Mean |
| 2 | 54 | 41 | 46.05 |
| 3 | 67 | 41 | 46.10 |
| 5 | 68 | 44 | 46.11 |

Fig. 12. (a) Latency between 2, 3 and 5 users

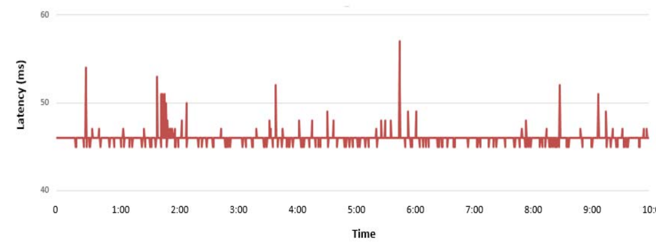


Fig.12. (b) Latency graph for 2 users

The scope of the VSE surgical training capabilities is being expanded to provide surgical training for residents in a process called the condylar plating surgical process. Condylar plating is an alternative surgery for fixation of fractured femur bone. The Condylar plating surgical has several advantages over LISS plating and other surgical processes, including more stable fixations in surgery, better preservation of blood supply and faster bone healing. Plans are also underway to incorporate online pre- and post-test modules for the participants with links from within the simulator.

## VIII. CONCLUSION

This paper discussed a Virtual Reality based Surgical simulator used for training medical residents for the orthopaedic surgical process called LISS plating surgery (which is used to which addresses fractures of the femur). This simulator consists of several modules to support training in assembling and inserting the LISS plate as well as in other steps of this surgery including positioning the plate and fracture reduction (among others). Emerging Next Generation networking technologies including cloud and Software Defined Networking (SDN) were explored to support collaborative training as part of related GENI and US Ignite project initiatives. Results of validation tasks with medical students showed significant impact on learning for a majority of participants after interacting with the VSE. Future research includes expanding the scope of the surgical training processes along with incorporating on-line pre- and post- test evaluation modules for residents and students.

## ACKNOWLEDGMENT

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