An Information Model Based Framework for Virtual Micro Surgery

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***Abstract*—In this paper we discuss the creation of a virtual reality environment for micro surgery. An information model was developed and used as the basis to understand the complex domain of micro surgery. An information model using a modeling language is used to propel the various simulation activities in the virtual environment. An enterprise level surgical manager, surgical planner and other components work together to enable the functioning of the virtual environment for micro surgery. The creation of a virtual surgical environment will enable surgical residents to learn the appropriate way of managing various conditions with safety considerations to the residents (students) and patients.**

***Key Words*—Virtual reality, Information model, micro surgery, surgical training, information technology**

I. INTRODUCTION

The use of Virtual Reality simulation in surgical training is gradually increasing as a result of changes in residency requirements [25, 26]. The need to develop safer, efficient environments has catalyzed the development of alternate techniques for the training of surgeons. The traditional methods run the risk of high cost and the possibility of post operative complications. Moreover, animal models are no longer an acceptable practice for teaching surgery. In this context there is a need to create virtual environments for teaching surgical and other procedures as well as for investigating new techniques for specific domains in the field of medicine. Micro surgery has been selected as the surgical field for various reasons. It has been acknowledged that the micro surgery field, in general, is in a crisis state as the number of surgeons being trained in this field has been gradually decreasing [27]. As micro surgery is considered more difficult than other surgical fields (requiring more years of training than other surgical fields), the number of medical residents entering this field has also reduced considerably. The creation of a virtual surgical environment for micro surgery will be useful in addressing this problem byaccelerating and supplementing existing training experiences for surgical residents (or students).

The creation of a virtual surgical environment will enable surgical residents to learn the appropriate way of managing various conditions with safety considerations to the residents (students) and patients. It will enable to assess as well as propose alternative ways to respond 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 students first merely observing a ‘live’ surgery and then gradually progressing to assisting experienced surgeons [25], [26]. Medical residents currently also acquire their skills by performing surgeries on cadavers; however, there are some inherent limitations with this approach such as availability, cost and the possibility of infections, which limit their usefulness. In this context, there is a need to develop virtual environments for micro surgery that allows students to acquire surgical skills and knowledge, which also addresses the limitations of current approaches.

In the paper, the focus of discussion is on findings of Phase I activities related to the Virtual Surgical environment for Micro Surgery (VSUMS) pertaining to the following aspects:

(a) the design of an information oriented process model (or information model) which is serving as the basis to design/build the VSUMS environment

(b) the use of an information model in propelling / guiding the various simulation activities

(c) the architecture and functioning of the VSUMS environment

The Phase I activities do not include implementation of the haptic module and validation of the environment. The emphasis in this paper is on the overall design of the VSUM environment as well as the use of information models to propel the simulation activities. The role of information models in obtaining a robust understanding of the micro surgical processes is also discussed in this paper. This surgical environment will be useful in educating and training surgical residents intending to specialize in micro surgery. As the proposed virtual environment evolves, it can also be used as a research environment where surgical alternatives can be explored by practicing surgeons.

Current trends for medical / health related education include the use of simulations in a range of areas such as heart surgery, dermatologic surgery etc. [28-31]. There have been a limited

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number of research efforts which have explored the use of Virtual Reality technology in developing simulation environments to facilitate various procedures including surgery [25, 26].

1.1 Understanding the complex domain of micro surgery using information oriented process models

The VSUMS Environment was created after interacting with micro surgeons who served as experts to this complex process domain. The emphasis is on 2 aspects: (1) obtain an understanding of the temporal precedence constraints and relationships among the various tasks and sub tasks (2) create an information oriented process model (or simply an information model) that reflects the attributes under (1). The information model serves as the basis to create VSUMS. The creation and content of the information model is discussed in section 3 of this paper. While several research initiatives have attempted to create virtual environments [1-19], a major drawback is the lack of emphasis is obtaining a structured understanding of the target surgical process being simulated. In our approach, we stress that this formal and structured understanding lays the foundation for a robust surgical environment which captures the complex relationships among the various entities, inputs and controlling factors coming into play during a target surgical process.

1.2 Propelling the simulation activities using an information model

One of the major drawbacks of other virtual environments for medical applications is the inability to easily modify or extend the scope of the simulations for various training activities. To overcome this problem, we have proposed the use of an information model which can be interfaced with the functioning of the various modules in the virtual environment. In our approach, the subject experts or other knowledge engineers can quickly update, change or modify the behavior of the virtual environment by changing various entities in the information model. The advantage of such an approach is that by changing the information model, the simulation activities can be changed at various levels of abstraction. For example, a given surgical processes which involves a specific tool and a specific surgical path/approach can quickly be modified to demonstrate a different surgical path/approach involving a different set of tools and information inputs. We refer to this as an information model driven simulation approach.

1.3 Architecture and modules of the VSUMS environment

The discussion of the architecture and the various modules is limited to the progress in Phase I of this project. VSUMS is under development at the Center for Information based Bioengineering and Manufacturing (CINBM) at Oklahoma State University (OSU). The long term interest is to create a robust high fidelity virtual environment that will enable a surgeon in training to be assessed as well as allow the budding surgeon to propose alternative ways to surgically respond to a specific medical condition. Such virtual environments are essential to educating / training young budding surgeons and /or surgical residents.

Section 2 of this paper provides a literature review of relevant research projects relating to use of virtual environments for surgery and medicine. The design of the virtual suturing modules and the other main modules of the VSUMS is discussed in section 4 of this paper. Section 5 is the conclusion.

II. REVIEW OF RELATED LITERATURE

In this section, a brief overview of related research involving virtual reality and surgery is provided [1-23, 28-34]. The use of surgical virtual reality devices has increased over the past decade and there has been a steady evolution from basic non haptic based training tools to more advanced procedural simulators. Virtual Reality simulators have an advantage over other traditional computer based systems as they allow the users to practice and improve their skills as well as compare their performance with their peers. They provide objective assessments of the tasks performed by the user as against the traditional systems which are subjective and based on the judgment of the observer [17].

Currently, virtual reality simulators are mostly used for cardiac, dental, dermatology surgeries [25]. In the domain of dental surgery, a recently published paper discusses the design of a virtual dental surgical environment. This simulator allows dentists to diagnose and treat the periodontical diseases by interacting/visualizing a 3D ‘virtual mouth’ region which also provides tactile sensations using haptic technology [16].

Virtual Reality can also be used for planning surgeries. One such approach is discussed in [15] that involve liver surgery domains. In this reported project, virtual reality based tools facilitate planning approaches which includes three main stages (a) Image analysis, (b) segmentation refinement, and (c) treatment planning. The treatment planning tool is used to elaborate a detailed strategy for surgical intervention including an analysis of important quantitative indices such as volume of healthy liver tissue that will remain after surgery [15].

The analysis of the virtual reality systems revealed that training on virtual reality simulators reduced the time taken to complete a given surgical task as well as clearly distinguishing between the experienced and the novice trainees [14].

Another surgical tool is “SPRING”, which is a real-time surgical simulation system that supports soft tissue modeling, and anatomy acquisition. It provides a general framework for surgical simulation that can support the requirements of many surgical simulations with an emphasis on real time performance [13].

One of the research studies involved analyzing the effect of proficiency-based VR training on the outcome of the first 10 entire cholecystectomies performed by new residents. The results showed that training on the VR simulator to a level of proficiency significantly improves intraoperative performance during a resident’s first 10 laparoscopic cholecystectomies [32]. Another report outlined the use of a 3D virtual reality system for planning minimally invasive neurosurgical procedures ; the preoperative 3D model provides enhanced surgical confidence [33]. A number of studies have been conducted to demonstrate that skills acquired during VR training, transfer to the operating room [34].

There has been only a limited amount of research conducted in the area of information collection and domain understanding in the context of medical surgeries. Jalote-Parmar et al [24] discussed the role of a Work flow integration matrix (WIM) to support the design of surgical information systems. WIM uses theories of human behavior in problem solving and seeks to explore the role of evidence-based decision-making for the development of new surgical technologies. In general, there has been a lack of emphasis on using formal information models to gain a better understanding of target surgical processes. Further, the reviewed simulation environments do not have a direct or easy way to expand the scope of their capabilities nor have an easy way to modify a surgical procedure. In this paper, we emphasize addressing these two issues by using an information modeling approach (section 1.1 and 1.2 provided an overview of these principles).

III. OVERVIEW OF THE ARCHITECTURE OF THE VIRTUAL SURGICAL ENVIRONMENT

The architecture and main components of the VSUMS environment is illustrated in Fig. 1. The interactions with the user (which could be a surgical resident or surgeon or others) are managed through an advanced user interface.

The overall software environment is managed by an enterprise level manager called the Surgical Scenario Manager (SSM). One of the unique attributes of VSUMS is the role of information intensive process models. These process models drive the overall interactive process to ensure that the simulation activities adhere to a process driven emphasis similar to process engineering activities in various engineering domains. This information model was created using eEML (the engineering Enterprise Modeling Language) and used as the foundation to also understand the complex process of micro surgery. This information model and modeling approach is discussed in section 4 and 6 of this paper.

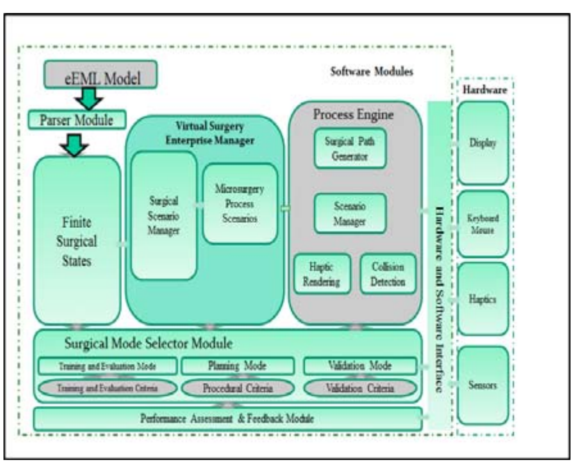

Fig.1. Architecture of VSUMS

The information model can be created using MS Visio and stored as an XML file. The details of the various fields (or attributes shown in Fig. 15, for example) can be retrieved or extracted with the help of a parser, which has been created using C++. The functioning of this information model driven interface is discussed in section 4.

The simulation, visualization and interaction are managed by the Virtual Reality Process Engine. There are several modules managed in this engine which include the surgical path generation module, the scene management module, the haptic interface module as well as the collision detection module. The virtual reality environment was created using C++ and Coin 3D libraries. The CAD models were created using Caligari TrueSpace and ProE.

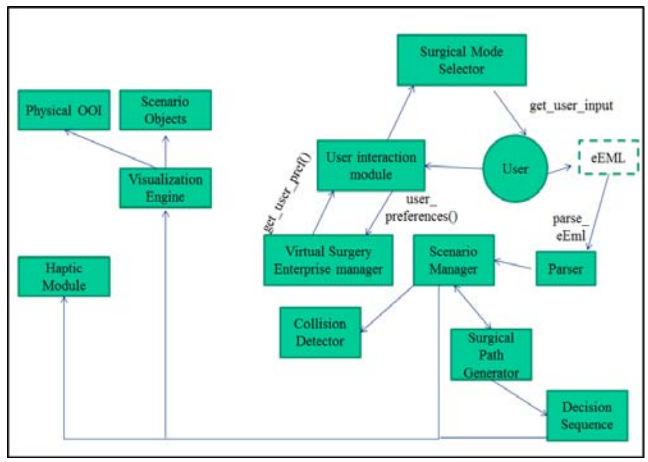

Fig. 2. Interactions among the various modules of VSUMS

3.1 The User Interaction Module

Using this module, the user will provide all necessary information for the simulation including the mode of interaction. Users can select a specific mode of interaction which can be:

(a) Training and Evaluation mode (b) Planning Mode (c) Validation Mode

The user can input an information model based on eEML as well as provide other necessary inputs. In phase I, the Virtual Surgery Enterprise Manager (VSEM), which is a software manager for the VSUMS, only provides the option for a data file for a given surgical approach (this is discussed in the later sections of this paper). In Phase II, the automatic generation of a 3D surgical path will be addressed. The eEML model is created using Visio software, which can then be exported to an XML file. This XML file contains various eEML decompositions of the tasks in a given surgery as shown in Fig. 5.

3.2 The Parser Module and Scenario Manager

The purpose of the parser module (Fig. 3) is to extract the surgical process information from the eEML model. First, an eEML model is created in Microsoft Visio (figures

15,16,17,18); subsequently, this eEML file is exported as an XML file. The parser (written in C++) then reads the information attributes in the eEML model via an XML file. These attributes include constraints, information inputs, physical inputs, teams, physical resources, software objects, information objects, physical objects, new information, feedback information, and updated information. The main C++ classes used to extract this information as well as interface with other VSUMS modules (Scenario Manager and VSEM) are indicated in Fig. 5. The parsed information is then sent back to the Scenario Manager and the VSEM to be used as the basis for managing the simulation scenarios. The VSEM creates a decision sequence flow chart which governs the overall process to be simulated. The changes in the decision objects (DOs, see Fig. 16-18) highlight the key state changes within a target process being simulated. Each activity in the simulation corresponds to the E-n entity in a given eEML model. For example, for the process, 'perform the knotting procedure', the Scenario Manager reads the extracted information using the parser and then calls the appropriate functions to orchestrate the simulation. For the process shown in Fig. 18(see E-5), the Scenario Manager executes the function for the knotting procedure which is the key information driver for this process. Once that simulation process (for knotting) is completed, it updates the decision sequence flow chart which stores three specific variables in each scenario: new information entity, updated information entity and physical object entity. As a knot has been simulated, the physical object entity will update its status to 'completed knot'. New information and update information entities will update their entries based on the process itself. If a user has not satisfactorily completed a knotting procedure (indicated by being not able to follow the suture trace shown in the virtual environment, see Fig. 20), this will be displayed

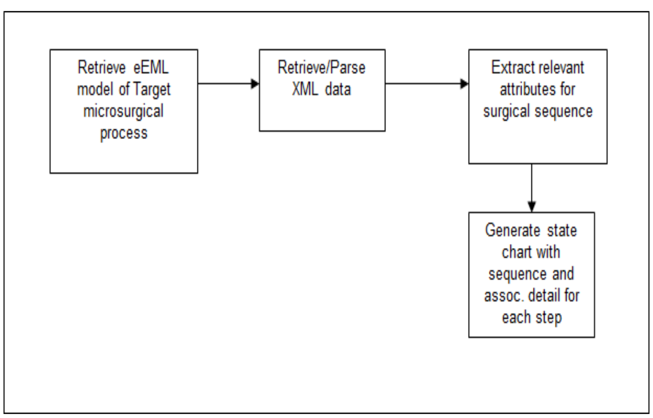

Fig. 3. Using the eEML model to propel the simulation activities

In the training mode, the surgical residents can choose a specific scenario to be trained. When a user chooses to understand a given surgical process (an option is provided for such an interaction), VSUMS provides a detailed simulation highlighting the key steps from start to finish.

With the help of the planning, interaction and haptic interface modules, these residents can complete specific micro surgical procedures interactively. The planning mode is primarily responsible to allow expert surgeons to specify tasks involved in a target surgery. They can interact with VSUMS either through eEML models or specify lower level path plans which indicate the path of the surgical tools and other entities. The validation mode enables expert surgeons to validate the surgical plans and details proposed by the automated planner. In phase I, only the training mode is the focus of implementation. Phase II targets the remaining modes for implementation.

A surgery process is divided into scenarios, which in turn are decomposed into activities (these in turn can be decomposed into other child activities depending on the user's level of detail and interest; Figures 16,17 and 18 are examples of these decompositions). In Fig. 8, the surgery process is indicated as the verb phrase in E-0 (which corresponds to 'Perform the suture of blood vessels') with six corresponding scenarios (E1 through E6, in Fig. 16-18). E1 is decomposed into other surgical activities (E1-1 through E1-4). Depending on the scenario involved, the Scenario Manager may require additional input from the user. For example, for E 5 (performing the knotting procedure), in Phase I, there is no automatic generation of the 3D suturing path. This path is input through a data file by the user. A data adaptor manages the data exchange specifications (see Fig. 6).

The input data (or information) is necessary for path planning and simulation management. After a given eEML model has been parsed, the VSEM instructs the Scenario Manager to request the needed information (based on this model); such information drivers are identified in the information input attributes of the eEML model for that scenario. For some scenarios, the appropriate data is requested from user or from legacy data files. Examples of such legacy data is the definition of incisions with parameters such as depth, width, etc. VSUMs supports popular and modern format XML (Extensible Mark-up Language). XML is preferred because this neutral format is currently very popular and flexible. XML has gradually become the standard for data and information transferred over Internet, between web applications and web services. Following is the typical format for XML input data for a virtual suturing session:

XML format:
...
<Suture Path>
<ObjectFile FullPath="...">
</ObjectFile>
<Pt1="..."
<Coordinate1 x="..." y="..." z="..."></Coordinate1>
<Coordinate2 x="..." y="..." z="..."></Coordinate2>
<Coordinate3 x="..." y="..." z="..."></Coordinate3>
<Others>.. </Others>
</Suture Path>

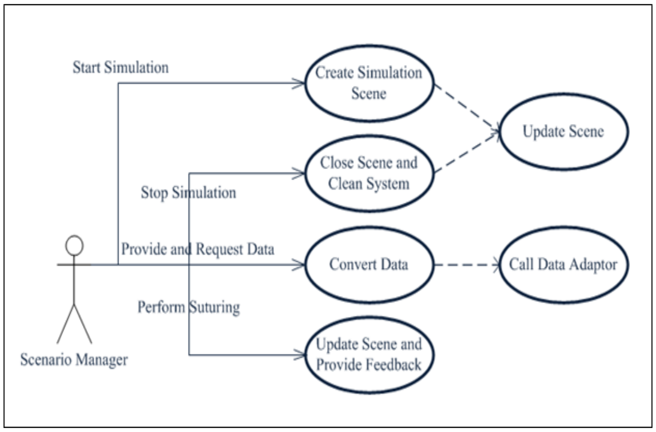

Fig. 4. The Scenario Manager

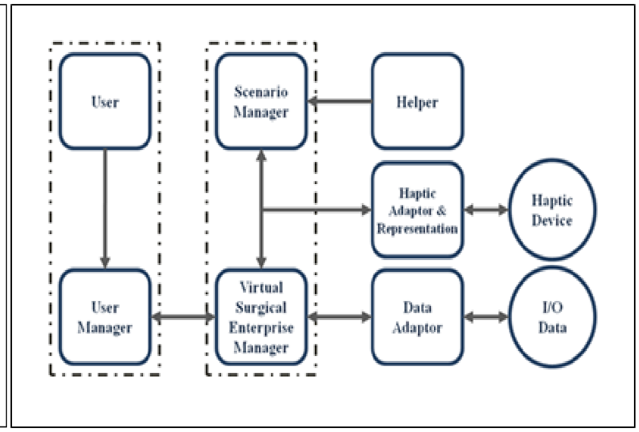

Fig. 6. Interactions between Surgical Enterprise Manager, Scenario Manager and related modules

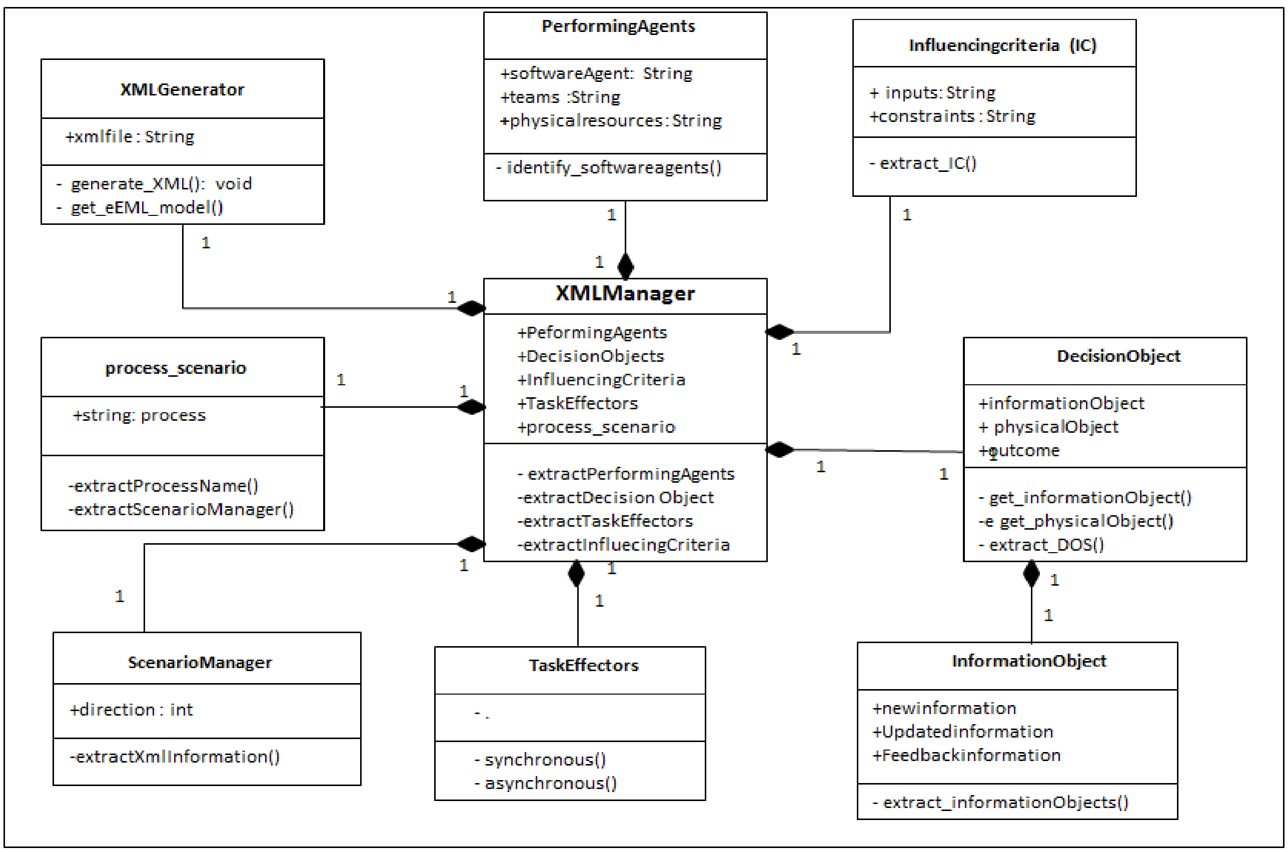

Fig. 5. The main classes involved in the extraction of the eEML model

The Scenario Manager manages the Virtual Environment for target surgeries including managing interfaces with relevant display devices and environments (Fig. 4 and 5). The VSEM is also the software coordinator responsible for managing the homogeneous virtual environment with many simulation threads and input data from many sources. In the long term, it will also provide a mechanism for collaboration between other dedicated surgical environments for other surgical processes (such as orthopaedic surgical process, etc.).

The User Interaction Module (UIM) also contains user's profile and settings for each user including temporal and persistent information. The User Management module is responsible for multi-user collaboration during a given surgical process or scenario. It has a list of users' profiles, settings and the mechanism and communication protocols. The Data Adaptor provides an interface to accept input as well as provides analysis outputs after a simulation session. The Helper module facilitates translation between input/output (I/O) formats and make them standard if it is applicable. The Haptic

Adaptor and Representation module communicates with many types of haptic devices and represents haptic device in the virtual environment as a graphic avatar. The Helper module comes with many external libraries and data converters for 3D CAD and other models.

IV. SURGICAL PLANNING AND MANAGEMENT IN THE VIRTUAL REALITY ENVIRONMENT

In phase I, the emphasis is on supporting planning and training related to micro surgeries involves veins and arteries. An expert surgeon can specify the detailed path and provide details such as the direction of the surgical needle (for example) as well as interactively specify the path followed in performing various surgical details. The overall approach can be illustrated using an example involving suturing a nerve (as seen in Fig. 7).

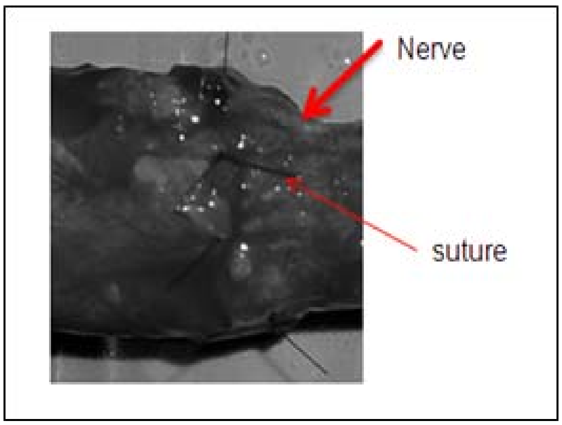

Fig. 7. Suturing a nerve through micro surgery

A surgical simulation process is composed of corresponding process scenarios which in turn contain the detail of the actual surgery to be simulated in the form of a state chart. The eEML model provides this process context by indicating which attributes are relevant for a specific simulation. Using a unique set of modeling attributes constraints, performing agents and decision outcomes, a detailed state chart can be maintained which propels the functioning of the simulation environment. The structure of the eEML models is discussed in the next section of this paper.

The E0 activity (see Fig. 15) corresponds to the target surgical process of interest (in this case suturing of blood vessels). This process (as described earlier) is composed various scenarios (E1 through E6); the simulation of these scenarios and the interactions between the user and the simulation environment forms the basis of the training, planning and validation sessions. For the suturing process (shown in Fig. 7), the preliminary step involves building a corresponding eEML model or obtaining it from eEML data base (containing standard surgical processes). In VSUMS, each micro surgical process has a corresponding detailed eEML model which spans various levels of detail or abstraction. In the information model shown in figure 8, the overall process E-0 is divided into 6 children activities or scenarios (E-1, E2,…E-6).

Subsequently, each of these scenarios can be further divided into other detailed child activities (see E-11, E-12, etc, in Fig. 5; a limited number of the corresponding eEML model decompositions in Figures 16-18). The details of a target process are stored as an information scenario file (which is a Visio file). Subsequently, a corresponding XML file is generated corresponding to this scenario. This XML file contains the detailed attributes to describe the overall flow of

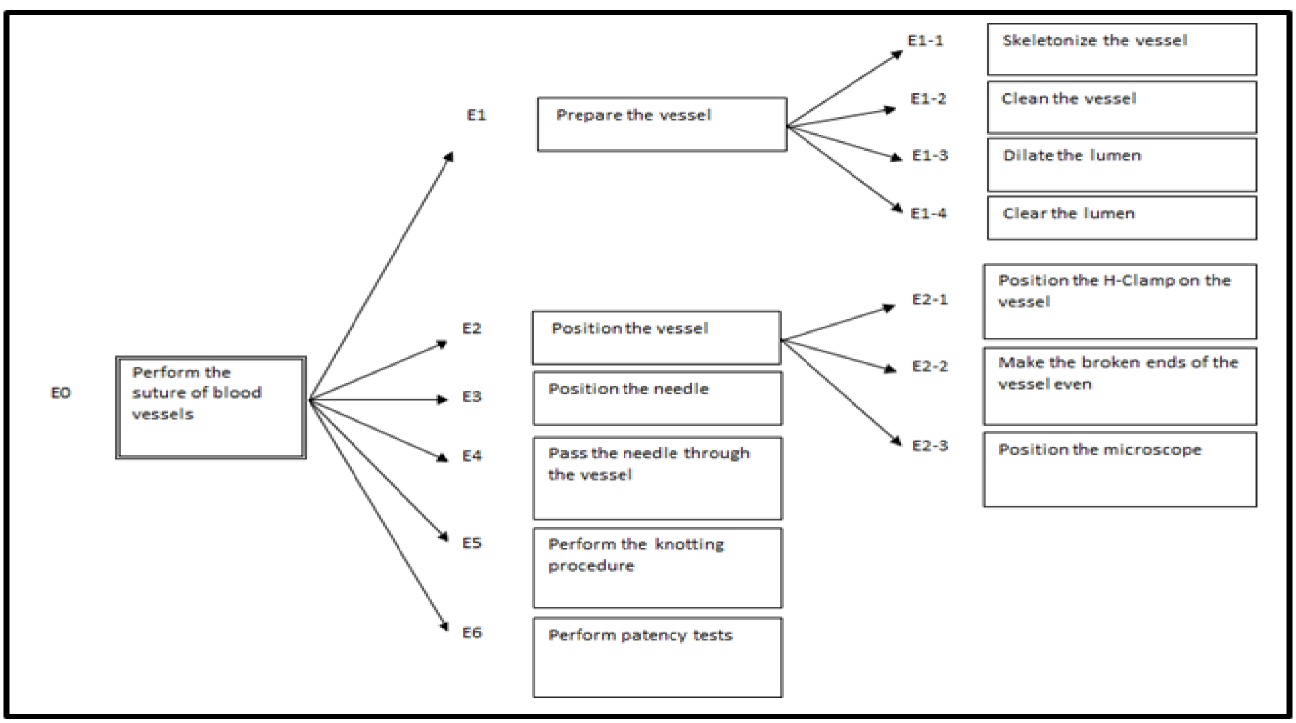

Fig. 8. The decomposition of the suturing process in micro surgery

activities for micro surgery. A parser written in C++ extracts this information for use in VSUMS. The Scenario Manager uses these attributes to simulate the lower level process characteristics which begin with positioning the blood vessel, and continues with positioning the needle, passing the needle through vessel, knotting the suture and then finally performing the patency tests. The various attributes used to describe these scenarios are discussed in section 5 of this paper. The eEML provides an information rich process context which enables the creation of a detailed simulation environment.

The virtual environment is composed of various entities of interest (Fig. 10). The EOI's can range from physiological attributes such as veins, arteries (and other attributes corresponding to organs in a human body) as well as mechanical attributes used in surgery by the micro surgeon. These mechanical attributes can range from a blood vessel dilator to an H-clamp used during surgery. A real world view of a micro surgical environment is shown in Fig. 9. In Fig. 10, the corresponding virtual environment created is shown involving the same entities.

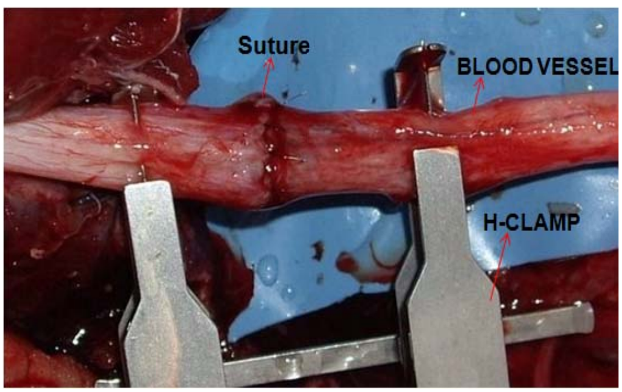

Fig. 9. The mechanical and physiological entities in a typical micro surgical scenario

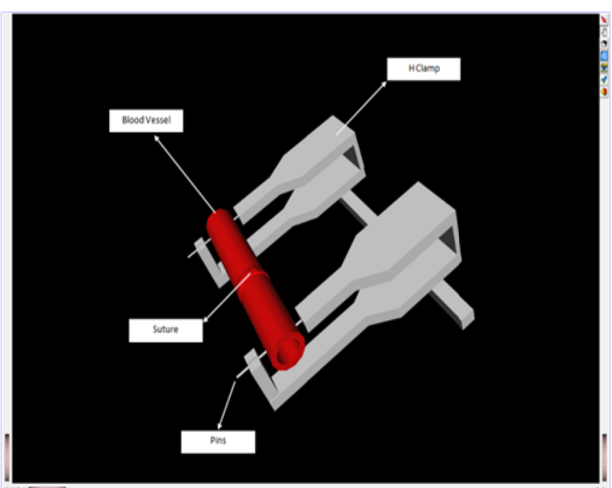

Fig. 10. A view of VSUMS' virtual suturing process environment for microsurgery

V. DESIGN OF THE HAPTIC MODULE AND OTHER INTERFACES

The complete haptic interface implementation in VSUMS is not within the scope of the Phase I activities. However, an overview of the preliminary design of haptic and other interfaces is provided in this section to enable a better appreciation of the overall scope of VSUMS. We have explored the use of the Sensible Phantom haptic device with the VSUMS environment. The Phantom is a 3 DOF physical device and 6 DOF force feedback, resolution is 3 millimeters so it can simulate many suturing scenarios with typical instruments such as needles and clamps. The friction and the mutual reaction forces need to be computed for haptic feedback during a suturing session.

The feedback model for a typical Virtual Suturing session begins when the user (medical intern or surgeon) moves the stylus (handle) of the haptic device. The encoder (which is light sensor) inside the device locates the position (pose) of the haptic device and transmits this data via a device driver program to the Haptic Adaptor module (Fig. 11 and 12). The Haptic Adaptor receives and processes this data and generates necessary information which can be interpreted by other modules.

The Scenario Manager then obtains this haptic information and is ready to render the scene. The haptic device is represented in scene as a corresponding virtual graphic object (or avatar) in the virtual environment. The design of the main C++ classes in the haptic module is shown in Fig. 9.

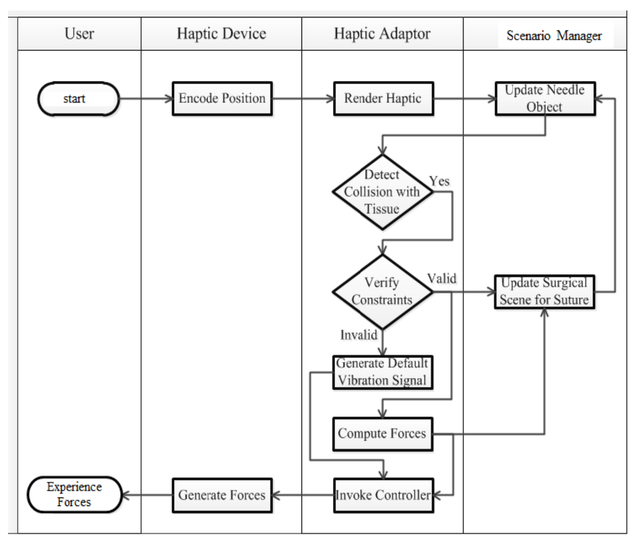

Fig. 11. Force Feedback Model for the Virtual Suturing Process

The haptic avatar can assume various 3D shapes relevant to a given surgical process and scenario. For the suturing process, the shape of the needle appears as a fishing hook (Fig. 19 b) and smaller as a human hair; in a micro surgery, the surgeon uses a needle holder to complete the surgical process (Fig. 19 a). The collision detection feature is invoked when the needle starts touching the surface of a target tissue area. The collision detecting approach is based on computing a convex hull of the two bodies which can potential come into contact. Testing for

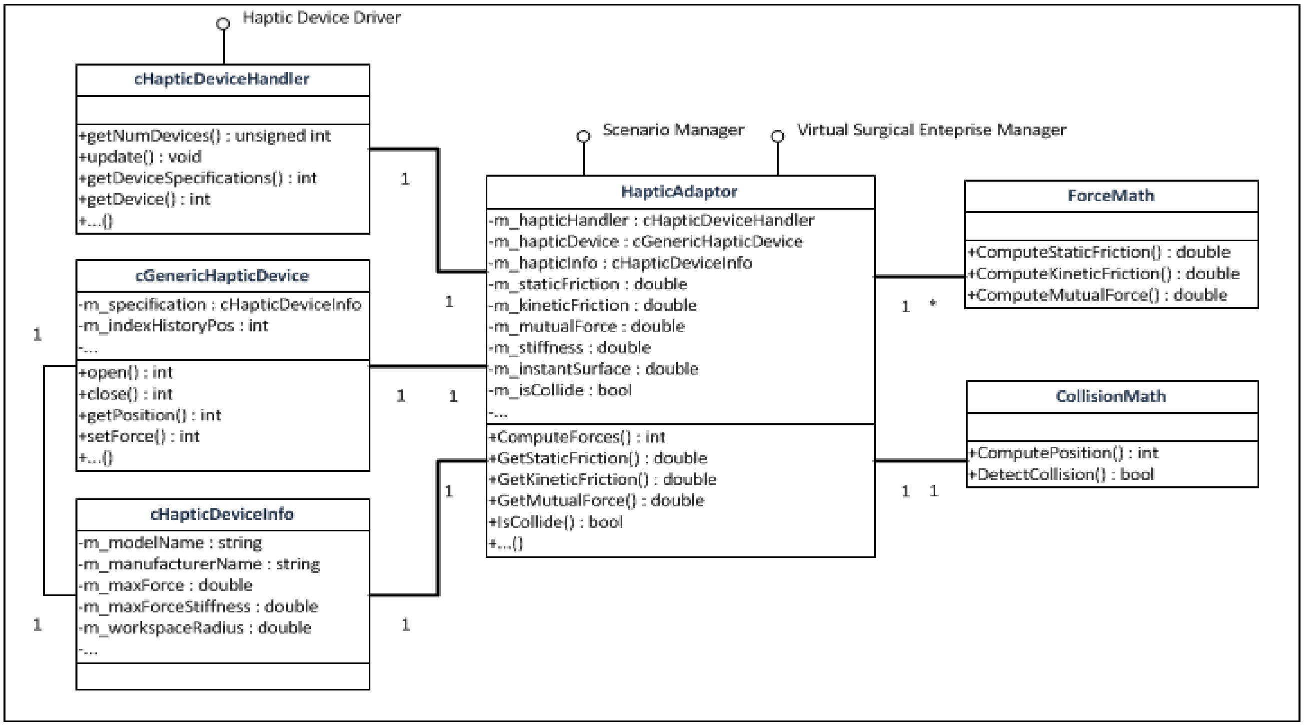

Fig. 12. The main classes designed for the Haptic module

intersection of these convex hulls enables the detection of collisions. If the contacting points are not over the allowance offsets from the planning path, the relevant forces are computed and sent to controller to which in turn is communicated to the haptic device for generating simulated forces. However, if the student or user goes along an incorrect path (this is detected by the path of the virtual needle), a default vibration signal is sent to controller which can be used to display a warning message to the user during the simulation. In these situations, the scene is only updated when the needle moves (active) or after a collision event (passive) triggers.

When using VSUMS, there are 2 options provided to the user:

(a) The non-immersive option (Fig. 21) where the user can interact and be trained on a regular PC environment without being completely immersed within the virtual environment.

(b) the immersive option Fig. 22) which allows users to navigate using stereo vision eye wear, trackers and sensors which support complete immersion using a PowerWall system (from Mechdyne). Several modes of interaction are being explored. In the constrained mode, a user can only perform the surgical steps the system allows them to be trained in. With the help of haptic cues and constraints, the system allows only movement in the direction and path of a target scenario (for eg: the suturing path discussed earlier). In the unconstrained mode, a user can first propose a suturing path and then proceed to complete the suturing task of interest.

In Phase I development cycle, evaluation and feedback of a surgical resident's performance is not provided. These are addressed in the Phase II developmental cycle. The second option within training (which will be implemented in Phase II) is to select the interactive evaluation process. In this option, the user attempts to perform a process he/she has studied through an earlier simulation and then repeats this process. During such an interactive process, the user's responses and interactions are constantly evaluated by a set of response / reasoning rules, which can provide cues when the user has deviated from a recommended path.

When using the immersive option, the VSUMS environment provides an interactive interface which allows users to navigate more effectively using motion trackers and 3 D stereo eyewear (Fig. 22) which are linked to an advanced PowerWall system (from Mechdyne). While one surgical resident (or primary user) can interact using a controller and an active stereovision eyewear, up to four other surgeons or residents can also be immersed with the primary user. This allows the medical training team to compare options, discuss strategies and communicate more effectively inside the virtual environment. The controller allows the user to zoom in/out, turn, fly around (see Fig. 22). A directional wand in 3D enables the user to be aware of a general direction of movement.

The internal management of the various virtual entities is the responsibility of the visualization engine. The visualization engine uses a scene graph approach and is implemented using Chai 3D and C++ tools. A scenario for simulation is first created using the relevant CAD models corresponding to the physiological and mechanical entities (shown in Fig. 10) which correspond to the ruptured vein, H-Clamp, Pins (etc.) and are imported into this scene database. The ancillary attributes are added as children to their respective group nodes. Each of these group nodes contain commands for accurate positioning and orientation of CAD models (rotate, transform and translate). Additional discussion on the implementation using Chai 3D is provided in section VII of this paper.

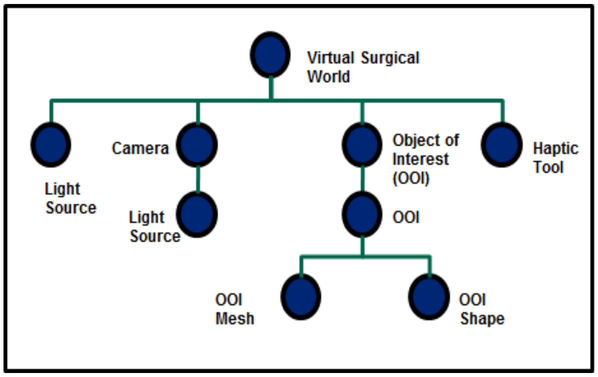

Fig. 13. Internal representation of various entities in the virtual environment

VI. ROLE OF INFORMATION MODELING IN VSUMS

The virtual reality simulators for surgery which are currently in practice have not explored the use of information models. In VSUMS, an unique aspect is the use of information models which can be used to propel the overall surgical simulation process.

In VSUMS, the distinguishing focus is on understanding the “process” of performing micro surgery. Micro surgery has been studied from a process engineering perspective with an emphasis on information centric modeling. These Information modeling techniques have been used to obtain a better understanding of the micro surgical process. The various key relationships, constraints and performing mechanisms along with the temporal precedence constraints will be modeled using the engineering Enterprise Modeling Language (eEML). A key emphasis was on identifying functional relationships among various attributes underlying the process of micro surgery with a view towards using that understanding to create an advanced virtual environment to train micro surgeons. We have developed an information model based on interactions with expert surgeons (as part of our interest in obtaining an understanding of the surgical activities). A specific emphasis is also on the planning activities involved in micro surgery. While other virtual surgical environments have been developed in various domains, a major drawback is the lack of interaction between the domain experts (or surgeons) and the virtual environment developers as well as the lack of a structured process model as the foundation of such an environment.

A language termed eEML (the engineering Enterprise Modeling Language), was used to develop this model; in the past, eEML has been used by CINBM researchers to model a range of complex processes. This model captures the key or driving assumptions, information inputs, skill constraints, the intermediate ‘attribute’ outcomes between various steps or stages of the process in reference as well as the crucial performing ‘agents’ (which can range from the medical personnel involved in the diagnosis and surgery itself to the medical assistive devices which play a key role in the outcome of various steps in this surgical process). This information model can be viewed as a baseline information intensive model that captures the functional relationships among related tasks at various levels of abstraction but also enables the representation of temporal precedence constraints among sub-tasks [26].

The information model was built after interaction with Dr. Pirela-Cruz (who is an experienced micro surgeon) and was developed through interviews, discussions, attending cyber lectures, watching videos, etc. After identifying the core tasks involved in a target micro surgical process, subsequently the other details were identified including the constraints, the information inputs and decision outcomes for tasks and sub tasks in this process. We also captured the temporal precedence constraints for the accomplishment of these tasks. By emphasizing a process level of details, our approach has sought to satisfy the functional requirements of micro surgery. Fig. 14 illustrates the importance of the role of the information models. The information models can be viewed as an outcome of understanding the complex surgical process. Subsequently, it becomes the foundation to create the VSUMS. In Phase I, we have used process models as a basis to understand the process of suturing in the virtual environment. In Phase II, we propose to automate this process for various other microsurgical activities.

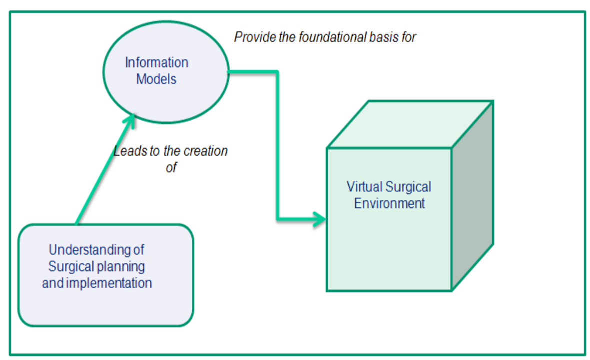

Fig. 14. Using Information Models to understand micro surgical processes

As the detailed information model is lengthy, for the purposes of brevity, we will only highlight the top level views of this model. The surgical process can be viewed as set of core tasks and sub tasks (see E-0 in Fig. 16) along with associated performing entities (called performing agents PA’s) and outcomes (called decision objects DO’s). Constraints, information and physical objects can be modeled as Influencing Criteria (IC’s). A core task such as E-0 (in Fig. 9) can be decomposed into a corresponding set of sub tasks E1…En. The surgical process can then be modeled and studied as a collection of tasks with a corresponding set of relationships. By developing a map from this information model to the simulation environment, the activities (which are simulated within the virtual environment) can be modified as necessary. By using relevant temporal constraints (such as ‘AND’ and

'OR'), the modeling of synchronous and asynchronous tasks can also be modeled explicitly.

In an eEML model there are four categories of information attributes: the Influencing Criteria (IC), the Associated Performing Agents (APA), the Decision Objects (DO) and the Task Effectors (TE). Using these attributes, a target set of activities can be modeled, studied and analyzed at various levels of abstraction.

Influencing Criteria can be categorized as information inputs (II) and constraints (CO), which directly impact the accomplishment of the target activity (being modeled). Constraints can be viewed as controlling factors influencing the process being modeled. The information inputs are the information attributes which are required to accomplish the target process being modeled. The Associated Performing Agents (APAs) refer to the software, personnel and/ or machines/tools agents, which perform the identified tasks. Decision Objects (DO) can be grouped under information and physical objects, which refer to the information or physical outcomes (respectively) of activities performed. The end effectors indicate flow of task accomplishment in either a synchronous or asynchronous manner (synchronous accomplishment is represented using a symbol '&' and asynchronous tasks can be represented using 'V'). Logical 'AND' and 'OR' relationships can also be represented.

A list of the major attributes used in eEML is shown in Fig. 14 along with their abbreviations (which appear in the eEML diagrams). Consider the eEML diagram for the suturing process as shown in Fig. 15. This diagram, which represents the highest level of abstraction, illustrates the general layout and use of attributes in eEML (for suturing process in this case). The primary, secondary and tertiary importance of the various attributes is indicated using 'P', 'S' and 'T' symbols. This is determined by the modeler based on their perception of the level of importance of a specific attribute. A modeled (target) activity E-0 can be decomposed into a set of related activities E-1, E-2, etc. In general, after the context, modeling perspective and objective have been formalized; the focus unit level is created. At this E-0 level, the various ICs, APAs, and DOs are identified as well as prioritized (as primary, secondary and tertiary); the temporal relationships among these activities are also captured using appropriate junctions. Subsequently, the tasks that comprise the focus unit are identified in the decomposition and the process is repeated.

This information model was developed after closely interacting with a micro surgeon (which has been lacking in other virtual surgical research initiatives). Fig. 19 are images of some of the various tools by a micro surgeon. These were used to create the CAD models which in turn became part of the virtual environments created in VSUMS.

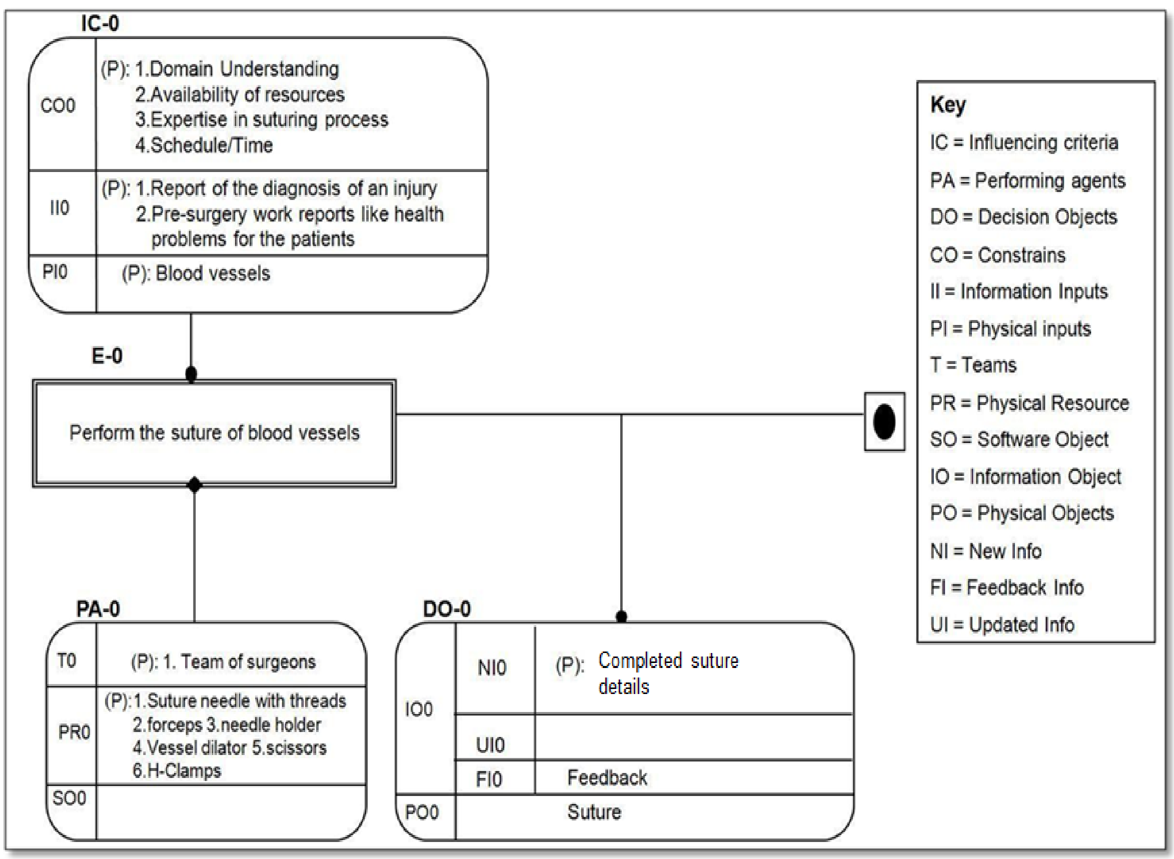

Fig. 15. (E-0) Top Level view for eEML Model

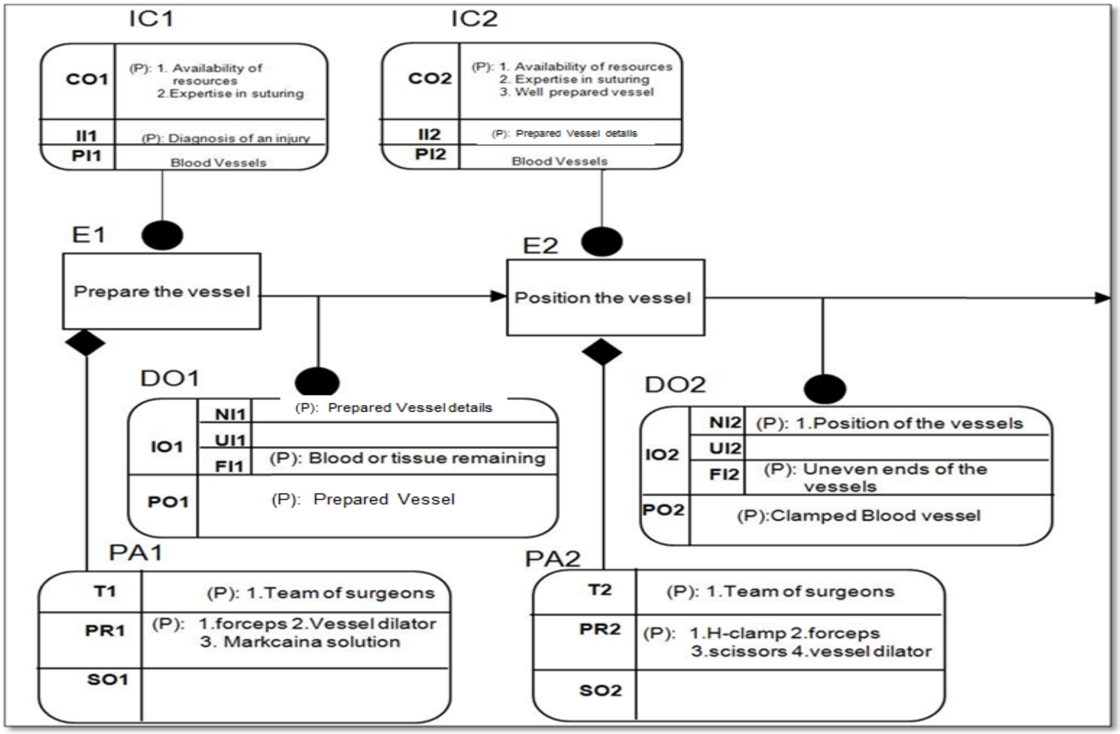

Fig. 16. Decomposition of E0 level showing E1 and E2

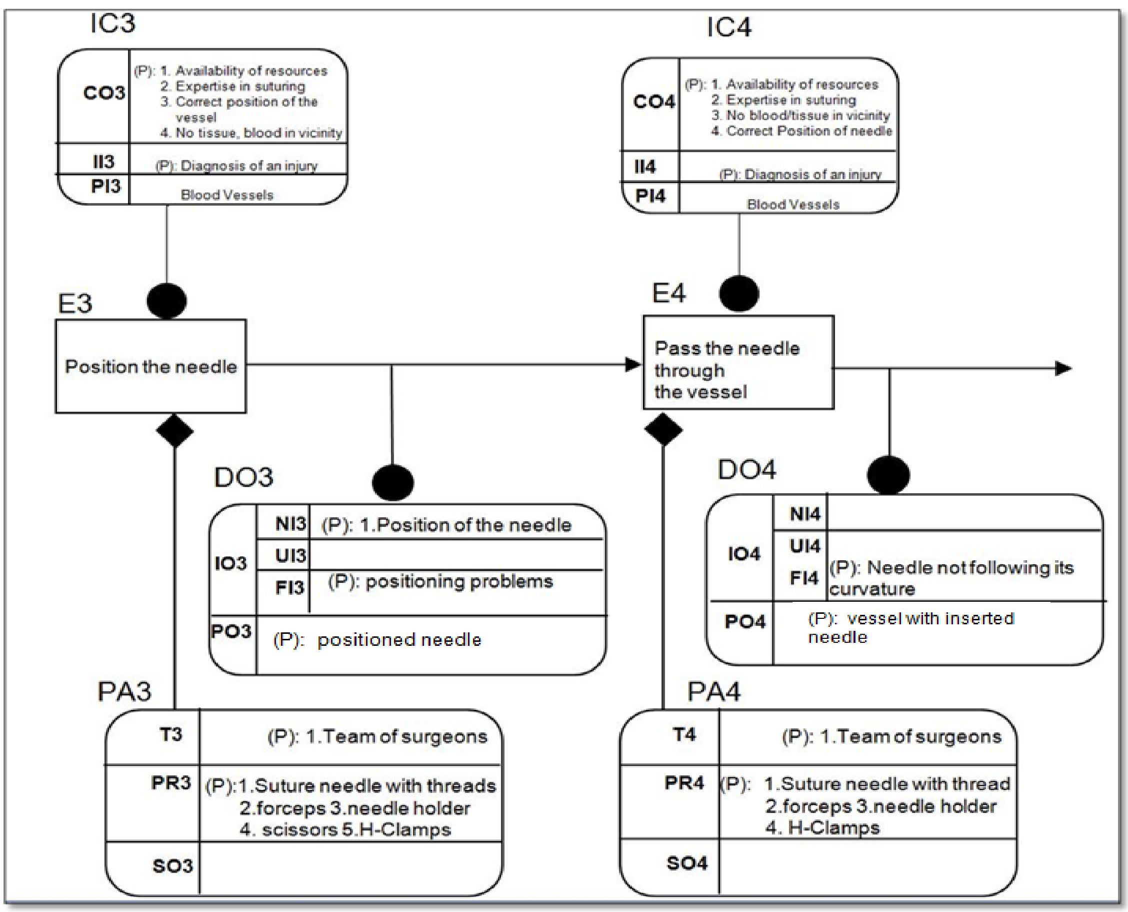

Fig. 17. Decomposition of E0 level showing E3 and E4

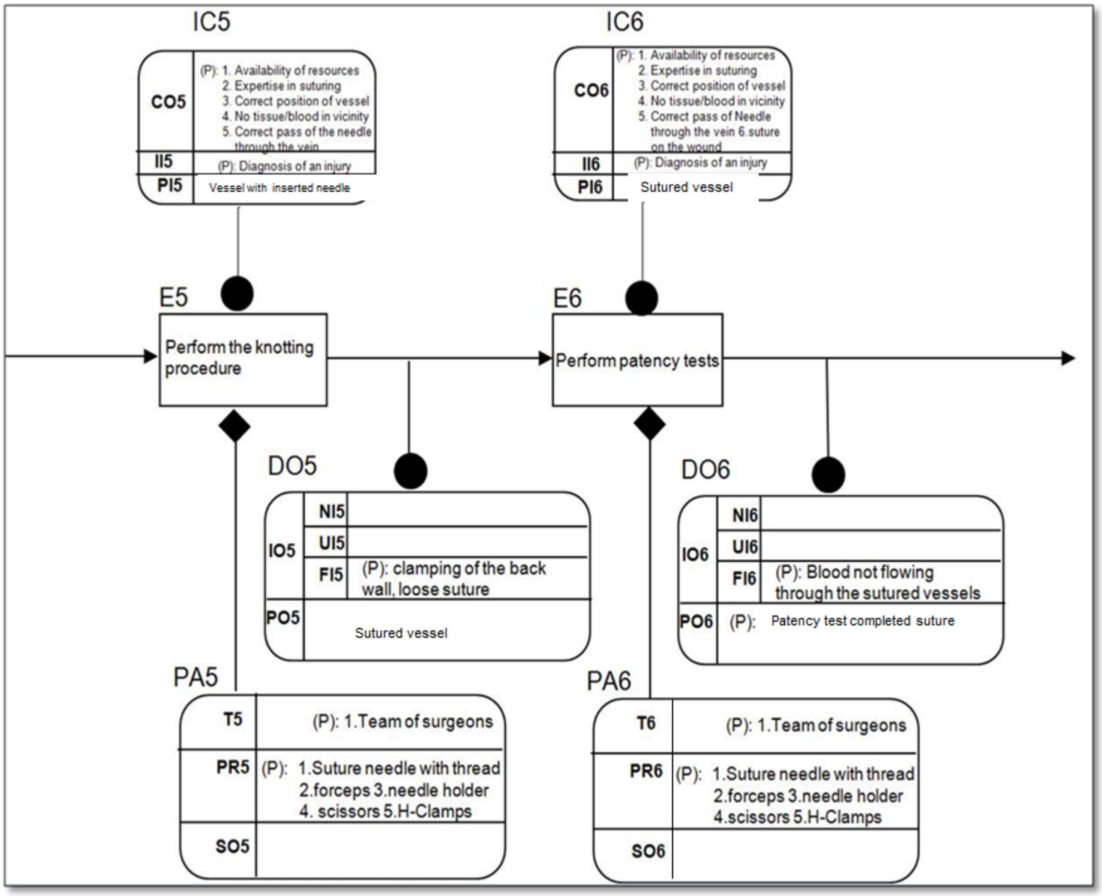

Fig. 18. Decomposition of E0 level (contd.)

VII. AN EXAMPLE INFORMATION MODEL

For purposes of brevity, the discussion in this section is limited to the process of performing a suture on blood vessels. The detailed information models developed includes planning and surgical activities for a variety of procedures using an array of surgical options.

Consider the top level process (E-0) 'Perform the suture of Blood Vessel'. This is the main process being modeled (viz. suturing a blood vessel). At the E-0 level, the influencing criteria shown in Fig. 9 include constraints such as domain understanding, schedule, expertise in suturing process, availability of resources etc. This model not only provides the inputs required before surgery but also identifies key decisions in the surgical process. The information inputs provided are reports of the diagnosis of the injury and any preoperative medical problems associated with the patient. The key decision outcomes include the successful completion of the surgery (which is a suture, indicated in the physical object category in Fig. 15). Fig. 16 and 17 show the decompositions of E-1 through E-6. Only these decompositions at the top level are shown for brevity. The key objects are the Physical Object (PO) entities in theses diagrams. They indicate the status changes as the micro surgery task progresses. For example, clamped blood vessel, positioned needle, vessel with inserted needle, complete knot and completed suture are the key status changes in the overall progress of a successful surgical process. An overview of the 6 activities comprising E-0 follows.

E1: Prepare the vessel
In this pre-surgery stage, the surgeon lifts the vessel and cleans the tissue and blood within the vicinity of the blood vessel with the help of 0.025 markcaina solution, the scissors and scalpel. The surgeon then expands the vessel with the help of a vessel dilator and clears the lumen. The key constraints in this stage are availability of resources and expertise in suturing process. The information input for this process is diagnosis of the injury (report). The key performing agents are Team of surgeons and the physical resources are the tools used viz. Forceps, Scissors and scalpels and the markcaina solution used for cleaning the vessel.

E2: Position the blood vessel: In this step, the surgeon positions the cleaned vessel correctly. He/she makes both the ends of the vessel of the same size to remove the irregularity in their size so that the suturing can be performed with precision. The surgeon positions the H-clamps on the vessel in such a way that the vessels are neither too loose nor held too firm.

E3: Position the needle: The surgeon then positions the suture needle with a curved needle holder. He/she surgeon makes the needle point in the right direction/angle and avoids the downward pointing of the needle to prevent the back clamping of the blood vessel.

E4: Pass the needle through the vessel: The surgeon averts the tissue edge to provide distortion and to make the needle pass at right angles through the tissue. Using a left hand forceps on the topside of the tissue, the surgeon makes the needle follow its own curvature. This is done to avoid the back clamping of the vessel. The surgeon avoids the through stitch and pulls the needle through in one straight movement and in the process pulls the suture through.

E5: Perform the knotting procedure: This is the actual suturing process. The surgeon ties the surgical knot in which she/he picks up the suture with a left hand forceps and makes a loop on the tip of the right hand forceps. The short end of suture is picked up with the right hand close to the loop length. The surgeon makes a single loop and then completes the first half knot. The surgeon then turns the needle holder forceps and pulls the loop, tightening the knot. The longer segment of the thread with forceps is held, pulling the loop and tightening the knot.

E6: Perform Patency Tests: This is the post-surgery step in which the surgeon removes the H-Clamps, cleans the vessels and the area in the vicinity and performs the patency tests to check whether the vessel is open and blood flows through it.

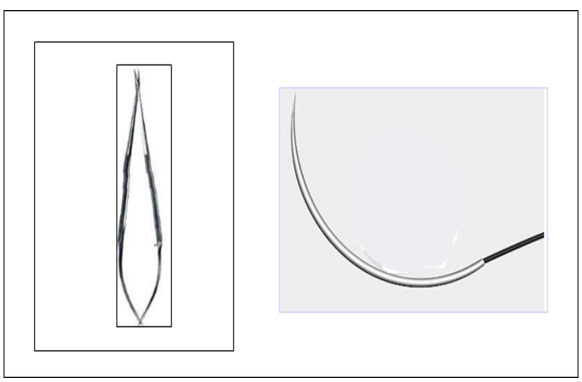

Fig. 19. (a) A needle holder (left) and (b) close-up view of a micro surgery needle (right)

VIII. DISCUSSION AND CONCLUSION

Organic objects in VSUMS such as the blood vessels (arteries, etc.) are created by using sophisticated mesh models. We use Caligari TrueSpace to model these objects and later import them into a software tool called Chai3D. Because these objects are deformable during suturing phase, their meshes are computed at specific time intervals. In addition, we also take advantage of the Tetgen library to help recomputing the mesh with optimal number of faces. Chai 3D maintains a scene graph type of representations which allows fundamental objects including world (graphic universal object), camera (view), and light source (visibility) with appropriate arguments. When objects of interest (OOI) in the above world require sophisticated meshes and force models, two other kinds of world entities can be added (with external libraries): the ODE world (good for solid and unmovable objects) or GEL (good for deformable and movable objects). When other objects are added (such as clamps, etc.) inside the above world, some appropriate arguments for their properties (materials, textures, etc.) are included. Other definitions allow basic interaction and graphical capabilities such as "update-graphics", "resize-window", "update-camera", "close", "GLUTRender", etc. Overall, using Chai 3D, the VSUMS environment renders the defined world by invoking "GLUTRender" function and begins a target simulation (the graphic loop) by calling the "glutMainLoop" function.

When a user resizes a window, wants to turn around or zoom in/out, the "update-graphic" function is called. This function calls other appropriate graphic functions to update the scene (swap buffers). VSUMS invokes "close" function to clean everything when user stops the simulation.

Our literature review has indicated that while various other virtual environments for surgery have been designed and reported in the literature, none of the previous approaches have underscored the need to build an information model to understand a target surgical process; further, other approaches have not used an information model to propel the various simulation activities. Sections 1.1 and 1.2 provided a summary of the innovative use of information models in the development of VSUMS.

The VSUMS environment was tested and evaluated as part of the Phase I activities. Specific surgeries for blood vessels (both arteries and veins) were simulated and studied. Initial feedback based on this evaluation indicated the following:

(a) Users preferred to have a text based and voice based introduction about the capabilities of VSUMS before starting a training session.

(b) While the eEML models were not difficult to build or modify, some of the users requested additional descriptions of the various entities being modeled (such as the decision objects, information inputs, etc).

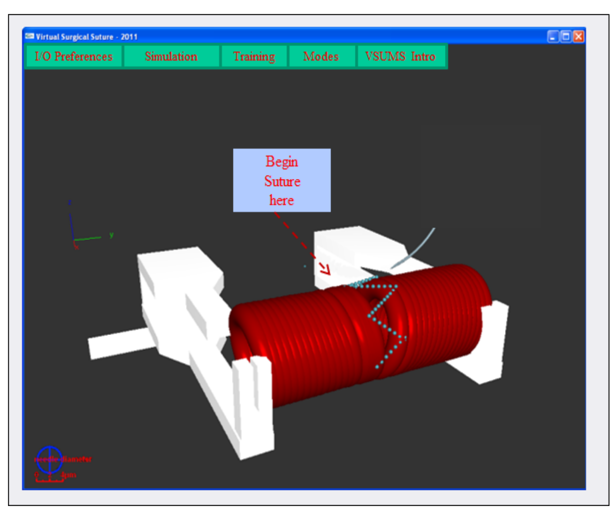

Fig. 20. View of the suturing path displayed within VSUMS during training

(c) The accomplishment of knotting procedures was identified as an area for improvement. Some of the users indicated that a separate training module highlighting the detailed knotting procedures would help in providing a better training experience.

Since VSUMS' initial evaluation and feedback, an introduction about capabilities of VSUMS has been provided as an option to users (see menu options in the menu bar shown in Fig. 20). Other points will be addressed during the continued implementation in Phase II of this project.

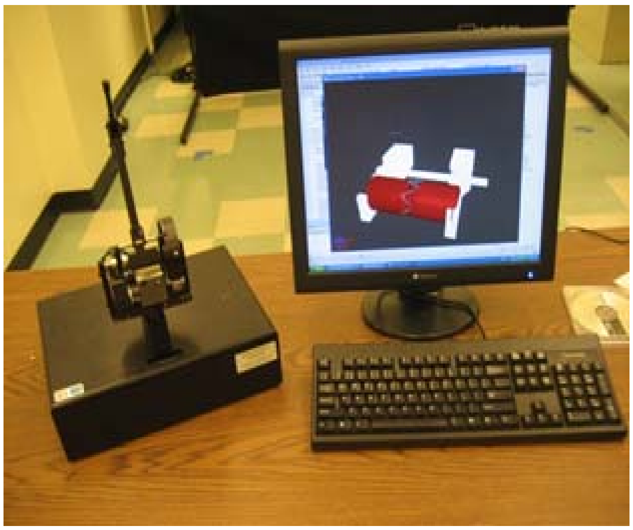

Fig. 21. View of the non immersive mode of VSUMS during training

In Phase II, the development of VSUMS will continue with an emphasis on the computation of forces and haptic module implementation.

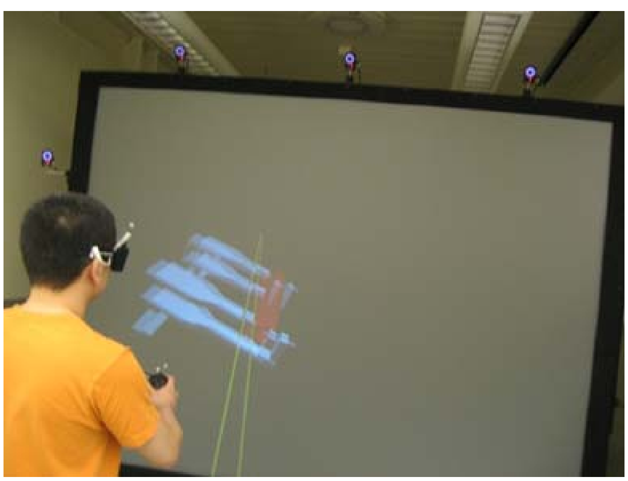

Fig. 22. View of the immersive mode of VSUMS using the Virtual Reality PowerWall (image appears blurred when not viewed with stereovision eyewear) (Color Plate 4)

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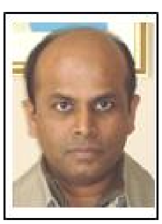

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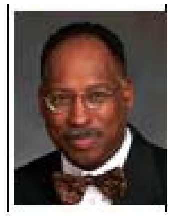

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