# COMPUTER-BASED SURGICAL SIMULATION SYSTEM FOR STUDENTS TRAINING

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**Abstract**

Computer-Based surgical simulation systems are one of the most recent technologies in virtual reality development. These systems have changed the traditional medical training and the surgical certification scenarios. They have become a training method and an effective tool to acquire valuable information and skills for many medical students and practitioners. The aim of this paper is to introduce a functional prototype of a computer-based surgical training and assistance simulator for medical students. The system allows students as well as surgeons to interact with anatomical and biological structures by modeling and operating on virtual objects displayed on the computer screen. The system consists of: a personal computer, graphical monitor and a haptic feedback device. A 3D virtual representation of the bones constituting the wrist of a patient is shown. Also, algorithms that model objects using the convex hull approaches and simulate real time exact collision detection between virtual objects during the training on the surgical operation are presented. In addition, a force feedback device is used as a haptic interface with the computer simulation system. This leads in the development of a low cost system that is used by students with the same benefits as professional devices. In this regard, the wrist arthroscopic surgery can be simulated and students can easily acquire the system and can learn the basic skills required with safety, flexibility and less cost.

**Keywords: Virtual Reality, Computer-Based Simulation, 3D modeling and Visualization, Convex Hull, Collision Detection, Haptic Feedback.**

## Presenting Author's Biography

Fadi Yaacoub received his Bachelor degree (B.Sc.) and his Master degree (M.Sc.) in Electrical Engineering from the University of Balamand Lebanon in 2003 and 2005 respectively. He is currently a PhD student at Université Paris-Est and A²SI laboratory of ESIEE-Paris France. He works on the development of a virtual reality simulator for arthroscopic surgical training. His research areas of interest include: Virtual Reality, Computational Geometry, Signal and Image Processing, Medical Imaging, Modeling and Biomedical Instrumentations.

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## 1 Introduction

Virtual Reality (VR) is not only a hardware system, but also an emerging technology that changes the way individuals interact with computers. The VR technologies have opened new realms in the practice of medicine. One of the most recent technologies in VR is the Computer-Based surgical simulation systems. For a long time, scientific and biological educations have relied on drawings and pictures of many organs to describe the human anatomy. Nowadays, researchers on medical education depend heavily on computer-based simulators that have become one of the main components of changing radically the traditional medical training and the surgical certification scenarios [1],[2],[3]. Furthermore, the low availability and high cost of cadaver and animal specimens for traditional medical training and the public concern with the inhuman treatment of animals have become another impetus for the medical students to use computer simulations in their education and their training to gain valuable information and experience.

Computer simulations allow the process of iterative learning through assessment, evaluation, decision making and error correction which create a much stronger learning environment. Also, computer simulations can aid in navigation by augmenting the limited endoscope view with a more global view of the patient's anatomy and can provide guidance by preventing the surgical instruments from moving into pre-defined sensitive regions. An important application is the arthroscopic surgery simulation. In arthroscopy, the object is visualized and accessed through small portals. An optical endoscope equipped with a video camera allows the visualization of the procedure through one of the portals, while surgical probes and other instruments are inserted through additional portals. Moreover, volumetric information about the internal anatomical structure is particularly important for realistic modeling and visualization of complex 3D objects. With the small incisions and reduced tissue disruption, arthroscopy is increasingly being used in the treatment of the hand. Wrist arthroscopy, in particular, has proven to be extremely valuable in both diagnosis and therapy. It is an important skill for all hand surgeons, in exactly the same way as shoulder and knee arthroscopy [4].

This paper introduces a functional prototype of a computer-based surgical training and assistance simulator for medical students. The system allows the students to interact with anatomical and biological structures by modeling and operating on virtual objects displayed on the computer screen. The system consists of: a personal computer, graphical monitor and a haptic feedback device. In addition, algorithms that model objects using the convex hull approaches and simulate real time exact collision detection between virtual objects during the training on the surgical operation are presented. Also, a force feedback device is used as a haptic interface with the computer simulation system. This leads in the development of a low cost system that is used by students at home with the same benefits as professional devices. Then, the procedure can be performed on real patients with much less risk and injury. The rest of the paper is structured as follows: Section 2 reviews some of the previous surgical simulators. The computer simulation system is presented in section 3. Section 4 shows a 3D virtual wrist model. In section 5, algorithm to construct the convex hull is implemented, then the problem is formulated and a linear programming solution is obtained to test whether a collision exists or not. A force feedback device that is used as a haptic interface with the computer simulation system is presented in section 6. Finally, conclusions are given in section 7.

## 2 Prior Work

Surgical simulators have been developed for a wide range of procedures. Two major classes are described: the needle-based simulators and the minimally invasive simulators.

### 2.1 Needle-Based Simulators

The Immersion Medical CathSim Vascular Access Simulator was developed to train nursing students in the proper technique for starting an intravenous line [5]. The system uses a developed haptic interface device to simulate the needle and the catheter. The device reports three Degree Of Freedom (3-DOF) orientation data, and provides one DOF haptic feedback along the direction of needle insertion. A desktop personal computer controls the device, and real-time visual and haptic feedback is provided during the simulation process. The same hardware configuration was used to develop needle-based trauma procedures such as pericardiocentesis and diagnostic peritoneal lavage [6],[7].

### 2.2 Minimally Invasive Simulators

Minimally invasive procedures use specially designed instruments. The instruments are introduced into the body via small incisions. Visual feedback is obtained via inserted scopes, cameras or fiberoptic devices and a video display monitor is used to show the image.

The LASSO project [8] is an integrated development effort to construct a laparoscopic simulation platform. The abdominal cavity is modeled using data from the Visible Human [9]. Organ surface features are generated using a combination of texture analysis/synthesis, procedural texturing and L-systems-based methods for growing vascular networks. Real time deformation, haptic and rendering performance is achieved using a 64-node parallel processor. Moreover, the Karlsruhe endoscopic surgery trainer [10] is based on the KISMET environment for virtual surgery development. A simulated laparoscopic cholecystectomy procedure was developed on this system. This simulator uses an SGI Octane/MXE workstation with two 250 MHz Mips R10000 CPUs to achieve a visual update rate of twenty frames/sec. A PC based system records the instrument positions and joint angles then sends the information to the SGI via a serial interface. However, this system does not provide force feedback.

Besides, a laparoscopic simulator VESTA is developed for training and assessing surgical skills [11]. Unlike the Karlsruhe simulator, VESTA provides force feedback using modified PHANToM haptic interface devices [12]. Also, commercial laparoscopy trainers include products from Surgical-Science [13] and Mentice [14]. Both systems are PC based and use a non-force reflecting laparoscopic interface from Immersion Medical. In the Mentice system, trainees can learn hand eye coordination by manipulating spheres and other geometrical objects in an abstract environment. Whereas, the Surgical-Science simulator uses a simplified rendition of the abdominal cavity as a practice environment. Students can manipulate vessel-like structures that cause bleeding due to careless handling. Furthermore, Bro-Nielsen et al. described a PC-based bronchoscopy simulator [15]. In addition to realistic visual effects, this system uses a haptic interface designed to provide realistic force feedback during scope insertion. The system has been expanded to include colonoscopy and flexible sigmoidoscopy. These simulators are very expensive and also do not treat the issue of the wrist arthroscopy. Thus, the problem of building an inexpensive and practical simulator for training medical students remained.

## 3 Computer Simulation System

Medical images are processed to generate volumetric object models. These 3D models are presented both visually via rendering on the computer monitor and haptically with a force feedback device. Visual parameters such as viewpoint, zooming, colour and lighting effects can be interactively controlled and object models can be manipulated with force feedback to change relative probe and object positions, and to simulate many surgical procedures. Also, simulations include algorithm that model objects using the convex hull approach and a method that detect collision between virtual objects during the operation. The interaction between the haptic device and the computer closes the feedback loop between the user and the simulator, offering a better understanding of the anatomical structures and the functions in the patient's model. Figure 1 outlines the main components of the computer-based simulation system.

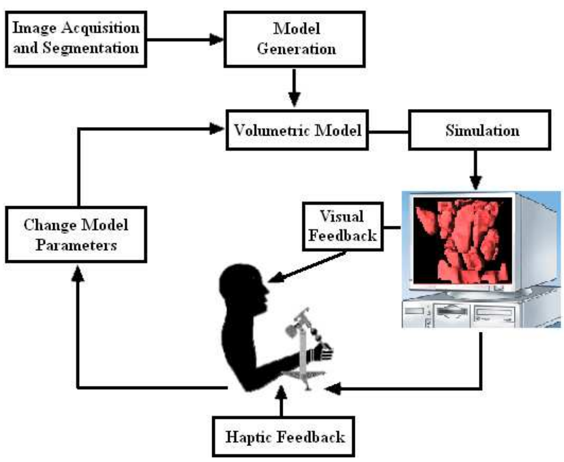


Fig. 1 Computer-Based Simulation System

Three main benefits of the proposed system can be summarized as follows:

**1- Safety**: The use of the computer-based system to simulate medical activities allows the students to learn in a safe environment. They can practice on the models without endangering any patient. Once they have learned sufficient skills on the models, they can perform the real surgeries.

**2- Cost**: The cost of education is also reduced. Medical students can interact with the system very quickly and cheaply. They can perform a particular training scenario as much as required without any additional cost. This would be impossible with real patients.

**3- Flexibility**: The system allows the simulation of any particular surgery with the mastering of the procedure. Also, students can apply different procedures (and treatments), scenarios that would not normally be experienced. Consequently, their theoretical knowledge can be immediately applied in a practical setting.

## 4 A 3D Virtual Wrist Model

The anatomy of the wrist joint is extremely complex. With the development of better and smaller equipment, arthroscopy of the wrist offers the same benefits achievable with arthroscopy of the knee, the shoulder and the elbow. Techniques of performing wrist arthroscopy have been developed to evaluate and treat various wrist disorders, such as Scaphoid fractures. Figure 2 shows a high resolution 3D virtual representation of the bones constituting the wrist of a patient. This volumetric object model is derived from segmenting a sequence of CT images. This representation provides the surgeon with precise and detailed information for training and education purposes.

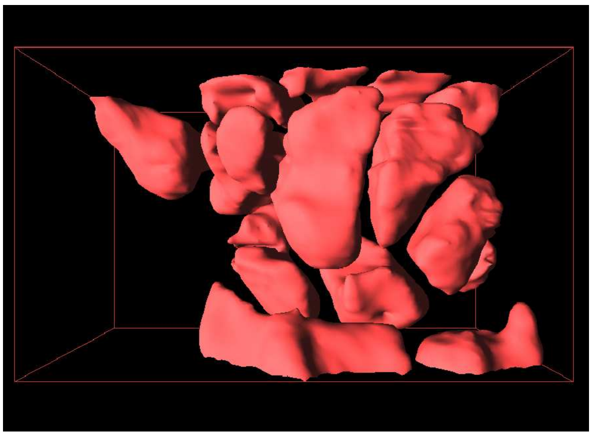

Fig. 2 3D Virtual Model of The Wrist Bones

There are fifteen bones that constitute connections from the end of the forearm to the hand. The wrist itself encloses eight small bones, called carpal bones. These bones are grouped in two rows. The first one is the proximal row. The proximal row of carpal bones is made up of three bones the Scaphoid, the Lunate, and the triquetrum. The second row of carpal bones, called the distal row is made up of five bones: the Trapezium, the Trapezoid, the Capitate, The Hamate, and the Pisiform. The proximal row of carpal bones connects the two bones of the forearm, the Radius and the Ulna, to the bones of the hand. The bones of the hand are called the metacarpal bones. There exist five metacarpal bones ($1^{st}$, $2^{nd}$ $3^{rd}$, $4^{th}$ and $5^{th}$ Metacarpal). These are the long bones that lie within the palm of the hand. The metacarpals attach to the phalanges, which are the bones in the fingers and thumb [16].

## 5 Collision Detection

The goal of the medical simulator is to support medical students during training and practicing on surgeries with high precision. For this reason, medical objects are modeled with a tightness fit i.e. each object is modeled by its corresponding convex hull. This will give the simulator a high degree of precision but at the same time an increase of cost in the complexity and the computational time for collision check. Therefore, by taking advantages of the speed and robustness of Linear Programming (LP) techniques the problem of Collision Detection (CD) is formulated and solved. In addition, convex objects allow the LP algorithm to converge quickly and detect the collision if it exists. Therefore, convex hull of each object is reconstructed. Then, the CD problem is formulated as an optimization problem based on convex objects and solved using linear programming (simplex method).

### 5.1 Convex Hull Algorithm

Most exact collision detection systems work almost exclusively with convex objects because they allow CD algorithms to converge quickly. Moreover, convex envelopes have less contact points then real objects, this leads to a decrease in the size of the system of equations needed to calculate the collision. In addition, convex envelopes can be quickly computed so the real time performance of collision detection algorithms increases and the algorithms become faster. A hybrid technique that is based on QuickHull [17] and Gift Wrapping [18] algorithms is developed to construct the convex envelop of the 3D medical object [19].

The algorithm is a hybrid approach that is decomposed into two stages. The first stage reduces the number of the input points. This step is followed by reconstructing the corresponding convex envelope. The hybrid method is initiated by applying the QuickHull algorithm to divide the input points into two subsets (upper and lower) with an initial plane with the vertices $(x_{min}, x_{max}, x_d)$. Then, a polyhedron of new facets is created by calculating the point having the maximum distance $(x_{dmax})$ with respect to this plane. Consequently, points that are inside the polyhedron are inside the convex envelope and they are discarded. The same procedure is repeated for the lower set. This leads to the reduction of the number of input points and the formation of a new data set. The new set is fed as an input to the Gift Wrapping algorithm. Consequently, wrapping steps are performed by scanning the new data to obtain the final convex envelope. That is, the hybrid method applies the initialization phase followed by a series of wrapping steps. It computes the facets of the hull one at a time, in the counter clock wise (ccw) direction using the sequence of the wrapping steps. The wrapping steps are repeated recursively for every explored edge until all facets have been examined. The convex hull approach is applied on the 3D data constituting the virtual wrist of a patient. Figure 3 shows an example of the algorithm that reconstructs the convex hull of the medical objects.

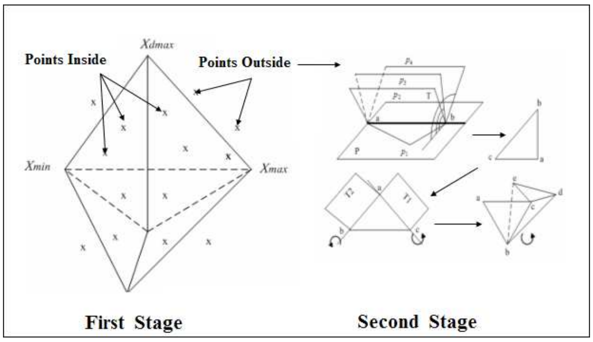


Fig. 3 Example of Convex Hull Algorithm

Figure 4 shows different bones constituting the 3D wrist model: $1^{st}$Metacarpal (a), $2^{nd}$Metacarpal (b), $4^{th}$Metacarpal (c), Scaphoid (d), Capitate (e), Hamate (f), Radius (g) and Ulna (h). Each bone is covered with its corresponding convex envelope.

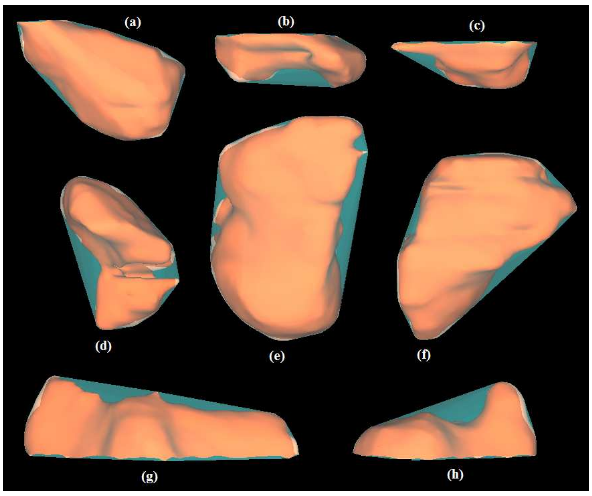


Fig. 4 Bones from the 3D Wrist model enclosed by their corresponding Convex Hulls

### 5.2 Linear Programming Solution

To construct the collision problem, each facet $i$ of the convex envelope is represented by the plane inequality in the form of:

$$a_i x + b_i y + c_i z \leq d_i \quad (1)$$

Any point lying on the object must satisfy the inequalities of the plane constituting this object. These equations form the constraints of the collision problem and represent the facets that separate two regions in space. Therefore, if a point satisfies two sets of inequalities simultaneously, it belongs to the corresponding convex objects. Thus, a collision is detected at that point between these two objects [20].

The problem becomes that of maximizing an objective function in the form of $(x + y + z)$. It is formulated as follows:

$$max\ c^T X \tag{2}$$

subject to

$$AX \leq b \tag{3}$$

where $X = [x\ y\ z]^T$,

$$A = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \\ . & . & . \\ . & . & . \end{bmatrix} \tag{4}$$

$$b = [d_1\ d_2\ d_3 \ldots]^T, \qquad c = [1\ 1\ 1]^T \tag{5}$$

The coefficients of the matrices $A$ and $b$ are calculated using the facets obtained from the convex hulls reconstructed by the approach presented in the above subsection. Using the duality property, the problem becomes:

$$min\ b^T \pi \tag{6}$$

subject to:

$$A^T \pi \geq c \tag{7}$$

Having formulated the problem, the dual system is solved using a linear programming algorithm (simplex approach). If the system is bounded, a feasible solution exists and consequently, a collision is detected. Otherwise there is no collision.

## 6 Haptic Interface

Force Feedback is a very interesting technology in the context of human machine interface [21]. It is used as a haptic interface in order to make 3D models and simulations accessible to users and participants. This will help medical students to develop more their abilities and to connect theoretical principles with physical reality. Figure 5 shows the main blocks that constitutes the haptic feedback system.

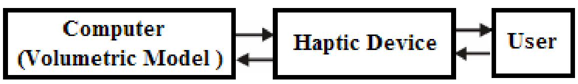


Fig. 5 The Haptic Display System

The standard keyboard and mouse rely principally on visual feedback. Therefore, other approaches have to be adopted to allow the student to feel the collision in the virtual environment. A 4-DOF joystick is selected as the force feedback device that is incorporated in the computer simulation system [22]. This will enhance the surgical performance by guiding the surgeon or the medical student and give them a sense of touch and resistance when collision is detected. Such a device is fully programmable and is compatible with Windows XP and can be connected to a PC via a USB connector. This tool features four axes of control that define, for example, the medical probe movements. Three axes control the movements along X, Y and Z directions (Left, Right, In, Out, Up, and Down). Feedback forces can be applied to these axes to prevent collision to occur and alert the user to the situation. The $4^{th}$ axis is a $4^{th}$ DOF ($\Theta$) that perform the rotational movement of the medical probe. Feedback Forces is not applied to this axis. The joystick interface contains a dll file created using the Microsoft Visual C++ version 6.0 and DirectX 8.1 [23]. It allows the reading of X-Y-Z and $\Theta$ positions from the joystick. Also, forces with desired magnitude can be applied along the X-Y-Z axes when collision is detected. Figure 6 shows the flowchart of the haptic feedback algorithm implemented and tested for the computer-based simulation system.

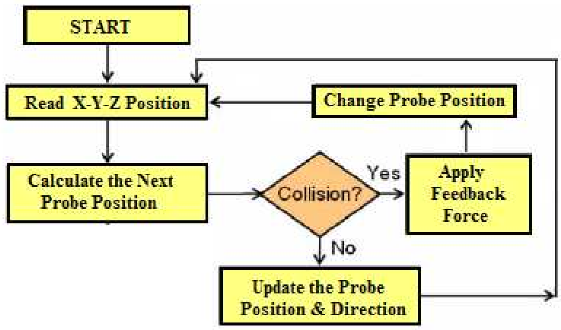


Fig. 6 The Haptic Feedback Algorithm

The virtual environment contains information about the magnitude and the direction of forces to be applied to the user, usually depending on the position of the cursor or the medical probe in this environment. When the user moves the haptic device, the position of the cursor or the virtual probe will change. Thus, a dynamic interaction with the virtual environment is allowed. That is, at every step the position of the probe is computed and the collision is checked by applying the CD algorithm on the updated matrices that constitutes the collision detection problem, i.e. solving the system of equations at every step change. If collision is detected, a force is applied against the motion of the user that uses the haptic device. Therefore, the user can feel the resistance of this applied force against his hand motion, i.e. against the force applied by the student to move the haptic device. Then, the user changes the position of the probe. On the other hand, if there is no collision, the position of the probe is updated. This force-reflecting device enables medical students during their training to mimic the real feeling of touch. This enhances the capability of the system and gives the user the feeling of so called "Immersion".

## 7 Conclusion

Computer-Based surgical simulators play an important role in the generation of virtual models and the practice of surgery for medical education and training. These simulators improve patient care and assist medical decision-making. An innovative application is the hand surgery, especially wrist arthroscopy, which has proven to be an extremely valuable tool in both diagnosis and therapy. This paper presents a functional prototype of a Computer-Based simulation system that can be used by students with the same benefits as professional devices. 3D virtual model of the wrist of a patient is shown. Algorithms that model objects using the convex hull approaches and simulate real time exact collision detection are presented. Also, a force feedback device coupled with a haptic simulation algorithm is incorporated with the system. This system can be applied to simulate the wrist arthroscopic surgery and students can easily run it with their own personal computers. Therefore, they can learn the required basic skills and then perform the training procedure on real patients. This low cost system is safe, flexible and can provide the students with precise and detailed information for training and educational purposes.

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