Development of virtual reality based robotic surgical trainer for Patient-specific deformable anatomy

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ABSTRACT

The need for training surgeons for robotic surgeries is increasing with the increase in number of laparoscopic procedures performed with robots. The commercial simulators available are expensive and hence not available to all. This paper provides a method to develop a virtual reality based simulator with open source software and a game engine. Another feature included in the simulator is the use of patient-specific organ models. This is advantageous since it is safe and less expensive compared to other simulators, and also is more flexible due to the use of game engine. For a realistic simulation, a model of tool-tissue interaction is carried out between the tool and an external tumour using the method described. The reconstructed geometric organ model, after being meshed, is integrated into the laparoscopic surgical simulation system consisting of a haptic interface device and a graphic display.

Keywords

Virtual reality, surgical simulator, haptic device, laparoscopy, game engine

1. INTRODUCTION

Laparoscopy, though claimed to be more than a century old, was introduced with laparoscopic cholecystectomy (LC) procedure by Phillip Mouret in 1987. He is largely credited with launching the revolution in Minimally Invasive Surgery (MIS). Also, recently it has been said to be revolutionised by Robot Assisted Laparoscopic Surgery (RALS) [1]. Surgical training is the inevitable part of refining surgical skill. The traditional method of training in the field of open surgery has been following the *Halstedian principle* which is “see one-do one-teach one” [2]. Unlike open surgery, laparoscopic surgical training is more challenging because of the need for enhanced hand-eye coordination and fundamental psychomotor skills of trainee surgeons for spatial and depth perception, as well as to work without the realistic experience of force feedback during tool–tissue interaction [3]. Additionally, surgeons are left with only a monocular visual cue, which is a 2D projection of an original 3D environment, or a passive 3D view. As extensive training is needed for critical application like laparoscopic resection for malignant tissue, quality of such complex laparoscopic surgical procedures can only be ensured after rigorous training [4], which is implausible with a conventional trainer. Animal and human cadaver tissues, synthetic bench models, mannequins and box trainers are common modes for training of MIS/RALS that allow trainees to hone their skills in a safe environment [5]. With the evolution of technology and surgical procedures, methods of training evolved as well, towards virtual surgical environment which is accepted well by the surgical community globally [6].

From various studies, it is evident that training on a Virtual Reality (VR)-based simulator results in more adept doctors for robotic surgery [7]. It also ensures improved patient care, by reducing the time required for surgery and most importantly, increasing the surgical accuracy. Another significant advantage of VR simulators over box trainers is that the former provide flexibility on the selection of the training scenario, which can be tailored to the required procedure accompanied by the augmented anatomies with Digital Imaging and Communications in Medicine (DICOM) images. Unlike the case of open surgery, a learning process assessment is a challenging work for laparoscopic surgery which makes the training curve reasonably stiff. Efficiency of the training process and the performance assessment is conventionally carried out only via expert supervision or review of recorded videos. [8] Following the popular archetype of pilot training, over the last decade, virtual reality has been introduced for training in MIS. [9] Virtual Reality (VR)-based system involves a graphical model of 3D anatomical structures on a 2D screen. The required manipulations are performed by the trainee with the help of a human interface device, which captures the pose of the surgeon’s hand [10].

While repeated training with a visual cue dramatically increases the performance of a surgeon, a haptic cue reinforces the training accuracy significantly [11]. A combined approach will be a worthy choice for a patient specific laparoscopic surgical training. A patient specific surgical training system is more relevant in case of deformable anatomy where stereotactic surgery really underperforms [12]. Though there are some existing devices that provide a virtual training environment [13], these devices do not allow incorporating patient-specific real anatomies with the augmented training tasks. An augmented virtual surgical training environment is highly advantageous since it includes both dry lab training and anatomical lesions. The virtual model can be used for simulating, analysing and evaluating preoperative surgical treatment options prior to performing an actual case, which may increase surgeon’s confidence in the upcoming procedure.

A comprehensive VR based system design with the aforementioned features will be a useful device which can be used for more efficient laparoscopic surgical training. In this paper, the development of a VR based surgical simulator for the purpose of patient specific training for RALS and MIS procedures is thoroughly presented. The rest of the paper is structured as following: first, a description of architecture of the virtual environment that was developed with the use of *graphical computation framework (graphical engine)*, which reconstructs the deformable anatomy, is provided. The front end of the simulator is described subsequently, which combines the virtual environment with a haptic enabled human interface device

AIR '15, July 02 - 04, 2015, Goa, India

DOI: http://dx.doi.org/10.1145/2783449.2783465

as an interface between the trainee surgeon and the simulated environment. This is followed by the method to obtain patient specific organ model being described. Finally, a case study is carried out for removing an external tumour from the liver by using the simulator developed through the given method.

2. ARCHITECTURE OF THE PROPOSED SYSTEM

The proposed architecture of the virtual simulator system, that integrates a graphic calculation framework with an input module and a visual display, is shown in Figure 1.

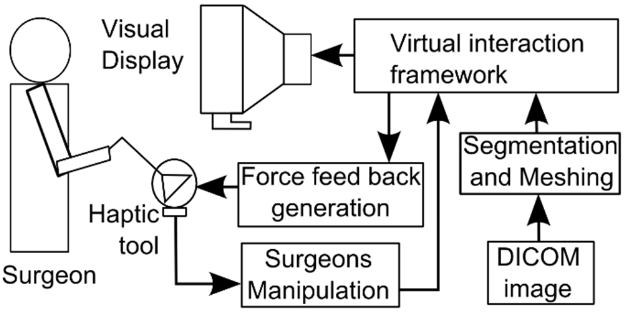

Figure 1: Schematic representation of the VR simulator system architecture

The organ models of patients are reconstructed, meshed and imported into the virtual environment frame work. The surgeons' hand motions are captured using an input device such as joystick, game pad, haptic devices etc. The input device is mapped to a virtual instrument by the virtual interaction frame work. The rendering of the organ, tool and the environment is done with the help of a reconfigurable virtual scene development tool (game engine) and projected on to a visual display. Surgeons can interact with the organ models using the input device and get a visual and haptic feedback for carrying out the virtual surgery. The design and implementation details of the simulator is explained in the following sections.

3. DESIGN OF THE VIRTUAL SIMULATOR

The simulator has been designed with three important modules as shown in Figure 2. An Input module (IM), Rendering Module (RM) and an Image Re-construction module (IR).

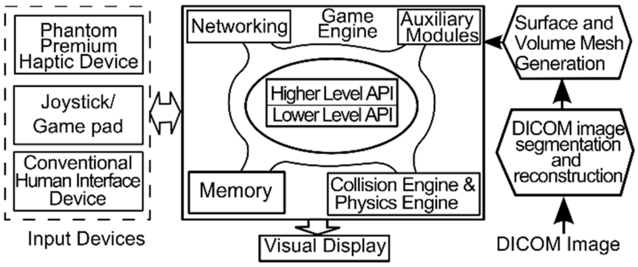

Figure 2: Important modules of the simulator

The virtual environment was rendered with the help of a game engine that consists of various modules within itself. This central engine works as a nexus for the input system deformation and collision detection framework. The provision of detachable input device is an advantage of this proposed framework and the replacement of the tools are possible as surgeon's choice. The graphics engine in the environment provides the support for any visual data as seen during rendering. The Collision and Physics engines are responsible for detecting a collision and responding to it accordingly. The sound feature could be used to play back the same sound as heard during a surgical procedure, to give a more realistic feel of surgery to the surgeon. The memory and networking modules are essential for any simulator and these are managed by default in a game engine. The Artificial Intelligence in a game engine, though has not been used in the scope of this paper, can be used to provide feedback regarding the performance of the surgeon. Details of each module and their utilisation in the development are listed below.

3.1 Game Engine

Game engines are a software framework that have been designed to render a virtual scene with augmented realistic characteristics of the scene object. The engine was competently used here as a medical environment simulator. A typical game engine consists of a rendering engine, also commonly known as a graphics engine, which is responsible for the 2D or 3D graphics, and a physics engine that handles mathematical models for calculating the rigid or soft bodies, collision detection, sound, artificial intelligence, networking, and memory with associated modules. The game engine is not just responsible for rendering but also for the mechanics of the process [14].

The graphics engine is responsible for loading and displaying rendered anatomy, as well as managing data related to graphical content. The graphic engine also takes care of texturing, lighting and animation. The meshed organ can be loaded and viewed in a simulator with the help of it. The physics engine performs advance mathematical calculation required for the collision response of the body.

3.1.1 Graphics Engine

A graphics engine is a graphics library or framework that allows one to generate 2D or 3D models on a computer program. All the different aspects of the scene are defined such as the geometry, viewpoint, texture, lighting, shading and all the information of the scene. This data is read by the engine which processes it and outputs it to a digitally rendered anatomical part on the visual display. The Graphics engine used in the medical simulator integrates features for visual representation some of which are dynamic shadows, particle systems, and collision detection to provide a better realistic experience to the surgeon in the rendered environment.

3.1.1.1 The Rendering Equation

The rendering equation represents the principal theoretical concept of rendering. The main objective of any rendering is to solve the rendering equation. It expresses the radiance emitted at a given point on a surface in a particular direction, as the sum of reflected radiance resulting from the light from other surfaces and self-emitted radiance. There are multiple methods of solving the rendering equation like finite element methods which use the *Radiosity Algorithm* [15], Monte Carlo methods which uses many different algorithms such as Metropolis light transport and photon mapping. The equation in general is formulated as

$$L_0(x,\omega_0,\lambda,t) = L_e(x,\omega_0,\lambda,t) + \int_\Omega f_r(x,\omega_i,\omega_0,\lambda,t)\; L_i(x,\omega_i,\lambda,t)(\omega_i\cdot n)d\omega_i \quad (1)$$

where, λ denotes a given wavelength of light, t denotes time and x is the location in space, ω_0 signifies the outgoing light's direction,

ω_i signifies the negative direction of incoming light, $L_0(x, \omega_0, \lambda, t)$ denotes the net spectral radiance of wavelength λ at time t and a particular position x, directed outward along direction ω_0,

$L_e(x, \omega_0, \lambda, t)$ denotes emitted spectral radiance, Ω denotes the unit hemisphere which consists of all the possible values for ω_i ,

$f_r(x, \omega_i , \omega_0 , \lambda, t)$ represents bidirectional reflectance distribution function determined by the proportion of light reflected from ω_i to $\omega_0$at position x, time t, and at the specific wavelength λ,

$L_i(x, \omega_i, \lambda, t)$ represents spectral radiance of wavelength λ directed inward toward x from direction ω_i at a given time t,

$\omega_i . n$ denotes the weakening factor of inward irradiance due to the incident angle, as the light flux is spread across a surface whose has an area larger when compared to the projected area perpendicular to the ray.

Equation (1) represents the generalised mathematical framework for rendering. The movement of light in an environment depends on the way rendering equation is implemented in a graphics engine. This plays a significant role in the selection of the engine to provide a realistic simulation both for local and global lighting scenarios. Here the *Radiosity Algorithm* was utilised within OpenGL environment for a high quality anatomical environment generation.

A rendering engine has set of routines, protocols and tools used for building a software application known as Application Program Interfaces (APIs). They can be categorized into two sets- a Lower Level API and High level API, which work together hierarchically. Here we have used OpenGL as Lower Level API and IRRLICHT for our higher level API.

Using the Irrlicht engine for graphics in the case of the medical simulator ensures high performance real time 3D rendering using OpenGL, along with optimized math and container libraries. It also provides the advantage of importing commonly used 3D file formats, providing flexibility in the rendering system. It provides fast and easy collision detection and response in the visual domain, which is not present in most open source graphics engines. These parameters play a significant role in the development of a simulator since the computational capability in systems are not as fast as what is required for real time rendering. Hence, satisfying these conditions would result in a system that is the closest to real time rendering of a surgical procedure. The lighting conditions, after solving the rendering equation correctly, and appropriate movement of deformable particle also result in a realistic model of training.

3.1.2 Physics Engine

A physics engine is a framework or set of libraries that provide a simulation of certain physical systems like collision detection (which is an integral part of a physics engine), rigid body dynamics and soft body dynamics closest to a realistic model. The physics engine chosen for the purpose of the simulator was Bullet Physics, which is one of the most widely use collision detection and rigid body dynamics library. It is one of the very few open source engines which incorporate both soft and rigid body properties of models. The soft body and the rigid body dynamics attribute to the structural properties of the rendered deformable anatomy and rigid surgical tool as well, while the collision detection does the job of the intersection and overlapping detection of multiple objects. The Bullet Physics engine has simulation capabilities which enable assigning soft and rigid body properties simultaneously in a single simulation, in this case assigning the instrument and liver with different physical properties. This hence results in a feedback similar to that observed in an actual surgical procedure. The virtual interaction is possible only after assigning the physical property to the objects in a scene, which is followed by the collision detection through a sub section of Physics engine called collision engine.

3.1.2.1 Collision Engine

A collision engine is a subset of a physics engine. It essentially checks for the sprites or if models are intersecting and hence detects a collision. The collision engine majorly consists of two parts, namely, collision detection and collision response.

The collision detection is of two forms, namely, Continuous and Discrete. A Discrete collision response are used generally, which is a O(n^2) [16] (2 nested loops) loop through all the different object pairs, it checks for an overlap in between the objects. Each object has multiple spatial data, bounding shape and multi-part convex sub shapes.

The spatial data structures for the object like Dynamic AABB trees are fast and good for handling a greater number of moving objects and others like KD-Tree are more suitable for static level geometry that objects collide with. Since there are varied advantages and disadvantages to these data structures, most higher-end engines use more than one of them. In the proposed model, a diverse set of spatial data structures were used to handle the collision detection in a better way.

In the simulator that was developed, a continuous check for collision detection was carried out at the tip of the instrument. Once a collision was detected based on the bounding box interaction values of the tool and the organ, the value of the position was transferred, invoking a response from the physics engine.

The final step in collision detection is to determine the exact location of intersection of the geometry. The points of contact are then determined, which will in turn affect how the objects respond, a process known as contact manifold determination.

Once a collision is successfully detected, it evokes a Physical Response. The physics engine will use the information on colliding objects and their contact manifold, and determine the new positions required to separate the collided objects. The physics engine makes use of other forces acting on the objects, such as gravity, while calculate the objects' new velocities, and their new positions. The objects are then moved to these new positions. The velocity change generated from this push is also calculated, taking into account the restitution and friction values.

The graphics engine and physics engine work together so as to depict the exact change visually as well. Once the reaction forces act on the organ, the necessary deformation can be viewed on the visual display.

3.2 Patient Specific Organ Model

In order to create a patient specific deformable anatomy, DICOM images of radioactive (Computed Tomography) and non-radioactive (Magnetic Resonance Imaging) scans were utilised. The images were downloaded from National Biomedical Imaging Archive (NBIA) [17].

The organs were reconstructed using an open source segmentation framework (Slicer 3D™ 3.0.) It helps in generating virtual three dimensional model corresponding to human anatomical parts by segmentation of 2D slice.

For the purpose of collision detection and slicing in the virtual environment, the meshes are usually chosen to be tetrahedral in nature. The constructive solid geometry (CSG) models with boundary representation had to be attributed with optimised mesh structure for assigning 3D structural properties. Hence, a tetrahedral mesh generator (NETGEN 5.1®) package was used. A hierarchical mesh refinement was also ensured concurrently with the tool. Figure 4 shows meshed structure of liver, from (a) sagittal view (b) isometric view, (c) coronal view and (d) transverse view.

4. A CASE STUDY - RESECTION OF LIVER MALIGNANCIES

A case study was adopted in the virtual simulator for a resection of liver surgical procedure. Resection of liver (for hepatoblastoma) is considered to be challenging for novice surgeons and sometimes even for experienced surgeons. Accurate tumour resection within deformable anatomies are especially challenging in laparoscopic surgery because an accurate resection varies from case to case, with accompanied metastatic lesion. A patient specific surgical planning and training increases the accuracy and is a very helpful tool in such scenarios. The principal difficulties lie in this case is prohibition of palpation or manipulation, and the high surgical margin of error (>1 cm), ensuring minimal or no biliary leak [18].

As a first step in the organ model generation, a set of PET CT images (with F18-fluorocholine in patient) was used for generating a 3D liver model. The liver part with a left lobe metastasis was segmented out and reconstructed using a 109 transverse CT slices. A semi-automatic segmentation and 3D surface reconstruction was implemented in Slicer 3D. [19]

After constructing the 3D DICOM images, the software allows the generation of stereolithography (STL) files for rapid prototyping.

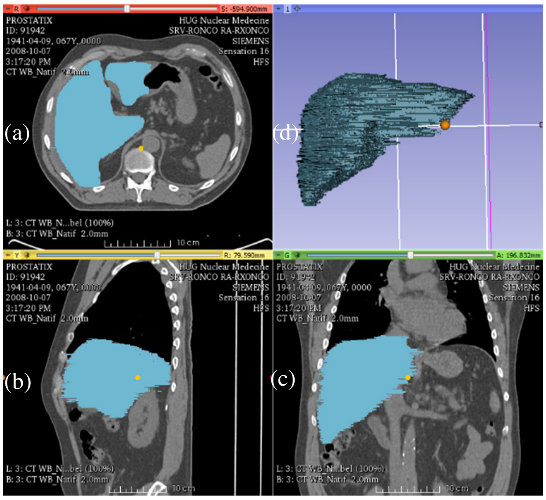

Figure 3: Reconstruction of Liver from DICOM images

Figure 3 shows the (a) transverse plane view, (b) sagittal plane view, (c) coronal plane view of the liver and (d) the reconstructed 3D volume with a coarse initial surface.

The STL file does not have any in-built mesh properties. Hence, the modelled organ was then used further for tetrahedral meshing with provision for variable mesh size. The meshing in this specific case has to reflect the topologies of the underlying structure. An uneven meshing of the liver part was implemented.

Finally, the meshed liver file was imported into the virtual environment for manipulation. A laparoscopic surgical tool was also mapped to the virtual tool in the environment.

The Irrlicht graphics engine is responsible for displaying the liver and the related deformable change that occurs. The Physics engine deals with the physical/mechanical properties of the system. Soft body collision is determined by the collision engine, which then relays the information to the collision response

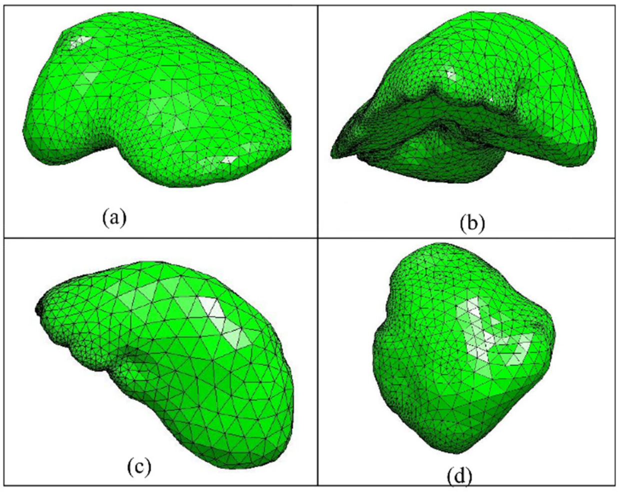

Figure 4: Different views of meshed organ

Once the stiffness value of the region to be cut is surpassed, the tumour can be removed from the liver. The stiffness value of the hepatoblastoma had to be different than the healthy part of the liver. The details of stiffness values are available with various reported work [20] [21].

The setup consists of a standard PC with 8 Gigabytes of memory along with a 2 Gigabytes of graphics processing unit which does not have the dual precision floating point performance being limited. The GPU provided increased display channels and faster scene colour rendering capability, thereby resulting in higher resolution and, hence, better clarity of simulation. A human interface device was connected with the PC with legacy serial/parallel protocol. Phantom Premium™ 1.5 (SensAble Technologies) was used as a haptic enabled device. The Phantom Premium is a 6 DOF input sensing (x, y, z, roll, pitch, yaw) haptic device to provide accurate 3D object manipulation, with haptic cue provided to the user. This provides a complete touch-based feedback, which enables the user to feel the collision forces along with the reaction forces on a path as realised in the virtual environment. The haptic provides movement that is similar to the lower arm pivoting at the elbow.

The developed simulator along with the hardware setup is shown in Figure 5.

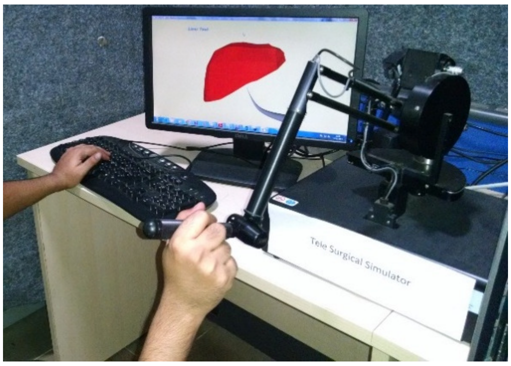

Figure 5: Hardware setup

Slicing of external tumour is an example of the type of slicing that can be carried out. Similarly, cutting open a liver and removal of internal tumour can also be modelled in the virtual environment. The stiffness of the liver is different from that of the tumour. The resulting haptic feedback from the organ can be felt by the surgeon, by a realistic sense of touch in all three directions.

5. DISCUSSION AND CONCLUSION

The design details of a virtual simulator for robotic surgery have been presented here. Primarily the simulator was designed to include liver-instrument interaction (soft and rigid body interactions) with haptic feedback and realistic modelling of a surgical procedure. Patient specific 3D model of specific anatomies was successfully incorporated into the simulator so that the surgeons will get an opportunity to do a pre-operation virtual surgery along with a surgical and allied treatment planning. It is important as the metabolic and functional changes after hepatic resection is highly case specific. On the other hand this would offer the trainee surgeon a practical feel of cutting a liver and a tumour by differentiating the way the instrument interacts with the different parts of the liver, or any other organ. The use of haptic tool in this system to provide a force feedback to the surgeon gives a realistic experience. Discrimination of the physical properties of hepatoblastoma and a healthy tissue with an increased scale is possible at a higher computational cost. At this primary level of the work, optimizations have been done to ensure that the graphics processing is smooth and occurs with a minimum of 30fps, ensuring lack of latency issues. Development of an integral platform to include the segmentation, reconstruction, and virtual manipulation with one application specific interface is the next challenging part of this work, which can be used for a better surgical training system in RALS and conventional MIS.

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