Virtual Surgery on Geometric Model of Real Human Organ Data

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Abstract

Traditional Surgery methods involve collection of patient's data, data study and providing specific instructions to carry out surgery. General issues while conducting surgery are limited degree of freedom, side effects such as infection, haemorrhage etc. Virtual Reality Technology has aided these methods by incorporating techniques such as 3D model visualisation, training in synthetic environments, pre-operative planning etc., thereby assisting a medical personnel in conducting a real surgery.

Existing Virtual Reality (VR) systems are implemented in two fronts i.e. visualisation, where real datasets are analysed in 2D/3D and surgery simulation, where pre-modelled datasets are used for simulating surgery scenarios. The literature documents that, attempts have been made to use real datasets for both visualisation and simulation. Hence, there exists a need to bridge this gap. This paper presents the development of a virtual surgery application that processes any real dataset in its native format into a geometric model, deploying realistic surgery scenarios.

Computed Tomography (CT) Images in Digital Imaging and Communications in Medicine (DICOM) format generated by the OsiriX Image Navigation Software, are processed into a geometric model containing contour surfaces. The model is deployed in the visualisation and surgery procedure scenes. The scenes are developed such that the user can perform 3D visualisation of the input dataset, navigate in the Virtual Environment and also conduct an incision procedure for user training and study. The implementation also involves a scalpel model used to conduct the procedure and applying textured environments for realism. Menu and text based Graphics User Interface (GUI), with VR device interfacing are implemented in the system for user interaction.

The system proves the concept of virtual surgery. Enhancements can be made to develop a full fledged system that would be beneficial to surgeons for pre-operative planning and performing mock surgery on real data. Also, medical students can acquire surgical experience while exercising surgery procedures.

Key Words: Virtual surgery, Virtual reality, Surgery, Surgery procedure, Incision simulation

1. INTRODUCTION

Several diseases are diagnosed by Medical Professionals, resulting in the treatment of infected areas by careful observation, procedure affirmation and procedure implementation using quality instruments needed for the task. Operations are considered a success or failure after undergoing systematic procedures followed by surgeons, who would perform them i.e. as schedule based procedures or emergency procedures depending on the need.

A usual scenario would be a patient being brought for diagnosis with complaints of pain in specific areas. The surgeon would then schedule his or her task depending on the seriousness of the pain after preliminary diagnostic procedures have been conducted. Careful observation and validation of the patient data acquired by scanning the area under investigation is done. Surgeons would then have to operate on the patient with the given information using surgical instruments by following standard surgical procedures. Common side-effects caused due to operations would be obstruction of other organ parts while conducting the surgery, a surgeon's limited view and degree of freedom in accessing tissue structures.

Moreover, an operation to be performed at its best would require a considerable amount of practice by surgeons, so that he or she can conduct them without hesitation. Medical students would suffer this because he or she would need to gain experience for the first time, while young surgeons would need to develop and practice their usual skills. Practitioners would be trained on animal cadavers or mannequin to experience before performing an actual surgery. To the surgeons, visualising on light boxes needed placement or removal of scanned images for study and imagination of the actual anatomy. Animal cadavers used by medical students exhibit a different anatomy and simulation on mannequins is expensive. Fig. I shows traditional practices used in surgery. In Fig. I (a), [1] professionals are studying the patient data on a light box and in (b), [2] a mannequin is being used as part of a human patient simulator.

Fig. 1: Early Surgery Methods (a) Surgeons viewing data on light boxes[1] (b) A mannequin used as part of a simulator [2]

VR Technology assists traditional approaches by generating graphical images (2D or 3D) of real patient data, allowing user immersion in a synthetic environment, giving the practitioner a realistic feel of human organs. The Medical Practitioner can conduct virtual training on 3D models to gain experience on any
specific procedure. Systems are developed that would help visualise complex patient data, to the maximum closest extent, thereby assisting the surgeon or medical practitioner to gain understanding of the data. Surgeons can conduct a pre-operative surgery before touching the real patient. The entire process would be cost effective since the only requirement would be to attain computing resources having high processing capability and storage capacity and interfacing devices (Haptic) to generate feedbacks. Practitioners can develop their skills by undergoing virtual training on basic procedures such as cutting, grasping, suturing etc. Fig. 2, shows software's session screen shots of Virtual Environment (VE) generation [3] and Dataset visualisation [4].

2. LITERATURE REVIEW
2.1 Review Classification

The literature documents a wide spectrum of work carried in the past, with respect to the present scenario. The literature review is classified as (1) Choice of Library/Toolkit (2) Current VR Systems (3) Methods used Simulating Surgical Incision.

2.1.1 Choice of Library/Toolkit

Bierbaum and Just [5], discusses vital facts in the development of VR system. Firstly, effective immersive environments need high frame rates (15 Hz or better) and low latency. Secondly, the developed environment should be flexible enough to be able to adapt to many hardware and software configurations. Finally, the developed system should be easy to configure and to learn. A developer can choose between high-level interfaces (For E.g. Virtuos, Quest3D etc.) that contain scripting languages or low-level interfaces that requires rigorous development for a particular event. Modelling Interfaces can be chosen between external modelling interfaces or interfaces that contain the API to model them. The authors discusses some of the VR softwares (Iris Performer, Alice, Cave Automatic Virtual Environment (CAVE) Library etc.) along with their strengths and limitations. The paper gives a clear understanding on the features that need to be looked into while choosing a software.

Dresenon [6] has given a study on open-source softwares for medical images. The author describes the features of Open Source Software Libraries - The Visualization Toolkit (VTK) and Insight Segmentation and Registration Toolkit (ITK). VTK as an open source library containing many algorithms for 2D and 3D image processing and visualisation. The library implements the concept of data processing pipeline and contains numerous filters for reading, modifying and writing data. ITK is an extension of VTK, used for image analysis. The author describes software applications developed out of these open-source softwares i.e. OsiriX, Julius and (X)MedCon. A clear understanding on the software libraries, VTK and ITK is given and also its usability in a variety of platforms.

2.1.2 Current VR Systems

Robb [7], discusses Virtual Endoscopy or computed endoscopy a method of diagnosis using computer processing of 3D image datasets, CT or Magnetic Resonance Imaging (MRI) scans to provide simulated visualisations of patient specific organs similar or equivalent to those produced by standard endoscopic procedures. The system provides viewing controls and options such as direction and angle of view, scale of view, immediate translocation to new views, lighting and measurement are implemented. Visible Human Male (VHM) datasets from the National Library of Medicine, US, are taken as input datasets to perform visualisation.

The datasets are first pre-processed by transforming it into isotropic elements. These images are then brought into spatial synchrony and segmented to reduce the dataset to the desired specified anatomic structure(s). Surfaces are extracted by segmenting single anatomic objects from the 3D images. Theses surface are then converted to a meshwork of polygons, manipulating information such as color, lighting, textural patterns etc. A preview of the rendering is done by radiologists, surgeon or endoscopist to confirm whether the model is acceptable. If acceptable, visualisation of the models are done using advanced display procedures else re-processing of the datasets is done. The Virtual endoscopy models of the torso and its contents acquired from the VHM have been used for interactive visualisation. Simulations are done using fly-throughs captured of the segmented and modelled stomach (Fig. 3 (a) [8]), selected locations of the trachea, esophagus, colon (Fig. 3 (b) [9]) and aorta.

Fig. 2: Current VR Techniques (a) Rendering a VE in KISMET [3] (b) Dataset Visualisation in Mimics [4]

Fig. 3: Visualization Scenario in Virtual Endoscopy (a) Different sections of the stomach [8] (b) Different views of human organ models with an isolated colon model [9]
Kühnnapfel and Maß [10], discusses a VR system for simulation and training. The system is used for simulating minimally invasive surgery (MIS) using the simulation software KISMET. The software consists of a space-based modeler KisMo for the creation of virtual anatomies containing deformable anatomical organ models, generating a spatial mass-spring network equations for elastodynamic simulation. Simulation of active behaviour on interaction with virtual instruments is done making use of dynamic spring/mass equations solved by second order ordinary differential equations (Lagrange equation). A predictive equation, Newton-Euler, is used for determining the new position and position of masses at specific instants of time. The elastostatic Finite Element Method (FEM) is used due to high computations involved and the risk involved in numerical instability. Modelling sessions using KisMo can be seen in [10].

(a) Modelling the creation of a volume block (b) Modelling the cutting of a volume block

Fig. 4: Modelling and cutting a volume block

2.1.3 Methods used for Simulating Surgical Incisions

A paper by Bielser et al [12], describes ways by which the modelling and interactive cutting can be done. This can be used for surgery simulation in a virtual framework. The method of tetrahedralisation is used to perform this simulation. Incisions are simulated on a 2D mesh using a line object as scalpel. The approach is simulated on a 2D mesh using a line object as scalpel. The line object is intersected on the mesh, where the active (intersected) nodes are moved. This is followed by local remeshing of the active triangles. The methodology is implemented on 3D surfaces using single incision and multiple incisions. The authors use the Delaunay approach primarily to produce well-shaped meshes with few elements.

2.2 Summary

The summary of the Literature Review is given based on the Review Classification.

Choice of Library/Toolkits

- The literature review give a clear understanding on the choice of toolkits based on certain criterion such as software performance, flexibility, import and export capability and capability to interface with different VR devices.
- Libraries/Toolkits can be divided into two categories i.e. (1) High-Level and (2) Low Level.

Current VR Systems

- Preliminary tasks of acquiring organ data, handling large datasets, pre-processing datasets needed to be given importance for the development of a surgery application.
- Few systems have used Real Datasets for both visualisation and surgical procedure simulation.

Methods used for Simulating Surgical Incisions

- From the literature study, different approaches were used for simulating real life surgery. Incisions were simulated using subdivision, Delaunay mesh refining.
- Organ datasets are modelled based on Physics Principles i.e. mass spring, finite element method to simulate organ deformation.

3. PROBLEM DEFINITION

3.1 Problem Definition

Current Simulators make use of Pre-Modelled Datasets for training procedures and simulating real surgery scenes where as Real Datasets are used mostly for interactive visualisation. A few attempts are made in the past to use Real Human Organ Data both for visualisation and to perform mock surgeries. Thus exists a need for such attempts.

3.2 Problem Statement and Objectives

The aim is to develop a VR application for visualisation and practicing surgery on Geometric Model of Real Human Organ Data. The objectives are.

1. To develop an application that would process patient's Real Data into usable form.
2. To visualise the processed data, through user controlled camera navigation using appropriate environmental settings.
3. To develop a Virtual Surgery Procedure and surgical tool to conduct the procedure.
4. To develop the application GUI and VR devices interfacing.
3.3 Methodology
The methodologies used for the development are briefed below.

1. Patient’s Real Data in DICOM format, is processed into a Geometric format which is then rendered in a synthetic environment.

2. The visualisation scene is developed making use of a user controlled virtual camera for user navigation and dataset visualisation in the 3D environment. Textured environments, model material properties and lighting effects are applied to the virtual scene for realism.

3. The algorithm for the surgery procedure is developed, for which a Real Organ Dataset is taken and manipulated for simulation. A synthetic surgical instrument is modelled using basic geometric primitives - cylinder, cube and sphere.

4. The GUI is developed for dataset inputs and camera controls specification. VR devices interfacing is done for controlling camera movements in the visualisation module and the virtual instrument in the surgery training module.

3.4 Scope of Development
The following scope is used for the development of the application.

- An exclusive surgery procedure is considered for simulation. The surgery instrument is modelled for this procedure.
- Two datasets are considered for the testing and implementation of the application. The datasets are chosen, based on the size, commercial use, memory consumption and computation criterion.
- The application is built with hardware resources of appreciated configuration to deploy realistic scenes.

4. SYSTEM ANALYSIS AND DESIGN
4.1 System Analysis
A structured analysis is required for the development of the application. This stage of system development helps in fully realizing the system which is to be designed, developed and implemented.

4.1.1 System Parameters
This part of the analysis include the Input/Output requirements as well as the processes involved in the development of the application. Each of the requirements are specified below.

Input Requirements
- 2D DICOM Image Datasets
- Real-Time User Inputs from VR/Traditional input device

4.1.2 Hardware Requirements
- RAM ~ 4GB
- Graphic Card ~ 512 MB
- Processor Speed ~ 2GHz
- VR devices - Pressure sensing DataGlove and Gaming Joystick

4.1.3 Software Requirements Analysis
Choice of Toolkit
The preliminary task involves the study of different Software Libraries and Tools available for the development of this application. A comparative study on various toolkits are done and it is found that OpenGL (Open Graphics Library), VTK and ITK Software Libraries are useful for the development of the application. These tools are chosen for the following reasons.

- Since open some libraries are used, users are benefited by their adaptability in various Operating Systems and availability public free of cost.
- Each of the tools have got their specific areas of implementation that can be incorporated in the application development. For instance, VTK for complex visualisations, ITK for medical image analysis and OpenGL for its ability to interact between the former libraries, Interfacing user-interaction devices and GUI development.

4.2 System Design
4.2.1 Application Design Flow
The application begins with an initial display scene. Continuous polling of the interface devices is done. The user needs to input an event choice i.e. Visualising a dataset or Perform a surgery procedure. The visualisation process consists of dataset visualisation which is implemented by providing 'user specification' of the folder consisting of DICOM images. The surgical procedure module consists of training and simulation, where the user can perform a real life surgical procedure. The system ends when the user chooses the close option from the application. Fig. 5, shows the overall design of the application which are further divided into visualisation process and surgery procedure modules.
Visualisation Module Design Flow

Visualisation of a human organ dataset is an essential component in a virtual surgery application. Four operations are involved in the visualisation module i.e. reading the dataset, writing a volume, camera navigation and virtual scene setup. The folder containing the DICOM images is set by the user and the images are read by the system. The volume is written either in memory or to the storage disk, for visualisation. Camera movements are given to the user to navigate the virtual environment. To give a realistic impression of the actual surgery, virtual environments are modelled using organ textures mapped onto 3D objects. Textured objects along with the dataset input is placed in the scene for visualisation. Fig. 6 shows the module design.

Surgical Procedure Design Flow

The execution of surgical events involves three main operations; instrument collision with the dataset, modification of the dataset geometry and giving a visual response. The design is shown in Fig. 7, where the system receives coordinates of the virtual surgical instrument and a real-time collision check has to be performed, between the instrument intersection with the dataset. When the step is achieved a visual response due to dataset modification is given to the user.

4.2.2 Application GUI Design Flow

The GUI design of the system consists of primarily two parts i.e. Input GUI and Output GUI. The Input GUI consists of the user input of the dataset directory for visualisation or a surgery event. A choice of any of these two events leads to a 3D environment setup scene where the user can visualise. Fig. 8, shows the layout of the GUI. The Input GUI consists of menu based selection of the directory list or an event.

The Output GUI consists of Application Run-Time Information and Control Specifications for the devices. The control specifications mention user-inputs for camera navigation and instrument motion.

5. IMPLEMENTATION AND RESULTS

DISCUSSION

5.1 Implementation

Data Acquisition, Geometric Model Creation, Camera Navigation, Incision Simulation are tasks that are developed. The stages for the development of the tasks are described below.
5.1.1 Stages of Development

1. Data Acquisition

Experimental DICOM datasets are obtained from a CT/MRI source [14]. These datasets are used as sample datasets for the OsiriX Image Navigation Software (Mac OS X). The images contained in the datasets are segregated to specific folders for user input of the dataset directory path. The first dataset is a surgical-repair-of-facial-deformity of size 25.4 MB and a total of 48 images (Fig. 9 (a) [14]). The second dataset is a normal CT-Coronary acquired on a 16 detectors CT scanner of size 110 MB and a total of 220 images (Fig. 9 (b) [14]).

Fig. 9: CT Images in DICOM format [14] (a) Surgical-Repair-of-Facial-Deformity (b) Coronary

2. Rendering the Geometric Model

The directory containing dataset images is set using the ITK Grass Roots Dicom (GDCM) Library, Input Class. A series of DICOM images are read and copied to the computer memory as a volume dataset and also acquired as a 3D Model (.vtk) file for evaluation. The volume dataset in memory is exported to the VTK pipeline for visualisation, where contouring technique of visualisation is used. The contoured datasets can be seen in Fig. 10.

Fig. 10: Contoured Datasets (a) Facial-deformity dataset (b) Coronary dataset

3. Implementing the Visualisation Event

• Programming Camera Controls:
  Camera movements azimuth, elevation, yaw, pitch, roll, dolly are set for the user to move the virtual camera in the synthetic environment. These movements are controlled using keyboard inputs.

• Rendering a realistic surgery scene:
  A textured source is applied in the visualisation scene for realism. A human organ image is mapped to a 3D sphere object as a texture. The radius of the sphere is set with a value higher than the input dataset bounds.

4. Implementing the Surgery Training event

• Data Acquisition:

The Geometric Model of one of the test datasets is used as evaluation dataset for the simulation event. Dataset reading is achieved by making use of the dataset reader class in VTK. Part of the dataset is extracted and processed using contouring technique for visualisation.

• Determining line object coordinates in real-time:
  A line object is used as a preliminary virtual tool for detecting collision with the dataset. The end points of the line object are determined in real time and checked if any part of the dataset is collided.

• Collision detection:
  Line-dataset collision (intersection) is achieved in real-time by using cell search. The point along the line object that intersects with the dataset cell is stored in an ID array of size 3, one each for x, y and z coordinates. The closest points surrounding the intersection point in the dataset within a specific radius are determined for cell removal to achieve incision simulation. This is done by making use of the point selection algorithm. Fig. 11, shows the implementation in real-time.

Fig. 11: Scalpel Collision Detection Process

• Virtual Instrument Modelling:
  A virtual scalpel is modelled using 3D sphere for the scalpel blade and cylinder for the scalpel handle. The sphere and the cylinder geometry are modified to look like the scalpel blade and handle. The two objects are combined in an assembly and then translated, rotated and scaled to be rendered in the scene. The virtual scalpel is shown in Fig. 12 (a).

• Using scalpel coordinates for collision detection:
  The scalpel coordinates are then used to detect collision with the dataset.

• Collision Response:
  Surgical incision is done after achieving collision detection. The closest points located in the dataset are stored in an array and the attribute values i.e. scalar values corresponding to each of these points are altered for dataset clipping.

Fig. 12: Incision process (a) Virtual Scalpel (b) Simulating Incision with the Virtual Scalpel

The end result is a dataset with (i) Non-Intersected points and their corresponding attributes, (ii)
Intersected points and their corresponding attributes are extracted from the datasets using a clip value. The surgical incision is shown in Fig. 12 (b).

- **Realism Implementation Process:**
  Two datasets are extracted from the evaluation dataset for skin and flesh structure. The diffuse and specular properties of the two surfaces are set to imitate the effect of reflection from the camera-light object. A texture object is a 3D sphere and placed in the virtual scene with a radius greater than the coordinates of the flesh surface.

5. **VR Device Interaction**

VR Devices are interfaced for user interaction with the application. The Joystick device is used to control the virtual navigation and the DataGlove is used to control the movements in visualisation. Each of these devices is set using their userinterface libraries. These are then polled to retrieve the device information in the application begins. The devices are shown in Fig. 13 below.

6. **GUI Development**

This involves development involves user interaction with the application through display windows or menus. The display consists of bitmap texts rendered in a OpenGL render window and menu consisting of directories i.e. setting the dataset directory, loading the scene, visualising the set dataset with a different user value and performing the incision simulation. The dataset directory is initialised in the system directory 'c:'. The files and folders comprising the system directory are set by the VTK directory and copied to a string array. Each string is then a menu entry to the OpenGL menu creation. The final display menu consists of a list of the folders currently present in the system directory. DICOM Image Dataset Folder is also included. The 2D Scene Title texts are used for the Visualisation Surgery Training scenes.

5.2 **Results**

The final display of the application that involves realistic scenes can be seen in Fig. 14 and Fig. 15. Fig. 14 shows realistic visualisation of the Surgery-Repair-of-Fissure data and Fig. 15 shows the Incision simulation implemented. Two Parts of the dataset are extracted and visualised in a synthetic scene incorporating distinct material properties. The cutting simulation is performed between the 'flesh' structure beneath the 'skin' surface and the 'bone' surface. The sequence has been shown as follows.

7. **CONCLUSIONS**

Systems are developed that make use of Real Human Organ data for visualisation and Pre-Modelled Data for simulation and training. Attempts have been made in the development of applications incorporating Real Data for both these events. The paper discusses the solution to the problem and defines a system that serves both Visualisation and Simulation using Real Datasets. These datasets are processed in their native format to a usable form for the development of the application. The following conclusions are drawn.

- DICOM datasets are read by the system as input and processed for visualisation.
- The VE is developed for user navigation in the VE. The environment is developed imitating a real life surgery scenario, using appropriate scene settings.
- The surgery procedure is developed making use of a modelled surgical instrument to perform the procedure.
- Necessary GUI has been developed for the application. VR devices are also incorporated for user interaction with the synthetic environment.

The system can be developed to deliver advanced features compared to the existing ones. These features...
can include organ part segmentation, inclusion of multiple scene cameras for flexible navigation, interfacing other VR devices etc. Hand models in 3D can be incorporated in the surgery scene to simulate a surgeon's hand movement, tracked by using a motion tracker. The system GUI can be built in relation with the developed scenes. The fully developed system is beneficial to surgeons for pre-operative planning and to perform mock surgery as well as medical students to practice surgery procedures.

REFERENCES


