Virtual surgery system for abdominal organs based on VR helmet

Mujun Liu, Jinwen Deng, Yue Wang, Xuejun Zhang*
School of Computer, Electronics and Information, Guangxi University, Nanning, Guangxi 530004, P. R. China
* xjzhang@gxu.edu.cn

Xuejun Zhang*
Guangxi Key Laboratory of Multimedia Communications and Network Technology, Guangxi University, Nanning, Guangxi 530004, P. R. China

***Abstract*—Now Days doctors interpret the human body abdomen via CT images, which is always lack of intuitive, three-dimensional viewing. Statistics show that 80% of clinical errors are caused by human error. Therefore surgical training for young surgeons is very important to their experience growth. In order to observe the body structure of the human body efficiently and improve the technical proficiency of doctors, this paper designs a surgical system for abdominal organs based on VR helmet. Using 3D Labeling algorithm and time varying phase difference algorithm, the system can automatically segment the organs in medical image and transfer the reconstruction of the human abdominal body into three-dimensional model, from which a VR helmet could perform a real-time visualization of the human organs in different viewpoints. Our system provides a virtual tool set (scalpel, surgical clamp) that enable the use of collision detection and cutting algorithm to achieve the cutting effects of the abdominal organs. Experimental results show that our system are robust to achieve the establishment of three-dimensional abdominal organ model, and virtual surgery tools could help doctors to simulate the operation completely together with the use of force-feedback device.**

Keywords—Three-dimensional reconstruction; VR helmet; Virtual surgery

I. INTRODUCTION

Due to the rapid development of computer technology and medical imaging technology, information technology is widely used in many important areas such as medical applications [1]. Currently Medical imaging techniques widely used in clinical diagnosis, including Computed Tomography (CT), Radionuclide Imaging (RNI), Magnetic Resonance Images (MRI) and Ultrasonography (USG). The invention of various medical imaging techniques and the progressive development of imaging equipment have led to the rapid development of medical practice. In recent years, virtual reality (VR) technology [2], developed from simulation technology and three-dimensional computer graphics technology, has been applied in medical surgery, leading to a new research field of computer virtual surgery [3].

Virtual surgery can provide users with a virtual 3D environment and interactive operating system, simulating the whole process of clinical operations. A trainer is able to observe the internal structure of the human body from different viewpoints, and accurately determine the space location, size and geometry shape of lesions, as well as its relation between the space and biological tissues around, making diseases diagnose more effective and faster. Surgeons, with the help of a virtual surgery system, can repeat the operating procedure on monitor to find out the best surgical solution and improve proficiency before actually performing the operation. Such operation in the virtual environment will not have medical malpractice, which has special significance for the development of medical research and teaching. In the late 1980s, Delp and Rosen designed a simulation system for observing the procedure and results of joint transplantation [4], which was firstly recognized internationally and regarded as the first virtual surgical simulation system. In 2010, the national institute of information and automation (INRIA) in France developed a virtual system for liver cutting surgery, which led to the introduction of force feedback devices [5]. Harbin industrial university scientific research team developed a simulation training system with navigation technique for cerebral vascular interventional surgery [6], which can realize real-time analysis of catheter navigation. The "universal interactive visualization environment" developed by CAD&CG national key laboratory of Zhejiang University is focused on the key technology of virtual surgery. In 2016 years Shanghai Ruijin Hospital operating room, Professor Zheng MingHua, the chief expert on laparoscopic surgery in China, successfully performed the 3D laparoscopic radical resection of the right colon cancer of an elderly patient through the live broadcast of virtual reality technology. In 2017, a Japanese dentist used a VR helmet to show the patient's X-ray image and other details in 3D by a VR simulation project for dental surgery known as the WK2 project. The virtual reality technology has great progress, but how to provide users with a truly immersive environment or application experience also have huge technological limitations for developers, and some problems still have no good solution by now.

This paper proposed a surgical system for abdominal organs based on VR helmet. The abdominal organs model was built based on edge detection method, and a VR helmet could perform a real-time visualization of the human organs in different viewpoints. A virtual tool set (scalpel, surgical clamp) is enable the use of collision detection and cutting algorithm to achieve the cutting effects of the abdominal organs.

This work was supported in part by two research support from the National Natural Science Foundation of China (Nos.81460274 and 81760324), and by JSPS Grant-in-Aid for Scientific Research on Innovative Areas (grant number 26108005).

II. METHOD AND MATERIAL

The flow of proposed method is shown in Fig.1. multi-phased CT images were collected from GuangXi People's hospital in 2016. the three-dimensional model of abdominal organs was generated by our automatic algorithms [7-9]. Programming by the Unity software platform, surgical tools with VR helmet is enable virtual surgery to be implemented in a closed environment.

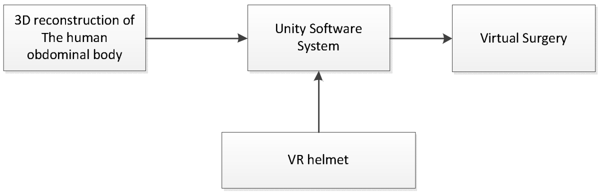

Fig. 1. Flowchart of our proposed method

III. ABDOMINAL ORGANS MODELING

Medical image segmentation is a tough work because the boundary between organs is not obvious and the gray value is not uniform. Therefore, no algorithm can be universally applicable to the segmentation of all organs and tissues by thresholding technique. Edge-based segmentation algorithm has been proven more accurate in organ extraction [7], as edge detection doesn't require to select a proper threshold value. Areas within closed contour are picked up to be candidate organs by labeling and 3D model can be built after elimination of FPs.

A. Organ extraction

The organ areas are separated by many closed contour after applying Sobel and LoG filter on enhanced CT image. Selecting these areas always use labeling theory, which is an important tool for image segmentation to solve the problem of multi-object identification. In medical image segmentation applications, 3D labeling algorithm has two key factors: one is the threshold value and the other is the direction for labeling. The threshold value of an organ is 0 since all the tissue with similar gray value will turn black after differential operation, while its edge surface turn white to form an effect of separating the "black" organ from outside world. From a candidate pixel in red as shown in Fig.2, there are a total of 26 adjacent pixels in different direction. Continually traversing and labeling until the neighborhood no longer meets the conditions of the existence of connected pixels. Liver is firstly recognized from different labels by voxels calculation because it is the largest organ in human. Other organs can be extracted by refer to the features such as position/ intensity to liver, shape, etc. The final segmentation results are improved by FP elimination.

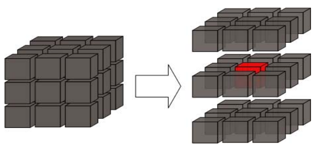

Fig. 2. Illustration of neighboring pixel

B. 3D Model

A fully automatic software was developed by our group for extracting abdominal organs [7], tumor [8] and vessels [9] from four phased CT scans. Segmentation results of abdominal components are labelled in different gray levels as shown in Fig.3 (right), from which a 3D model is built by surface rendering technology.

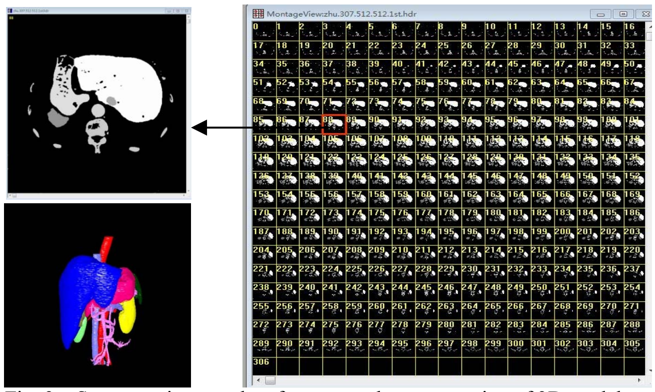

Fig. 3. Segmentation results of organs and reconstruction of 3D model

IV. VIRTUAL REALITY OPERATION

In a VR operation system, one of the most important function of virtual surgery is the plane cutting on organ, which is of great significance to the abnormal tissue localization. The cutting line and cutting position of a scalpel are critical to the safety and feasibility of the operation. Therefore, the success or failure of an operation are closely related to the selection of a proper cutting surface, such as whether the scalpel is touched to the vital nerve and vessels. Selecting reasonable cutting surface can greatly improve the scientific and accuracy of surgery

By using VR helmet, doctors can clearly observe the abdominal organ organization structure and play interactive operation, enabling more intuitive, clear observation and judgment of complex position relationship between various organs.

A. Unity Software System

Unity Technologies developed a cross-platform software-Unity3D that has a built-in integrated development environment to be able to combined with mobile devices, Kinect, HTC Vive, etc., and is regarded as the most commonly used software for virtual reality development. Unity has a powerful built-in editor MonoDevelop and scripting system, including several important modules: scene management, image rendering, lighting roasting, animation system, physical system, particle system, etc.

B. VR helmet

A VR helmet has three components that give the user immersive experience: a head display, two single-hand controllers, and a lighthouse that can track both the monitor and the controller in space. The use of VR helmet has now extent from initial game development to other areas, for example, medical and teaching fields. Students can wear VR helmet in virtual operating room to observe various organs, neurons, heart, brain, etc ., and thus for the relevant clinical trials with co-using of a force-feedback device as shown in Fig.4.

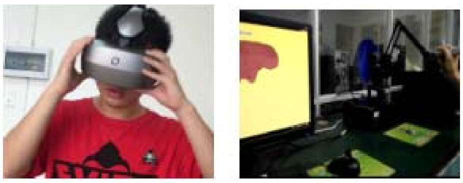

Fig. 4. a VR helmet (left) and force-feedback device (right)

C. Collision Detection

Collision detection in virtual surgery is provided in Unity, such as cube collider, ball collider, capsule collider and meshing collider. First, the Box Collider component and rigid body component are added to the operation tool in the Unity Software System. The principle of Box Collider is Axis-Aligned Bounding Box (AABB), adding Mesh Collider components and rigid body components to each organ model. If the surgical tool starts colliding into the model, the Unity listener listening method OncollisonEnter ( ) will be triggered to obtain contact points list as $C = \{c_0 c_1 ... c_{n-1} c_n\}$. If the surgical tool continue collides with the various organ models, the Unity listener will call the OnCollisionStay ( ) function where the recursive test whether the contact point is inside the AABB. If the contact point is $c_0(x_0 y_0 z_0)$, $AABB\{(x_{min}, y_{min}, z_{min}), (x_{max}, y_{max}, z_{max})\}$, then the following conditions need to be satisfied (1):

$$\begin{cases} x_{min} \le x_0 \le x_{max} \\ y_{min} \le y_0 \le y_{max} \\ z_{min} \le z_0 \le z_{max} \end{cases} \quad (1)$$

If a contact point is not in the AABB, it is removed from the contact set C. The recursion will be ended if the set $C = \varnothing$, Otherwise continue to every AABB child nodes, then the set C is the final contact points.

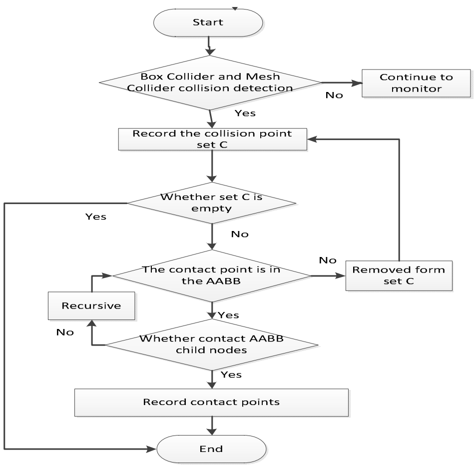

Fig. 5. Flow chart of collision detection

If the surgical tool contact to the organ model, the contact point is recorded as the closest contact point between surgical tool and organ model. Soft tissue deformation, bleeding and cutting will perform on basis of the contact points.

D. Cutting Algorithm

The model space is divided into two parts by the cutting plane according to the contact point of the surgical tool and the organ model. Our 3D model consists of triangles, from which cutting of a model is finally completed by traversing all the triangles in the model, judging the positional relationship between the triangle and the cutting plane, dividing the triangles intersecting on the cutting plane, forming the cutting boundary, and separating the model into two parts.

For each of the triangular pieces that make up the model, different processing strategies will be adopted in the algorithm according to the difference of the position relation of the cutting plane. The cutting plane divides the model into two parts: the upper and lower part. In the positive direction of the plane normal line is called the upper part (S1), whereas the lower part is the lower part (S2). The equation of the cutting plane (L) is $Ax + By + Cz + D = 0$, The positional relationship between the triangular pieces and the plane is judged by traversing each of the triangular pieces in the model and calculating the signed distance between the three vertices and the plane. Therefore, it is only necessary to substitute the three vertex coordinates of the triangle into the plane equation.

Taking point P as an example, the coordinate of the point is $P(x_1, y_1, z_1)$, and the D represents the distance between the point and the plane. The position relation between the point and the plane can be determined by (2).

$$Dis = Ax_1 + By_1 + Cz_1 + D \quad (2)$$

if $Dis > 0$, P is on the positive side of the plane

if $Dis = 0$, P is on the plane

if $Dis < 0$,P is on the negative side of the plane

The triangular piece is △ABC. *DisA*, *DisB*, and *DisC* represent the distance between the three vertex coordinates and the cutting plane, respectively.

1) If △ ABC and the plane intersect each other, Fig.6 and Fig.7, should be divided into two cases.

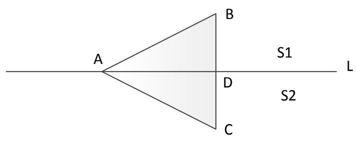

Fig. 6. Intersect plane with a vertex through cutting line

a) If one of *DisA, DisB,* and *DisC* is 0, and the other two values are different, then △ ABC is divided into two small triangles, as shown in Fig.6. In this case, △ ABD is added to S1, while △ ACD is added to S2 since *DisC*<0.

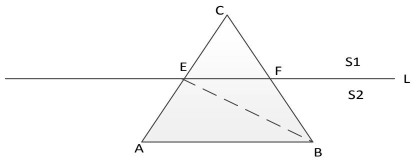

Fig. 7. Intersect plane with no vertex through cutting line

b) If distA≠0, distB≠0, distC≠0, △ ABC is divided into a triangle and a quadrilateral, as shown in Fig.7. Because of the basic elements of the composition model are triangles, a diagonal in the connected quadrilateral is divided into two triangles. In this case, △ CEF is added to S1. △ AEB and △ BEF is added to S2.

2) If distA=distB=distC= 0, △ABC is in the same plane as the cutting plane. In this case, the two submodel formed after the partition should contain the triangle, otherwise there will be a gap in the submodel, thus add △ABC to S1 and S2.

3) If distA>0, distB>0, distC>0, △ ABC is on the positive side of the cutting plane, thus △ ABC is added to S1.

4) If distA<0, distB<0, distC<0, △ ABC is in the negative side of the cutting plane, thus △ ABC is added to S2.

5) If distA, distB, distC, one of them is 0. the remaining two values are similar, You need to determine the relationship between two values and 0. If greater than 0, △ ABC is added to S1, else △ ABC is added to S2.

6) If distA, distB, and distC have two of them 0, the relationship between another value and 0 should be judged. If greater than 0, If greater than 0, △ ABC is added to S1, else △ ABC is added to S2.

V. RESULTS

As show in Fig.8, a 3D abdominal model were established successfully by our edge detection-based algorithm, and model cutting is implemented by two hand controllers when displaying in a 3D visual reality space by wearing a HTC VR helmet. Traversing all triangular piece of the model in cutting plane, our software could simulate surgical operation on most abdominal organs. Doctors may also “touch” the organ with the help of our force-feedback device in Fig.4, where the softness of an organ is set up in advance according to our elastic measurement algorithm [10]. The accuracy of the three-dimensional model yields a segmentation accuracy of 92%, and the surgical effect of our system is evaluated into grade 4 out of 5 in maximum by 5 invited medical experts in Surgical Department from GuangXi People’s hospital, P.R. China. The results indicate that a virtual surgical training and operation system designed in this paper is promising in future clinical practice.

VI. CONCLUSION

Three-dimensional model of abdominal organs was generated after segmentation of the human abdominal body on four phased CT scans, by which a VR helmet could perform a real-time visualization of the human organs in different viewpoints. Our system provides a virtual tool set (scalpel, surgical clamp) that enable the use of collision detection and cutting algorithm to achieve the cutting effects of the abdominal organs. Experimental results show that our system are robust to achieve the establishment of three-dimensional abdominal organ model, and virtual surgery tools could help doctors to simulate the operation completely together with the use of force-feedback device .

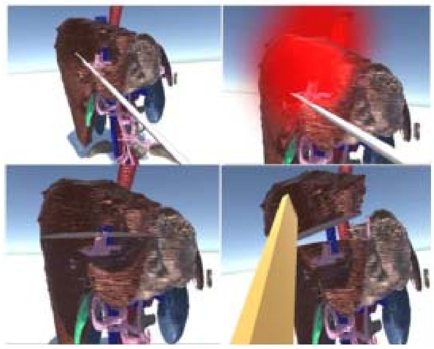

Fig. 8. a virtual tool set (scalpel, surgical clamp)

ACKNOWLEDGMENT

The authors would like to thank Dr. Dongbo Wu and his colleagues, who help us to evaluate the performance of our system.

REFERENCES

[1] Metzen J. H., Kröger T., Schenk A., “Matching of anatomical tree structures for registration of medical images.” Image and Vision Computing, pp.923-933, 2009.

[2] Sutherland I. E. “The ultimate display.” Multimedia: From Wagner to virtual reality,1965.

[3] P. Wang, A. Becker, I. Jones, “A virtual reality surgery simulation of cutting and retraction in neurosurgery with force-feedback.” Computer methods and programs in biomedicine, Vol.84, no.1, pp.11-18, 2006.

[4] T. Hei and H. Meinzer. “Statistical shape models for 3D medical image segmentation: A review”, Medical Image Analysis, Vol.13, no.4, pp.43-563, 2009.

[5] Courtecuisse H, hung H, Allard J, et al. “GPU-based real-time soft tissue deformation with cutting and haptic feedback” Progress in Biophysics and Molecular Biology, Vol.103, no.2, pp.159-168,2010.

[6] Y. Fu, H. Liu, S. Wang, et al. “Skeleton based active catheter navigation” The International Journal of Medical Robotics and Computer Assisted Suregery, Vol.5, no.2, pp.125-135, 2009.

[7] X. Zhang, G. Lee, T. Tajima, T. Kitagawa, M. Kanematsu, X. Zhou, T. Hara, H. Fujita, R. Yokoyama, H. Kondo, H. Hoshi, S. Nawano and K. Shinozaki, “Segmentation of liver region with tumorous tissues”, Proc. of SPIE, CA, pp.6512, 2007.

[8] Z. Zhang, X. Zhang, D. Wu, Y. Zhang, J. Deng, “Automatic extraction of primary malignant liver tumor for surgical liver resection,” Journal of Investigative Medicine, Vol.61, No.4, P.17, 2013.

[9] S. Kawajiri, X. Zhou, X. Zhang, T. Hara, H. Fujita, R. Yokoyama, H. Kondo, M. Kanematsu, H. Hoshi, “Automated segmentation of hepatic vessels in non-contrast X-ray CT images,” Radiological Physics and Technology, Springer, vol.1, no.2, pp.214-222, 2008.

[10] X. Tan, J. Lei, H. Bi, T. Liu, X. Zhang and X. Wang, “A novel method for Measuring Mass by Image Processing,” Advances in Computer Science Research, Atlantis Press, pp. 888-893, 2015.