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Virtual-real Registration of Augmented Reality Technology Used in the Cerebral Surgery Lesion Localization

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Abstract—*In the traditional cerebral surgery operation, the location of the lesion is difficult to calculate accurately. This paper designed a medical augmented reality system to locate the lesion via virtual-real registration technology. Firstly, a four-ball bracket was designed and fixed on the real skull. The virtual skull model with the virtual four-ball bracket was got by CT data reconstruct. The virtual lesion was added in the virtual skull model and the four-ball bracket was used for spatial position calibration of virtual model and real skull in the process of virtual-real registration. The whole virtual-real registration process was displayed on the computer in real-time. Finally, the application of virtual-real registration technology in the lesion localization of cerebral surgery was realized.*

Keywords—virtual-reality registration; augmented reality; lesions location

I. INTRODUCTION

Augmented Reality (AR) technology is a computer images processing technology. Because of the advantage of combination virtual and real, it has broad application in the fields of industry, medicine, military affairs and education. In medical field, AR can be used for preoperative planning of complex operation, to provide assistance for operation and information during the operation and predict the surgical outcomes. In addition, the development of telemedicine makes the application of AR more widely.

The results of operation usually depend on the doctor's clinical experience in general computer-aided operation. The AR technology which applies to computer-aided surgery can make up many deficiencies in traditional operation. Paloc[1] et al let the patient have MRI scan with three MR-visible markers attached to the patient's abdomen. Then finish the 3D reconstruction by image segmentation of liver images and MR-visible markers. Finally, the application of AR in computer-aided operation of liver is realized by virtual-real registration of the magnetic marker. In Frank's[2]image-guided operation, visible or magnetic marker tracking devices are used for achieving the preoperative and intraoperative medical image (X-ray, ultrasound, CT and MRI) registration, and enhancing the display of the patient's brain tumor and ventricle adjacent relationship in helmet mounted display. Domestic research on the application of AR in medical field is developing gradually. For example, in one's research[3], the AR technology is used in nasal endoscope navigation assisted surgery. The organs and tissues model reconstructed by preoperative CT or MRI, and then via the virtual-real registration technology to superimposes the brain tissue, eyeballs and blood vessel 3D model of the patient into the vision of endoscopic surgery. Zhu Ming[4] from Shanghai Jiao Tong University builds an effective path to finish the virtual-real registration of the virtual mandible model and the real model.

Conventional cerebral surgery usually determines the exact position of lesions and makes the operation plans according to the MRI or CT. In order to ensure the accuracy, the surgical incision tends to be relatively large and the doctors only can see the surface of the organs. If the blood vessels or the tissue are accidentally damaged, the consequences would be too ghastly to contemplate. If tumor removal not complete, serious sequelae may be caused after. How to determine the size and depth of the incision depends on the personal experience of the doctors. The advanced medical imaging technology is only used for assisted diagnosis and surgery planning. The help to surgical operation itself is still not enough.

This paper aimed at using AR technology to solve the above shortcomings of traditional cerebral surgery operation. The location of the lesion in the brain can be displayed in real time by the accurate virtual-real registration technology. With that, the scalpel under the guidance of the probe can approach the lesion step by step safely. In VS2010 environment, based on ARToolKit, the virtual model is imported into real-time video scene which is captured by camera. The doctor can see the location and shape of the lesion in real-time in the operation scene. A four-ball bracket was designed to accomplish the virtual-real registration.

II. SYSTEM DESIGN AND PROCEDURE ANALYSIS

A medical AR experimental system is designed to research the virtual-real registration technology application in the cerebral surgery operation in this paper. The system is

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shown in Fig. 1. The computer is used for 3D reconstruction of virtual skull, completing the virtual-real registration and displaying the experimental results; The experimental operation is based on the VS2010, Amira, 3dmax and ARToolKit software; The height and balance of the operation table can be adjusted to adapt the needs of experiment, at the same time, the light and the camera are installed on the table; The camera is used for capturing the real scene of virtual-real registration; The marker is mainly used for the virtual object localization and control.

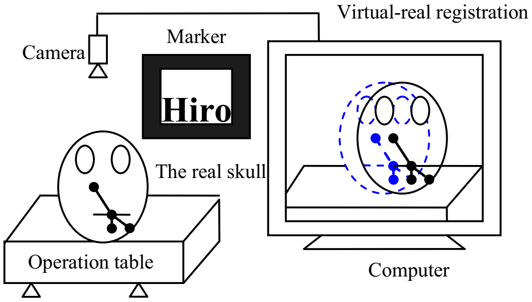

Fig. 1. Augmented reality system

Research on the virtual-real registration technology of AR in medical cerebral surgery operation mainly includes two aspects: model reconstruction and virtual-real registration. The flow chart is shown in Fig. 2.

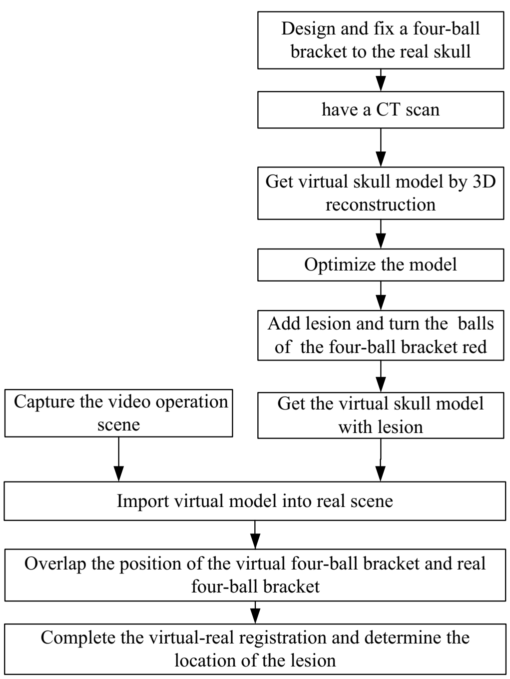

Fig. 2. Flow chart of AR applies to the cerebral surgery lesion localization

In the part of virtual model reconstruction, a four-ball bracket is designed and fixed on the real skull. The rigid bracket is composed of 3 stents, which are not in the same plane. On the end of each stent a 3mm radius ball is fixed on. The four balls' color is blue. The next work, a CT scan is made to get the virtual skull model by 3D reconstruction. Because of the fidelity of traditional virtual model reconstruction method is not good enough, the reconstructed model should be optimized. In order to finish the virtual-real registration and simulation of lesion localization in cerebral surgery operation, a virtual lesion should be added in the virtual skull model. Then the four balls of bracket are turned to red for displaying more clearly in the following step. In the virtual-real registration process, a camera is used for the real operation scene capture in real-time, and the reconstructed virtual skull model is imported into real scene to complete the registration. Finally, the virtual-real registration process is displayed on the computer screen.

III. PRINCIPLE OF VIRTUAL MODEL RECONSTRUCTION AND VIRTUAL-REAL REGISTRATION

The material of the skull model used in this paper is PVC (Polyvinyl chloride). The model has the same size with the real skull, as shown in Fig. 3. The image acquisition is finished with the Philips CT scanning equipment in Second Hospital of Jilin University and all the images are with DICOM 3.0 standard. The image size is 768×768 pixel, as shown in Fig. 4, and total numbers of slices are 283.

Fig. 3. Real skull model

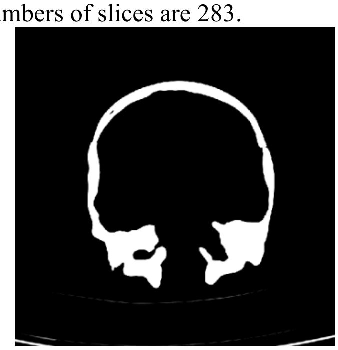

Fig. 4. One slice of CT images

A. The principle of virtual model reconstruction

The medical images observation and analysis is one of the basic methods in medical diagnosis. Traditional medical imaging techniques can directly obtain the two-dimensional projection images (such as X-ray imaging) or tomographic images (CT or MRI). The CT image is used in this paper. Visualization of three-dimensional reconstruction for CT images can provide more objective, realistic tissue and organ morphology for doctor's diagnosis. It will help doctors to overcome many shortcomings of traditional diagnosis like uncertainty and inaccuracy subjective imagination and judgment. In summary, the reconstruction technique of CT images has extensive clinical practicability.

The data sets which composed of a series of 2D images forms a 3D spatial data field. The reconstruction method of 3D structure from three-dimensional data includes two methods: surface rendering and volume rendering. The classical Marching Cube (MC) algorithm of volume rendering method is used in this paper.

MC[5] algorithm essentially extracts an isosurfaces from the three-dimensional data field. So it is also called the isosurfaces extraction method. On the isosurfaces in space, the change value of continuous function $f(x,y,z)$ is equal or in the range of finite. The core of MC algorithm is to find the isosurfaces from the given CT image data. The explicit isosurfaces extraction method is to reconstruct the continuous function $f(x,y,z)$ from the sampled data. Then compare the given threshold with the continuous function $f(x,y,z)$ to construct isosurfaces. Due to the restructure or resample error is large which lead the isosurfaces can't accurately reflect the object prototype and sometimes it's even impossible. In the practical application, the explicit isosurfaces extraction method is not used. MC algorithm is an implicit isosurfaces extraction method and directly acquires the isosurfaces information from the discrete data. The MC method extracts isosurfaces triangles according to the threshold which decided by the reconstruction tissue density value.

All sampling point of three dimensional data field can be seen in a three-dimensional grid system. The smallest unit is a cube constituted by the eight adjacent sampling points corresponding to the adjacent two slices of CT data, as shown in Fig. 5. The principle of MC algorithm is to process the cube in the data field one by one. Firstly, calculate the cube and determine the intersection point on the edge of it which intersects with isosurfaces. Then, the intersection points are connected into triangle in a certain way as the approximate expression of the isosurfaces in the cube. All the isosurfaces of cubes are generated. The integral three-dimensional object is formed by the triangular pieces. The MC method can determine the cube intersects with isosurfaces by comparing the gray value of the sample points with the threshold of the given isosurfaces.

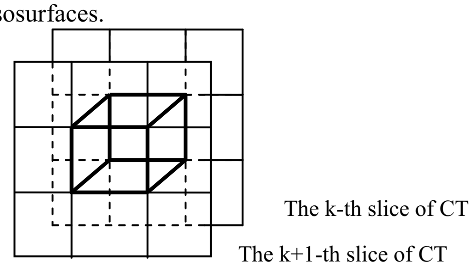

Fig. 5. Marching cube schematic

In the part of virtual skull model reconstruction, the 283 slices of CT data are imported into Amira and the parameters are adjusted in the Amira software. Amira software is an interactive 3D visualization and modeling software launched by TGS, France. This software can realize visualization of scientific data in various application fields. It is a set of object-oriented system, the module and data object is its basic system components, it is widely used[6] in the Biomedicine, materials science, geophysics and engineering. Connect the Amira's Orthoslice module to the data module can display the data in 3D-Viewer. The affine registration is used in it, which makes the point of the slice image correspond to the same position space. Next, reduce the image data by image cutting to prevent the amount of experimental data too large to deal with, while stressing the region of interest (ROI) and avoiding process the useless image data. The size of each CT slice data is 768×720 pixels after cutting. It greatly reduces the amount of data. Finally, the surface reconstruction is carried out by the MC algorithm. The triangular surface mesh can be used to reconstruct the skull for observing the surface of the object, numerical simulation and numerical calculation.

B. Virtual-real registration technology

ARToolKit is an AR system secondary development tools that jointly developed by the Japanese Hiroshima City University and the University of Washington. It runs on SGI IRIX, Linux PC and PC Windows operating system platform. ARToolKit mainly used in the labeled video scene. It is based on the traditional camera calibration technique to obtain the intrinsic and extrinsic parameters of the camera and detect the positional relationship between the camera and marker in real-time, based on vision registration technology to place virtual objects in the correct position on the plane marker[7]. With ARToolKit, the virtual skull model is imported into the real video scene in this paper, the virtual-real registration process as shown in Fig. 6.

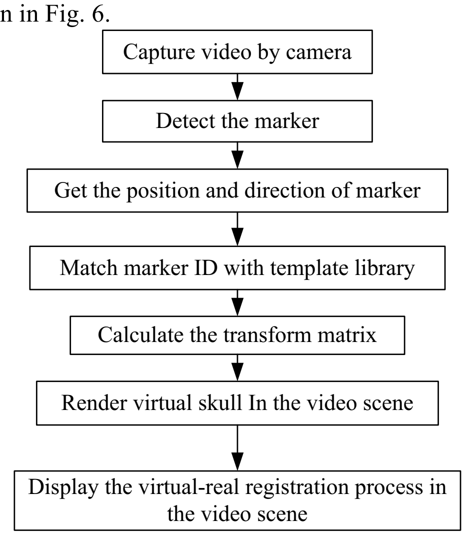

Fig. 6. The flow chart of virtual-real registration

The virtual-real registration mainly involved the following key steps:

1) Marker detecting

The marker detecting is essentially the process of extracting the marker from the background, and it is usually realized by the threshold segmentation method of the image. The purpose of detecting the marker is to locate and control the virtual model which imported into the scene.

2) Template matching

In the ARToolKit template library, different templates have different ID numbers. When the shape of marker this paper used is identified, the template will be given the ID number according to the shape in the rectangle in the store process. The ID number of the template library and the template this paper used are matched in the next step. If the ID number is the same, the template is successful matched.

3) Similarity comparing

In order to improve the accuracy of the whole system, the similarity compare is needed in ARToolKit. After getting the rectangle region via the marker extracting, ARToolKit will store the pixels in the rectangle region in the form of four 3×

16×16 arrays, and then define the image matching similarity (CF). Several rectangular regions may be qualified for the template matching, so it is needed to do the further similarity value comparison of them. The similarity maximum value is used in this paper, and the similarity (CF≤1) value more closer to 1, the matching success rate better.

4) Transformation matrix calculating

The essence of 3D registration is to detect the position relationship between the camera and the marker, so that the virtual object can appear in the correct position of the real scene. The position relationship can be represented by a 3×4 transformation matrix. To introduce coordinate system in the ARToolKit is to solve the 3D registration problem. The 3D registration problem comes down to calculate the transformation relation between the marker coordinate system with the camera coordinate system, which is the camera relative transformation matrix[8]. The ARToolkit coordinate system is shown in Fig. 7.

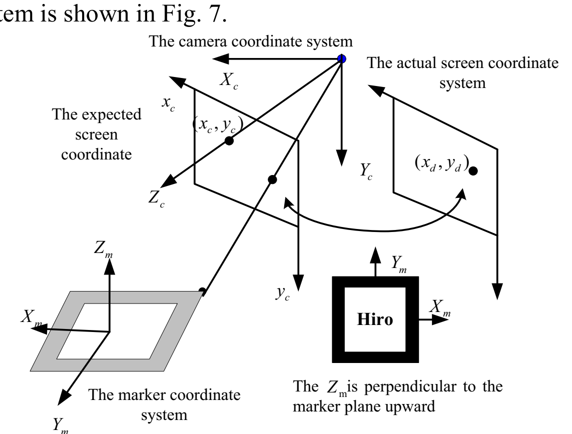

Fig. 7. ARToolKit coordinate system

Among it, $(X_m, Y_m, Z_m)^T$ is the marker coordinate system, $(X_c, Y_c, Z_c)^T$ is the camera coordinate system, $(x_c, y_c)^T$ is the expected screen coordinate system, and $(x_d, y_d)^T$ is the actual screen coordinate system.

At first, the object in the marker coordinate system is converted into camera coordinate system. Then transform the 3D information into the expected screen coordinates under the map of camera. Finally, from the expected screen coordinate system transform to the actual screen coordinates. According to the theory of computer vision[9], the transformation relation between the marker coordinate system, the camera coordinate system and the expected screen coordinate system are analyzed first. The relationship between marker coordinate system and camera is shown in (1). The T_{cm} is the transformation matrix of camera coordinate system relative to marker coordinate system. The R is a 3×3 orthogonal matrix. The matrix reflects the rotational component of the camera coordinate system which revolves around the X_m、Y_m、Z_m axis relative to the marker coordinate system. The T is a three-dimensional vector $(T_1, T_2, T_3)^T$, and it reflects the three translational components of the camera coordinate system relative to marker coordinate system.

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \\ 1 \end{bmatrix} = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = T_{cm} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} \tag{1}$$

The relationship between the camera coordinate system and the expected screen coordinates is (2). The S is the internal parameters of camera which the ARToolKit system has been given after starting the application initialization. Developers can correct the internal parameters by the ARToolKit library function. The h represents a moment. The f represents the focal length and the s indicates an inclination coefficient and its value always take 0. The a denotes the pixel aspect ratio and (u_0, v_0) represents the center of the image pixel.

$$\begin{bmatrix} hx_c \\ hy_c \\ h \end{bmatrix} = \begin{bmatrix} f & s & u_0 & 0 \\ 0 & af & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X_C \\ Y_C \\ Z_C \\ 1 \end{bmatrix} = S \begin{bmatrix} X_C \\ Y_C \\ Z_C \\ 1 \end{bmatrix} \tag{2}$$

We can know the relationship between the marker coordinate system and the expected screen coordinate system, as shown in (3).

$$\begin{bmatrix} hx_c \\ hy_c \\ h \end{bmatrix} = ST_{cm} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} \tag{3}$$

The S is known, the T_{cm} can be calculated by using the four angular points $(X_{mj}, Y_{mj}, Z_{mj})(j = 0,1,2,3)$ of the marker coordinate system and their corresponding points (x_{cj}, y_{cj}, z_{cj}) $(j = 0,1,2,3)$ of the expected screen coordinate system. ARToolkit has found the rectangular region of the marker via connected domain analysis. That is said, the coordinates of four angular points in actual screen coordinate system is known. The problem is turned into the conversion relationship between the expected screen coordinates system with the actual screen coordinates system. The transformation relation between the midpoint (x_c, y_c) of the expected screen coordinates and its corresponding points (x_d, y_d) in the actual screen coordinate system are shown in (4). The position of (x_0, y_0) is the center of optical distortion, the s is the proportional parameter and f is the distortion factor.

$$\begin{aligned} & x = s(x_c - x_0), y = s(y_c - y_0) \\ & d^2 = x^2 + y^2 \\ & p = \{1 - fd^2\} \\ & x_d = px + x_0, y_d = py + y_0 \end{aligned} \tag{4}$$

In fact, it is impossible to avoid the distortion of image and errors in the process of image processing. The T_{cm} is not accurate and must be further optimized. ARToolKit using nonlinear least squares to make T_{cm} precise, as show in (5). Among it, $x_{cj}^{\wedge}$ and $y_{cj}^{\wedge}$ are the coordinates of the four angular points in expected screen coordinates system according to the initial T_{cm} and the formula (3).

$$err^2 = \frac{1}{4}\sum_{i=0}^{3}((x_{cj} - x_{cj}^{\wedge})^2 + (y_{cj} - y_{cj}^{\wedge})^2) \rightarrow \min \qquad (5)$$

IV. Comprehensive experiment and discussion

On the basis of above principles, the experimental study of the virtual-real registration of AR technology used in the cerebral surgery lesion localization mainly include two aspects: the virtual skull model reconstruction and virtual-real registration.

A. *The virtual skull model reconstruction*

The virtual skull reconstruction process can be summarized as follows. Firstly, extract the surface from the segmentation results. In order to reconstruct the model more convenient, the resample of boundary is needed to reduce the amount of data, and then the original triangular surface is obtained by using the unique surface reconstruction module of Amira. The surface structure of virtual skull can be seen in Fig. 9.

Fig. 8. Real skull

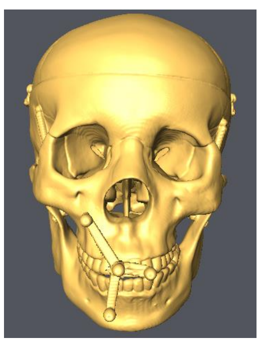

Fig. 9. Reconstructed virtual skull

The virtual skull model which imported into the real scene by ARToolKit is short of lighting authenticity. So the virtual skull model is imported into 3dmax software to add the lights and lesion. In order to complete the virtual-real registration, a four-ball bracket is designed and fixed on the real skull and a CT scan is made to complete the three-dimensional reconstruction with real skull together. Then turn the four balls red in 3dmax. The position of the four-ball bracket and the position of the lesion are changeless. As shown in Fig. 10.

Fig. 10. Add lesions and turn the four balls of bracket red

B. *Virtual-real registration*

In the course of the experiment, adjust the operation table to a proper height so that the real skull model placed in the range of captured vision by camera, as shown in Fig. 11. Then open the AR display interface, and import the virtual skull into the video scene, as shown in Fig. 12. Finally adjust the marker and the real skull model to finish the virtual-real registration. As shown in Fig. 13.

The relatively position of the four-ball bracket and lesion is changeless. So the position of the lesion is determined when the virtual balls complete the registration with the real balls. Then we can make a surgical simulation on the model after the virtual-real registration.

Fig. 11. The real skull model in real scene

Fig. 12. The virtual skull model in real scene

Fig. 13. The result of virtual-real registration in real scene

C. Discussion

The virtual model reconstruction method in this paper can comply with the requirement of medical imaging 3D reconstruction. The virtual model which reconstructed by MC algorithm is optimized in this paper. The optimized virtual model can reflect the structure of real skull more realistically and improve the accuracy of virtual-real registration in following steps. The further work will use the real human head CT data to reconstruct the virtual model of head. The image segmentation method will be used to extract the real lesion shape or location to prepare for further clinical research.

In order to complete the virtual-real registration, a rigid bracket is fixed on the surface of the skull. The color of the four balls on bracket is easy to recognize and the shape of the balls is round from any observation direction. The material of the balls is PVC, so the deformation will not occur and the accuracy will be improved. The surface of the skull has many cavities, so the four-ball bracket is fixed on the part where easy to segment on the face. When the positions of the four balls on the virtual and real bracket was detected overlap together in tracking process, the whole process of virtual-real registration is completed. In the further research of the surgery operation simulation, a CT scan to the human and virtual model reconstruction will be made before operation. Then, the four balls of real bracket will be tracked during the operation to make the virtual model and the real model registered. After that, the information of lesion will be determined and displayed on the computer in real-time. Under the guidance of the probe, the scalpel can approach the lesion safely, and then complete the operation.

V. CONCLUSION

Augmented reality technology has a number of potential applications in medical field. This paper mainly studies the application in surgical lesion localization. The advantage of combination virtual and real is used to solve the difficulty in lesions localization in traditional operation. The mainly work of this paper as follows. Firstly, in part of the virtual model reconstruction, the MC algorithm is used and the reconstructed model is optimized to improve the accuracy of medical 3D reconstruction. Secondly, in the process of the virtual-real registration, the principle of its application is analyzed, and the virtual-real registration process experiments are studied and demonstrated. At last, the whole research process and the target of next step work are discussed and analyzed. The reconstruction and registration method used in this paper achieve the requirements of the lesions localization in cerebral surgery operation and lay the foundation for the follow-up clinical research.

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