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Augmented Reality Based Preoperative Planning for Robot Assisted Tele-neurosurgery *

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Abstract - *Robot assisted telesurgery allow the surgeon to deliver the neurosurgical expertise to remote sites by remotely controlling medical robot to do minimally invasive surgery. An augmented reality based preoperative planning method is proposed to improve the safety of tele-neurosurgery. The position of four marks, which are attached on the head of patient and are used for surgeon to do preliminary preoperative planning with the support of sophisticated navigation software, is obtained by stereo vision. Besides of the establishment of bilateral audio, video and data communications, the virtual simulation environment is calibrated and overlapped with the real live images. Using the augmented reality, the surgeon at remote site can conduct virtual surgery to find and verify the most appropriate and safest planning and then deliver his planning to surgery site. This method has been successfully applied in clinical cases of tele-neurosugery..*

Keywords: Augmented reality, robot, tele-neurosurgery

1 Introduction

Robot can offer high precise positioning of the surgical instruments and better stability of tools, and it has been used for surgery [1][2][3]. Robots assisted frameless stereotactic neurosurgery is a kind of minimally invasive surgery[4]. The CT/MRI images of patient's head are transferred into computer and are used for surgeon to do preoperative planning. When the surgeon determines the insertion trajectory and orientation, the robot is controlled to move to the preplanned posture as a navigation tool. Then a very small hole (about 2mm diameter) is drilled on the patient head, and the instrument is inserted into the hole. Compared with traditional open sky neurosurgery, robot assisted neurosugry has many advantages, such as reducing the risk of infection, less pain and fast recovery[5][6].

With the development of network, it is possible to deliver the surgical expertise into remote site. Thus the transportation of patient, time of diagnosis and treatment, as well as cost, can be reduced[7]. Some cases of tele-surgery have been done, which demonstrated the feasibility of robot assisted tele-surgery. For example, a transcontinental robot-assisted remote laparoscopy surgery was conducted in 2002 with the assistance of da Vinci robotic system. In this tele-surgery, surgeons were in New York and the patient in Strasbourg[8]. In the area of neurosurgery, the advantage of tele-surgery is also exploited. There are already some cases of tele-neurosurgery [9].

The precision of robot assisted neurosurgery mainly depends on the preoperative planning system. One of the key issues is how to improve the safety of robot assisted neurosurgery, especially in the case of tele-neurosurgery. It is not easy for expert to do planning and remote registration using the information of surgery site, because of the long distance between surgical expert and patient. Generally speaking, medical images are the main source to guide the robot assisted sereotactic neurosurgery or tele-neurosurgery. Many kinds of sophisticated method has been proposed for the preoperative planning of local neurosurgery[10-15]. Mark based registration methods are often used in non-invasive (without touching) navigation to establish the relationship between the medical image coordinate and the robot coordinate, but either they are easy to be affected by environment factors or they cost expensively. Further more, the preoperative planning result made by surgical expert is directly sent to robot to execute without verification, thus increases the surgical risk.

Giving surgeon more training is useful to improve the quality of preoperative planning. Virtual reality is a powerful tool to simulate the procedure of surgery. The three dimensional viewing and interaction available through virtual reality make it possible for surgeons to practice many intubations without touching a patient. Surgeon can thus be trained by using virtual simulator[16]. A virtual environment of robot assisted neurosurgery is developed for surgeon to improve their abilities of doing preoperative planning [17]. These virtual simulators cannot connect with real surgery.

Besides of guaranteeing the safety of robot, constrained control flow, and development of sophisticated preoperative planning software[9], a low cost, augmented reality based method is proposed in this paper to facilitate the surgical expert to do preoperative planning and to improve the accuracy and safety of tele-neurosurgery, which exploits the advantages of both live video and virtual realty. The rest of this paper is organized as follows: Section 2 introduces the process of preoperative for tele-neurosurgery. Section 3 gives the method of measuring the position of marks using stereo vision. The overlay of live image and virtual simulated environment is proposed in Section 4. Section 5 gives some experimental results and clinical application, and Section 6 concludes the paper.

2 Preoperative planning

The remote stereo-tactic neurosurgery system is client/server system, shown as Figure.1. At local site (surgery site), one camera is used for global vision and two cameras are used to obtain stereo vision. The surgeon does preoperative planning at remote site (surgeon site). These two sites are connected with ADSL or ATM network.

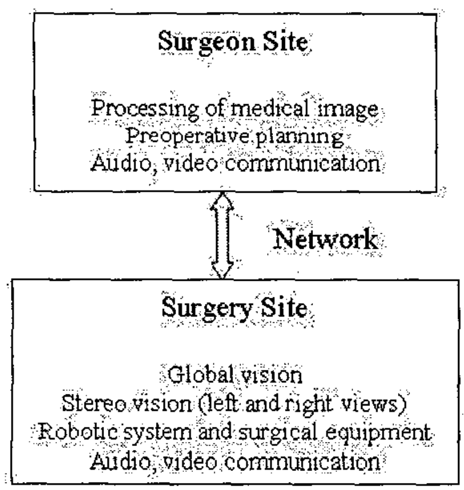

Figure.1 Preoperative planning for tele-neurosurgery

Firstly, the CT images that generates 512*512 pixel slices are transferred automatically using the DICOM 3.0 protocol from the console to the computer at local site. The computer is not only responsible for the control of robotic surgical system, but also responsible for the transmission of medical image and the real time capturing and transferring live video and audio.

Secondly, the surgeon at remote site deal with this 2D images using a sophisticated software[9] to plan the entrance path and posture. With the visualization of the brain model, the surgeon can properly define the route of the incision to avoid puncturing the critical vessel or nerves. At the same time, the cameras are calibrated at local site. The surgeon at remote site obtains the position of the pre-defined four markers on the patient's head using the stereo live vision transferred from local site. . Based on mark registration, the mapping between brain model and real patient head is created.

Then the virtual surgical robotic system is superposed on the live video image with mult-views to simulate and verify preoperative planning. By accurately overlying virtual wire model of surgical robot, tumor, puncture path, and base line of the head on video images, we provide the surgeon surgical augmented reality so that he can compare the virtual environment with real world. For the same puncturing path, there are maybe several solutions of robot poses. With virtual robot model, the surgeon can preview the robot's ultimate position relative to patient's head in order to choose the best pose solution. After choosing the best pose solution, the doctor will control the virtual robot to simulate the operation. If he thinks there is no problem during the operation process, then he will connect the real surgical robot to let the virtual robot drive the real one to repeat the motion for real surgical operation.

3 Marks registration

The preoperative planning is conducted in computer according to 2 dimensional images, but the planning result is conducted by medical robot. In order to accurately position the robot with respect to patient, making the mapping among the image space, robot space and patient's space is necessary. Four metal marks are fixed on patient's head, and these marks can be recognized by surgeon from patient CT/MRI images in computer in the process of preoperative planning. If the coordinates of these marks can be known both in computer space and in robot space , then the mapping among computer space, robot space and patient space can be obtained[9].

Here we use stereo vision to obtain the coordinate of marks in robot space. This is a kind of measurement without touching the patient's head using the end-effector of robot.

3.1 Positioning using stereo vision

The position of a space point cannot be determined by one camera, because of the lack of depth information. For example, all the points along the same projection line will form the same image point, as shown in Figure 2. The two images often referred to as a stereo pair, replicate the views that both eyes would receive if the observer were looking at the actual object. Stereo pairs can be created by using one or more cameras to take two exposures of the same subject from slightly shifted positions. If two cameras are used to measure the position of a space point, then their projection lines will intersect each other, and the position of the point can be calculated.

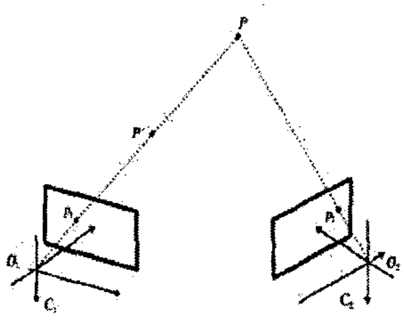

Figure.2 Principle of positioning by stereo vision

For an arbitrary space point P, suppose that its image points produced by camera C_1 and camera C_2 are point p_1 and p_2, respectively. After calibration[18], the projection matrixes of camera C_1 and camera C_2 are M_1 and M_2, respectively. The following equations can obtained:

$$s_1\begin{bmatrix} u_1 \\ v_1 \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^1 & m_{12}^1 & m_{13}^1 & m_{14}^1 \\ m_{21}^1 & m_{22}^1 & m_{23}^1 & m_{24}^1 \\ m_{31}^1 & m_{32}^1 & m_{33}^1 & m_{34}^1 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (1)$$

$$s_2\begin{bmatrix} u_2 \\ v_2 \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 & m_{14}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 & m_{24}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^1 & m_{34}^2 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (2)$$

where $(u_i, v_i, 1)^T$ is the coordinate of p_i (i=1, 2) in image frame, and $(X, Y, Z, 1)^T$ is the coordinate of point P in world frame.

Combining equation(1) and equation(2), we can calculate the $(X, Y, Z, 1)^T$ of point P using least square method.

3.2 Image space and robot space

Generally reference points are needed. The relationship between these reference points and their corresponding points in image is established first. Then these reference points are measured both in robot space and in image space.

Here we use the end-effector of robot as reference points. The robot is controlled to moved to different 28 positions, shown as Figure.3. The tip of its end-effector can be calculated both in image space and in robot space. Thus the calibration of camera and the mapping can be conducted in one step.

The points of robot end-effector first selected manually. Due to the error of surgeon when he select the points using mouse, only coarse position coordinates of these selected points can be obtained. Image processing technology is then used to recognize these points and to calculate their fine coordinates.

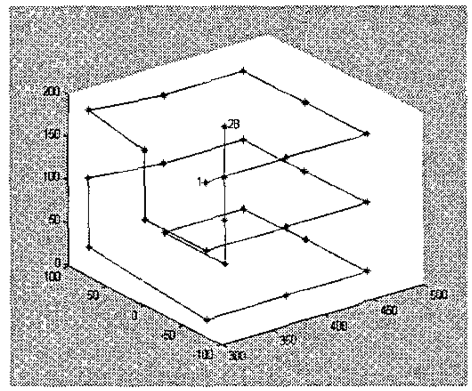

Figure.3 Measurement points of robot end-effector

4 Augmented reality

4.1 Parameters of camera

The live image is captured by camera and is shown on screen. The parameters of camera, such as the foci, the position and orientation of camera with respect to world frame, determined the view.

The relationship among view frames is shown as Figure.4. o' is the center of image frame, and its coordinates in screen frame is (u_0,v_0).The frame ouv denotes the screen frame.

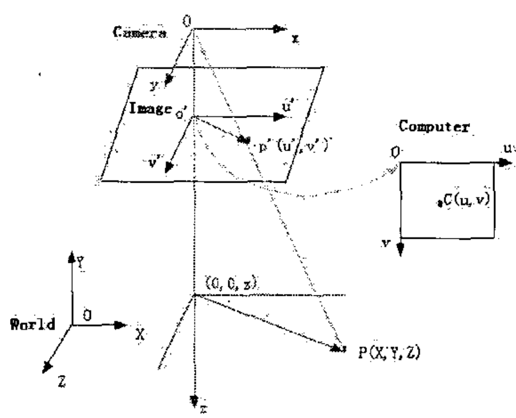

Figure. 4 Relationship among frames

Equation(1) can be written as

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_1 & 0 & u_0 \\ 0 & k_2 & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (3)$$

where (k_1, k_2, u_0, v_0) are the internal parameters of camera, $R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$ and $F = (t_x, t_y, t_z)^T$ are the rotation and translation matrix of camera frame with respect to world frame. R and F are the external parameters of camera.

From equation(3), we can obtain

$$u = k_1 \frac{r_{11}X + r_{12}Y + r_{13}Z + t_x}{r_{31}X + r_{32}Y + r_{33}Z + t_z} + u_0 \quad (4)$$

$$v = k_2 \frac{r_{21}X + r_{22}Y + r_{23}Z + t_y}{r_{31}X + r_{32}Y + r_{33}Z + t_z} + v_0 \quad (5)$$

A concise representation is shown as following equation graoup:

$$A_1X + A_2Y + A_3Z + A_4 - A_5Xu - A_6Yu - A_7Zu = u \quad (6)$$

$$A_8X + A_9Y + A_{10}Z + A_{11} - A_5Xv - A_6Yv - A_7Zv = v \quad (7)$$

where A_1~A_{11} are the mixed parameters.

The mixed parameters A_1~A_{11}can be obtained by solving above equation group. Generally, at least 6 groups of corresponding data between the points in world frame and the points in screen frame are needed. 9 points on robot are selected to make the corresponding data, as shown in Figure.5. The coordinates of these 9 points in world frame can be obtained by robot forward kinematics, and there corresponding coordinates in screen frame can be obtained by manually selected on screen.

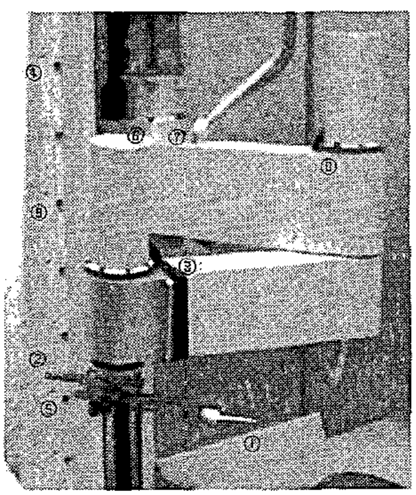

Figure.5 Corresponding points on robot

The internal and external parameters of camera then can be solved from the mixed parameters.

$$t_z = \frac{1}{\sqrt{A_5^2 + A_6^2 + A_7^2}}$$

$$r_{31} = A_5 t_z, r_{32} = A_6 t_z, r_{33} = A_7 t_z$$

$$u_0 = t_z(A_1 r_{31} + A_2 r_{32} + A_3 r_{33})$$

$$v_0 = t_z(A_8 r_{31} + A_9 r_{32} + A_{10} r_{33})$$

$$k_1 = \sqrt{A_1^2 t_z^2 + A_2^2 t_z^2 + A_3^2 t_z^2 - u_0^2}$$

$$k_2 = \sqrt{A_8^2 t_z^2 + A_9^2 t_z^2 + A_{10}^2 t_z^2 - v_0^2}$$

$$t_x = \frac{(A_4 - u_0)t_z}{k_1}, t_y = \frac{(A_{11} - v_0)t_z}{k_2}$$

$$r_{11} = \frac{A_1 r_z - r_{31} u_0}{k_1}, \quad r_{12} = \frac{A_2 r_z - r_{32} u_0}{k_1},$$

$$r_{13} = \frac{A_3 r_z - r_{33} u_0}{k_1}$$

$$r_{21} = \frac{A_8 r_z - r_{31} v_0}{k_2}, \quad r_{22} = \frac{A_9 r_z - r_{32} v_0}{k_2}, \quad r_{23} = \frac{A_{10} r_z - r_{33} v_0}{k_2}$$

4.2 Overlapping of live image and virtual scene

The parameters of real cameras are used to adjust the parameters of virtual camera which determines the view point of the virtual scene. Then the live image is introduced into virtual scene as background texture, and the virtual robotics system is rendered in term of wire-frame. Figure.6 is an example of the effect of overlapping.

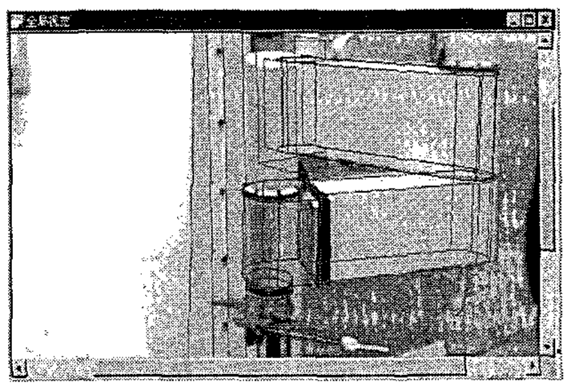

Figure.6 Overlapping of live image and virtual scene

The three views on the screen, which denote global vision and local stereo vision (two cameras), can be shown simultaneously in term of augmented reality by established templates for each view. The relationship between templates and views is shown as Figure.7.

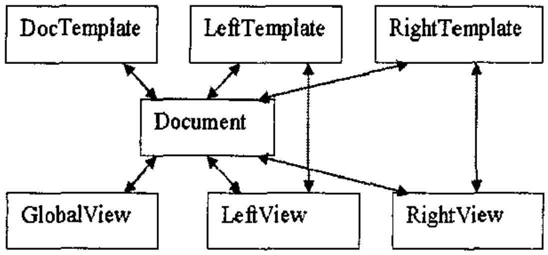

Figure.7 the relationship between templates and views

5 Experimental results

5.1 Positioning precision using stereoatic vision

When the position of end-effector of robot on the screen is selected manually, the position result is shown as Figure.8. The vertical axis denotes the error (in term of millimeter), and horizontal axis denotes the serial number of testing point.

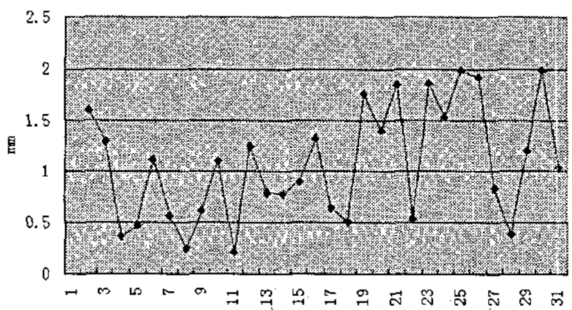

Figure.8 positioning precise without image processing

In this case, the maximum error is 2mm. When the position of end-effector of robot first selected manually and then is calculated by image processing, the position error decreases, as shown in Figure.9.

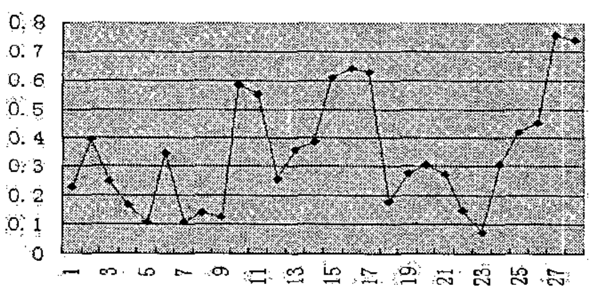

Figure.9 positioning precise after image processing

5.2 Augmented reality based preoperative planning

Surgeon can do preoperative planning based on augmented reality. Figure.10 shows the result of three augmented reality views displayed on screen, and the robotic system runs the preoperative planning in term of simulation. The top view is based on global vision, and the bottom two views are stereo vision (left view and right view, respectively).

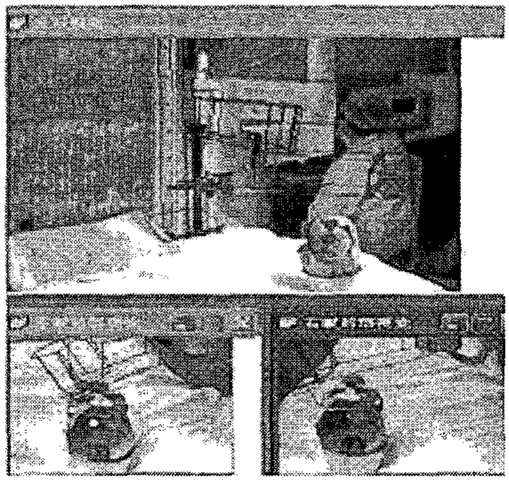

Figure.10 Simulated preoperative planning

5.3 Clinic application

Several clinic tele-neurosurgery cases have been successfully done[19]. Figure.11 shows the clinic preoperative planning based on augmented reality. The virtual robotic system moves according to surgeon's preoperative planning, and the surgeon can choose the most safe planning from different planning results.

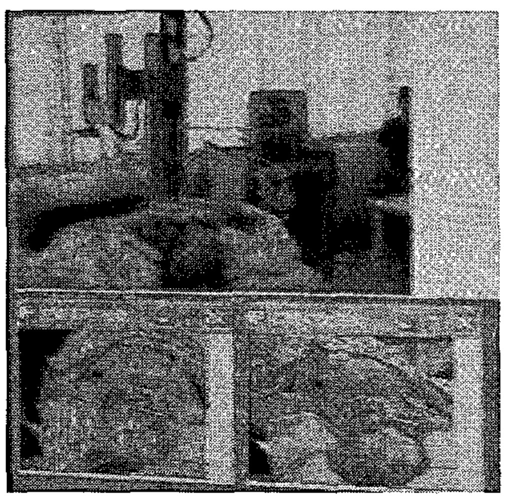

Figure11. Clinical application

6 Conclusions

Safety is one of the key issues of robot assisted neurosurgery, especially in case of tele-neusurgery. An augmented reality based preoperative planning method is proposed and successfully applied in remote clinical robot assisted neurosurgery. By exactly overlapping the virtual simulated robotic system on live image, the surgeon can simulate and verify the preoperative planning before it is transferred to remote robotic system. Taking the advantage of stereo vision, the marks can also be localized precisely, and the mapping between robot space and computer space can be obtained without physically touching patient' head. Experimental and clinical application show that the proposed method can facilitate the surgeon to do preoperative planning and to improve the safety of robot assisted tele-neurosurgery.

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References

[1] C.M. Hollands, L.N. Dixey. "Application of robotic surgery in pediatric patients", Surgical Laparoscopy Endoscopy & Percutaneous Techniques. 12(1):71-76 Feb 2002

[2] R.H. Taylor, "An image-directed robotic system for precise orthopedic surgery", IEEE Transactions on Robotics and Automation, 1994, Vol.10, No.3, 261-274

[3] C. Burghart,"A surgical robot system for Maxillofacial surgery", 1997 IARP, 2nd Workshop on Medical Robotics, Heideberg, Germany, pp2470-2475

[4] C. Burckhardt, P. Flury, and D. Glauser, "Stereotactic brainsurgery–integrated minerva system meets demanding robotic requirements", IEEEE Medicine Biology, 1995, Vol.14 No.3, 314–317

[5] Q. H. Li, "The application accuracy of the NeuroMate Robot—a quantitative comparison with frameless and frame-Based surgical localization systems", *Computer Aided Surgery*, 2002, 7:90~98

[6] K.Kan, M.Fujie, F.Tajima, K.Nishizawa, et al. "Development of HUMAN system with three micro manipulators for minimally invasive neurosurgery", *Computer Assisted Radiology and Surgery*, pp.144-149,2001

[7] J. Rassweiler, T. Frede, "Geometry of laparoscopy, telesurgery, training, and telementoring", *Urologe A*, 41(2):131-143 MAR 2002

[8] J. Marescaux, J. Leroy, F. Rubino, M. Smith, et al., "Transcontinental robot assisted remote telesurgery: feasibility and potential applications". *Annals of Surgery*, 235(4):487-492 APR 2002.

[9] W.S. Chou, T.M. Wang. "Computer and robot assisted tele-neurosugery". IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.3367-3372, 2003

[10]R.L. Galloway, "An optical device for interactive, image-guided neurosurgery", Engineering in Medicine and Biology Society, Proceedings of the 15th Annual International Conference of the IEEE, Oct 28-31, On page(s): 954 – 955, 1993.

[11]B. Westermann, R. Hauser, "Non- invasive 3- D patient registration for image- guided skull base surgery", *Computer & Graphics*, 2 0 (6) :793- 799,1996.

[12]W. E. L Grimson , G. J. White et al, "An automatic registration method for frameless stereotaxy,image guided surgery,and enhanced reality visualization". IEEE Transactions on Medical Imaging,1996,1 5(2) :129- 140.

[13]S.A. Tebo, D.A. Leopold et al, "An optical 3D digitizer for frameless stereotactic surgery", *IEEE Computer Graphics and Application*, 1996, 16(1) :55- 64

[14]P. St- Jean, R. Kasrai, D. Clonda et al, "Interactive 9 3- dimensional visualization tools for stereotactic atlas-based functional neurosurgery", In:Proceedings of the SPIE Conference on Image Display, 1998, 3335:1 98- 207

[15]L.M. Bates, D.P. Hanson, B.A. Kall et al, "Implementation of an oblique sectioning visualization tool for"line- of- sight" stereotactic neurosurgical navigation using the AVW toolkit", Proceedings of the SPIE Conference on Image Display,1998,3335:219- 22

[16]J. Mayrose, T. Kesavadas, K. Chugh, et al., "Utilization of virtual reality for endotracheal intubation training", *Resuscitation*, 2003;59(1):133-138.

[17]W.S. Chou, T.M. Wang, "Human computer interactive simulation for the training of minimally invasive neurosurgery", IEEE International Conference on Systems, Man and Cybernetics, pp. 1110- 1115, 2003.

[18]G.D. Hager, "A modular system for robust positioning using feedback from stereo Vision", *IEEE Trans on* Robotics and Automation,1997, 13(4):582~585

[19]C. Meng, T.M.Wang and W.S.Chou. "Remote surgery case: robot-assisted tele-neurosurgery", IEEE International Conference on Robotics and Automation, 2004