Application of a Robot Assisted Tele-neurosurgery System

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Abstract. In this paper, a new robot assisted tele-nuerosurgery system is presented. This system is mainly divided into three parts: surgery planning system, visual navigation system and robot arm. The application of a new type of visual navigation instrument makes patient registration much more easy and accurate. The system has successfully performed three tele-neurosurgery operations between Beijing and Yan'an. Experiments and clinical trials approved this system is feasible and safe.

1 Introduction

Telesurgery enables the surgeon to remotely operate on the patient under the help of medical robot. It frees the surgeon from the operating room, protects the surgeon from the radiation of X ray or radical medicine, and provides rescue for patient in remote rural area, ship at sea, battlefield. For these benefits, there have been many research works on telesurgery in developed contries. Italy hold the first remote telesurgery with PUMA robot through satellites and optical fibers[1]. France effected the famous transatlantic telesurgery with ZEUS robot through virtual circuit communication on ATM network[2].

China has vast territory and presents medical development diversity between eastern and western regions. It is important to utilize and promulgate the advance medical technology taking advantages of telesurgery. Beihang University and Beijing Navy General Hospital designed and developed several robotics systems for neurosurgery which were all clinically applied[4, 5, 6]. We focus our system goal on designing and validating a safe and low-cost telesurgery system suitable for China. In Sep. 2003, we performed Beijing Navy General Hospital to Shenyang Central Hospital tele-neurosurgery operation with the NeuroMaster surgical robot via special ATM channel[3]. This paper introduces our new robotic system, which has been successfully completed there tele-neurosurgical operations between Beijing and Yan'an via share bandwidth common public internet, which is low-cost and has improved safe ensuring characteristics.

2 System Structure and Surgery Flow

Neurosurgery needs 4 processes to complete the surgery:

1. *Registration*: project image data into robot coordinate;
2. *Surgical planning*: define surgeon optimized access route;

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3. *Robot control to implement plan route*: instruct robot arm to realize localization;
4. *Operation manipulation*: surgeon manipulation.

According to these requirements, we conclude the tele-stereotaxy system as a remote surgical plan and supervision system other than a tele-manipulation system. Experts at remote site take in charge of surgical plan, surgeons in operation room check and execute the operation under the supervision of the remote experts. System structure shows as Fig. 1.

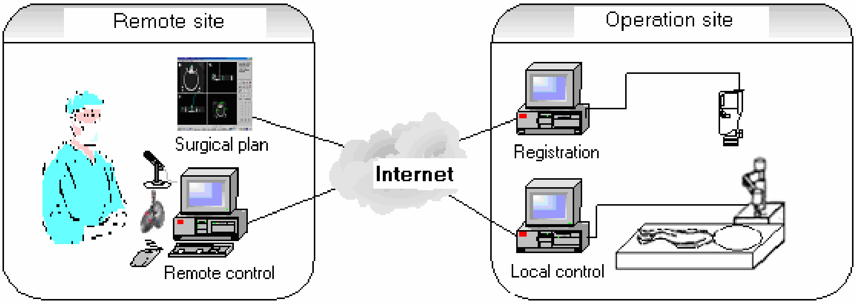


Fig. 1. Robot assisted tele-neurosurgery system structure

The tele-operation undergo 2 phases, A. preparation phase; B. operation phase. During preparation phase, patients medical images are collected in operation site and the CT/MR data will be transferred to remote site. The procedure starts with fixing four markers on the skin in the skull of the patient. Experts on remote site will identify them in the model of the brain. Then the robot locates the four markers in its own coordinate frame through the vision system. With the visualization of the brain model, experts on remote site inspect and decide the surgical plan and communicate with the operation site to do preparation. The both sides certificated surgical plan can be saved on control computer in operation room. In operation site, the control computer control the robot arm to finish stereo localization according to surgical plan, and the surgeons on operation site perform the surgical operations under the instruction and supervision of the remote site's experts.

3 Surgical Plan

Surgeons determine the pathological changes according to patients' medical images and determine the operation route aiming at the focus. The operation route is a straight line defined by puncture enter point and the target point. Following principles are important to determine the route:

1. to be as vertical as possible to the tangent plane which passes the puncture point of the skull;
2. evades blood vessels and important tissues;
3. shallow invade interval into brain;
4. it's much safer when the route is parallel to the long axis of the focus region.

Defining target point and puncture enter point is the normal method to plan the route, farther adjustment of the elementary plan are necessary and important. In Fig. 2, TXYZ is the 3D coordinate system of medical images, and TmXY is medical images' slice m 2D coordinate system. The elementary route is defined by puncture point Pm and the target point T. To enable surgeons rapid and convenient adjustment, the system provide cone based previewed plan method.

In Fig.2, after the target point T is defined, the route varies when Pm changes. The straight line PmPn conforms to equation (1).

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1 \tag{1}$$

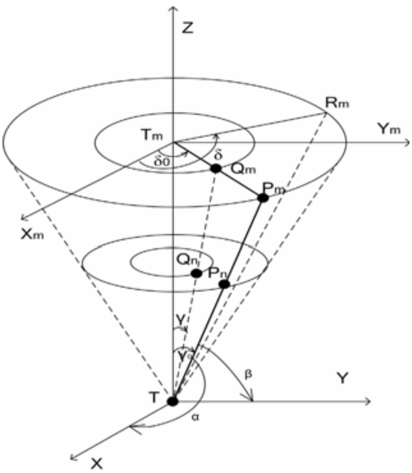


Fig. 2. Previewed plan locus restricted by plan cone

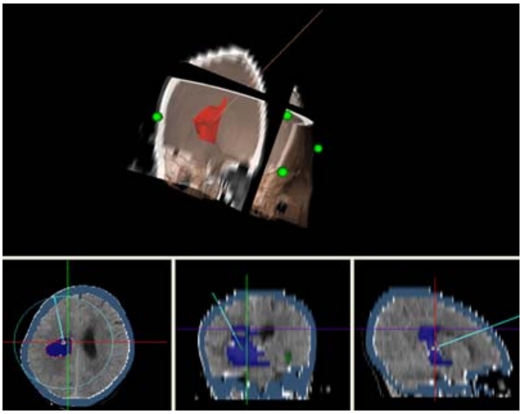


Fig. 3. Surgical plan interface and 3D model

Whenβand γ, The route moves on a cone surface which has a cone peak T and a cone angle 2γ. This make the route adjustment can be predicted and previewed. It is helpful for surgeons to make rapid and safe route surgical plan. At the same time, some different view point (surgeon defines) reconstructed images and 3D model are provided to inspect and affirm the route plan (Fig. 3).

4 Registration Base on Vision

In order to make the registration, the markers must be measured in the robot space. There are different types of measurement, such as mechanical, ultrasound, vision, etc. Traditional vision system mostly utilized two CCD cameras to track markers fixed to patient's head. But the camera calibration is so complex and the accuracy is not steady. Another shortcoming of general CCD camera is that it is only able to track still objects, but unable to track dynamic targets. To solve these problems, we adopt MicronTracker vision system (Fig. 4).

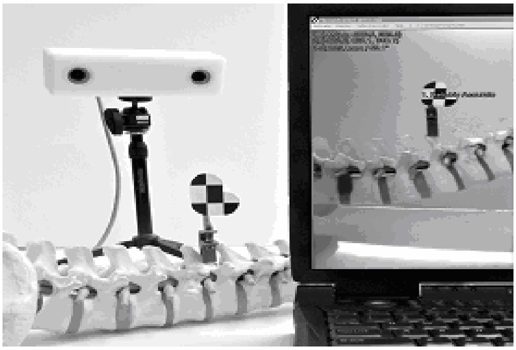
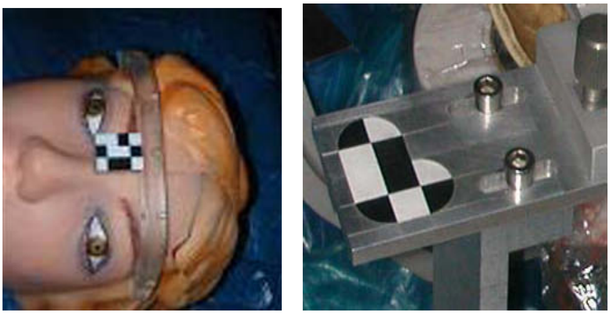


Fig. 4. MicronTracker vision system

MicronTracker is a real-time visual track instrument. It can not only track still objects, but also dynamic targets within its visual region. A pre-designed template was fixed to the surface of object that will be tracked. As shown in Fig. 5a, a template was fixed to the model of patient's head.

During the process of surgical planning, the four markers' positions under the image coordinate system have been obtained. By MicronTracker, we can attain the coordinate value under the MicronTracker's coordinate. In the same way, a template is also fixed to the end of the robot arm (Fig. 3b). These markers' positions under the robot coordinate could be calculated by designed robot parameters. Likewise, we can also obtain their coordinate values under the MicronTracker's coordinate.

After acquiring all the values, four coordinate systems can be created. We call them Head Affine Coordinate system (*HACS*), Image Coordinate System (*ICS*), Robot Affine Coordinate System (*RACS)* and Robot Coordinate System (*RCS*).



(a) (b)

Fig. 5. Markers templates

Microntracker has its own coordinate system, which we call Camera Coordinate System (*CCS*). So there are in total five coordinate systems. Through MicronTracker, we can establish relationships of these coordinate systems.

Four markers (they can not stay on a same plane) M_0 ,M_1 M_2 M_3 on the head can be used to establish an affine coordinate system *HACS*. In the coordinate system, every point's coordinate values Mp（xp, yp, zp）can be defined by these four markers' coordinate values. They conform to following equation:

$$\overrightarrow{M_oM_p} = x_p \cdot \overrightarrow{M_oM_1} + y_p \cdot \overrightarrow{M_oM_2} + z_p \cdot \overrightarrow{M_oM_3} \quad (2)$$

Since these four markers' coordinate values can be obtained on the images, their coordinate values under these two different coordinate systems are compared as in the following table.

Table 1. Coordinate values under two differnt coordinate systems

	HAC coordinate values	IC coordinate values
M_o	(0, 0, 0)	(x_o, y_o, z_o)
M_1	(1, 0, 0)	(x_{m1}, y_{m1}, z_{m1})
M_2	(0, 1, 0)	(x_{m2}, y_{m2}, z_{m2})
M_3	(0, 0, 1)	(x_{m3}, y_{m3}, z_{m3})

The mapping matrix between the *ICS* and the *HACS* can be obtained as:

$$T_1 = \begin{bmatrix} x_{m1}-x_o & x_{m2}-x_o & x_{m3}-x_o & x_o \\ y_{m1}-y_o & y_{m2}-y_o & y_{m3}-y_o & y_o \\ z_{m1}-z_o & z_{m2}-z_o & z_{m3}-z_o & z_o \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Then the transform equation between them is described as:

$$p_{IC} = T_1^{-1} * p_{HAC} \qquad p_{HAC} = T_1 * p_{IC} \tag{4}$$

Then each transform matrix can be obtained in same way:

$$p_{CC} = T_2^{-1} * p_{HAC} \qquad p_{HAC} = T_2 * p_{CC} \tag{5}$$

$$p_{CC} = T_3^{-1} * p_{RAC} \qquad p_{RAC} = T_3 * p_{CC} \tag{6}$$

$$p_{RC} = T_4^{-1} * p_{RAC} \qquad p_{RAC} = T_4 * p_{RC} \tag{7}$$

Our purpose is to obtain the transform matrix between the image coordinate system (*ICS*) and the robot coordinate system (*RCS*). Through multiplying above-mentioned matrix, we can create the final relationship:

$$T = T_4^{-1} \bullet T_3 \bullet T_2^{-1} \bullet T_1 \tag{8}$$

MicronTracker simplifies the creation of the relationship between the image coordinate system and the robot coordinate system, which greatly saves the surgical time.

5 Robot Design

A 5 DOFs robot arm is designed for route implement. Fig.6 illustrates the robot arm structure. Its main task is to offer a mount site for surgical instrument platform and provide the pose and location surgeons defined.

Taking the surgeon driven DOF(d6) into account, the robot has an analytical inverse kinematics solution as shown:

$$\begin{aligned} d_1 &= p_z - a_5 c_5 \\ d_2 &= -(p_y + a_5 s_5 s_{34} + a_3 c_3) \\ \theta_3 &= \arcsin \frac{p_x + a_5 n_x tg_5}{a_3} \\ \theta_4 &= (\theta + \theta) - \theta \\ \theta_5 &= \arcsin n_z \end{aligned} \tag{9}$$

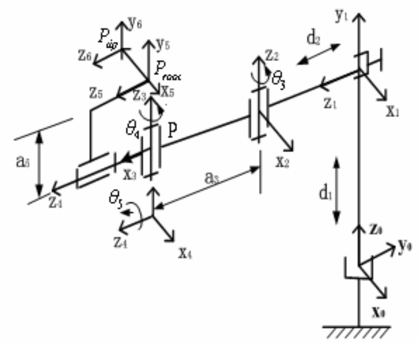


Fig. 6. Robot structure

The surgical instrument's parameter d6 and route direction(nx, ny, nz) are determined during surgical plan.

Dexterity analyses show the robot arm has a 200*200*200 dexterous work space (d_6=180), which is enough for neurosurgery operation, see Fig. 7.

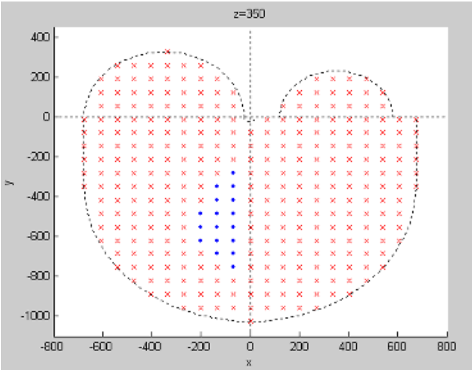


Fig. 7. Robot dexterity workspace example

6 Clinical Experiment

Before this system is used in the clinical application, a large numbers of experiments have been done. We use a skull to test the accuracy of the system. A steel ball of 2 millimeter in diameter is mounted inside the skull to serve as the target point for the surgical instrument. An accurate mechanical measuring device (Fig. 8) is used to measure the desired target position defied by the steel ball and the real target position defied by the tip of the robot end. The distance between the two points indicates the position error of the system (Fig. 8). For different positions of the target, the average position error is less than 1.5 millimeter.

Fig. 8. Experiments for accuracy

During 21st to 22nd Dec, 2005, the system successfully performed three tele-neurosurgery operations between Beijing General Navy Hospital and Yan'an University Hospital. The data communication is transferred on public internet, the General Navy Hospital is connected to public internet via a 2M enterprise ADSL of China netcom company Beijing branch, the Yan'an University Hospital is connected to public internet via a 4M enterprise ADSL of China Netcom company Yan'an branch.

7 Conclusion

The experiments and the clinical application prove the robot assistant tele-neurosurgery system is feasible and safe for remote neurosurgery. Especially, it is helpful to adequately utilize the advance medical resources in China.

Acknowledgements

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