Study On Robot-Assisted Minimally Invasive Neurosurgery
and its Clinical Application

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Abstract: This paper introduces the research project of robot assisted minimally invasive neurosurgery. Using visualization technology, the system reconstructs and displays the 3D model of the patient’s inner structure in the computer. Thus the surgeons can make the surgery planning on the model in the computer. Marker registration is used to create the mapping between the patient’s head and the 3D-brain model. Robot arm is used as a navigator to direct the surgery planning and as an instrument platform to assist surgeons to accomplish the operation. The results of the clinical application are given to show that the robotic system is effective.

Keywords: Robot, Planning, Registration, Execution, Stereotactic Neurosurgery, Clinical Application.

1. Introduction

Conventional neurosurgery is based on opening of the patient’s skull to make the brain organ exposed for operation. During the operation, the judgement of the location of the pathological tissue depends on the surgeon’s understanding of the relationship between the 2D images and the 3D structure of the patient’s head. This method also brings patients with great pain and risk of infection, and time spent on convalescence is long after operation. To overcome these shortcomings, more and more stereotactic neurosurgeries are applied to clinical recently [1,2,4,5]. In this method, the surgeon needs only to bore a small hole on the patient’s skull and insert the minimally invasive instruments into the brain for therapy. When the instrument reaches the pathological tissue, the surgeon can use it to remove the tissue or inject some medicine into the brain. Obviously, this method reduces the patient’s pain, decreases the risk of infection, and makes the patient recover in shorter time. Since surgeons are not able to see the patients’ brain directly, they rely on metallic frames fixed on the patients’ head to set the precise location. Unfortunately, these frames always limit the instrument’s access and become uncomfortable and inconvenient to patients.

Our group is working on a research project called Robot-assisted Neurosurgery System, aiming at developing a robot-assisted neurosurgery system. This system combines the visualization technology with a robot arm to realize frameless stereotactic neurosurgery. Discarding the cumbersome frame, the marker registration is used to make precise mapping among the patient’s head, the robot arm and the visualization of the patient’s brain model in computer. The robot arm is used as a navigator to direct the surgery planning and as an instrument platform to assist surgeons to accomplish the operation.
2. **System Architecture**

Our robotic system consists of three components: surgery planning and supporting system, marker-based registration, a powerless 6-joint robot arm (Fig. 1). This system provides surgeons with tools to make the pre-operative surgery plan and offers a navigator to direct the incisive site and the instrument orientation as well as the bore depth during surgery. It is also a platform for inserting the medical instrument to make operation. Significant experience has been gained to facilitate effective design.

3. **2D-image Segmentation and 3D-image Reconstruction**

3.1 **2D-image Segmentation**

When the original images are input into the system, some anatomical tissues and pathological region must be distinguished from adjacent tissues. Although there are some algorithms, which can automatically segment some distinct tissues, it is difficult to identify all critical tissue correctly. As a result, the surgeon’s judgement and decision are necessary. In order to do the correct segmentation, the system provides not only some automatic segmentation functions to get the edges of some tissues, but also the interactive tools to demarcate the pathological region and critical tissues (Fig. 2).

Although the surface of some tissues is complex and hard to characterize, their inner attribute is similar. We developed a new region border extraction algorithm [3], which automatically extracts the region of tissues. All boundary of the region (inner or outer) can be generated in one scanning process. The chain code, a border representation suitable for raster image, is used to represent the result of the extraction boundary, which is described as closed contours.

3.2 **3D-image Reconstruction**

After segmentation, the surface model of the anatomical and pathological tissues can be reconstructed by the system. The algorithm of tiling the triangles from planar contours is a choice [6, 7]. In this algorithm, the correspondence of contours is confirmed at first, then all contours are tiled with their adjacent contours by the

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**Figure 1.** Diagram of a robotic system for stereotactic neurosurgery

**Figure 2.** The white contour in the image is the region of the pathological issues demarcated by the surgeon.
triangles. After that, the model reconstructed from the images gets the triangular surface (it is called model in the following sections). Then the conventional illumination algorithms render the surface model and the surgeon can see the patient’s critical tissue and the pathological structure on the computer screen(Fig. 3).

![Image](image1.png)

**Fig. 3.** The surgery planning interface of the system. The red model (in right bottom) is the visualization of 3D surface model of the pathology. The purple line (in the rest of images) is the defined incisive route.

4. Marker-based Registration

In robot-assisted surgery, it is one of the key tasks to accomplish registration between model and surgical operation workspace. Now we have three different spaces: the first one is the space of model constructed in computer which is called model space; the second one is the space of the patient which is called patient space; the last one is the robot arm’s local space which is called robot space. The surgery planning is made in the model space, the operation is in the patient’s space, and the installation of the medical instrument on the tip of robot arm is in the robot space. Successful operation relies on the correct registration among these three spaces.

To make the registration, the direct and accurate method is to find out the transform relationship between the coordinate systems. Since all models are generated from the same patient, the relationship among different models can be determined by the rigid transformation, including rotation, scaling and translation.

The coordinate system of the model space is fixed when the orthogonal views are generated on the screen, but it is difficult to accurately depict the patient’s local coordinate system. So we must attach an external coordinate system to the patient’s head. In our system, a frameless marker-based system is used instead of the stupid metallic frame.

Marker-based method is easy to perform and give little discomfort to the patient. Four or more markers are fixed on the patient’s head before the operation (Fig. 4). Then the patient is put into the CT or MR scanner. Thus the marker will be visible in the CT or MRI images (Fig. 5). When these images are input into the system, the surgeon can identify them in the model of the brain.

![Image](image2.png)

**Fig. 4.** The marker, which is attached on the skull (Pointed by the arrow)

![Image](image3.png)

**Fig. 5.** The mapped marker in the CT image, which is referred in Fig. 7 (Pointed by the arrow)

To set up the patient’s reference system, we select four markers (every three of them can not stay on a same line, and the four can not stay on a same plane) to define a non-orthogonal coordinate system. One marker $M_a$ is selected...
as the original point of this reference system, and another maker \(M_{m1}\) is selected to form the X axis. The \(M_{m1}\)'s coordinate in this reference system is \((1.0, 0.0, 0.0)\). Similarly we use the other two markers \(M_{m2}, M_{m3}\) to form the Y axis and the Z axis. Then each point of the patient's head \(M_{p}\) can be thought as a triple \((x_p, y_p, z_p)\) and
\[
\overrightarrow{MM_p} = x_p \overrightarrow{MM_{m1}} + y_p \overrightarrow{MM_{m2}} + z_p \overrightarrow{MM_{m3}}
\]
(1)
When the corresponding markers are identified in the model, we can get their coordinate values in the model's reference system which are shown in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Patient Space</th>
<th>Model Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_s)</td>
<td>(0.0, 0.0, 0.0)</td>
<td>((x_o, y_o, z_o))</td>
</tr>
<tr>
<td>(M_{m1})</td>
<td>(1.0, 0.0, 0.0)</td>
<td>((x_{m1}, y_{m1}, z_{m1}))</td>
</tr>
<tr>
<td>(M_{m2})</td>
<td>(0.0, 1.0, 0.0)</td>
<td>((x_{m2}, y_{m2}, z_{m2}))</td>
</tr>
<tr>
<td>(M_{m3})</td>
<td>(0.0, 0.0, 1.0)</td>
<td>((x_{m3}, y_{m3}, z_{m3}))</td>
</tr>
</tbody>
</table>

The transform matrix from the patient reference system to the model reference system is installed which is described as follows:
\[
T_1 = \begin{bmatrix}
    x_{m1} - x_o & x_{m2} - x_o & x_{m3} - x_o & x_o \\
    y_{m1} - y_o & y_{m2} - y_o & y_{m3} - y_o & y_o \\
    z_{m1} - z_o & z_{m2} - z_o & z_{m3} - z_o & z_o \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]
(2)
Then each point in the patient reference system \(P_{patient}\) can be mapped into the model system by equation (3):
\[
P_{model} = T_1 \cdot P_{patient}
\]
(3)
\[
P_{patient} = T_1^{-1} \cdot P_{model}
\]
\[
P_{robot} = T_2 \cdot P_{patient}
\]
(4)
\[
P_{patient} = T_2^{-1} \cdot P_{robot}
\]
After the surgeon fixes the patient's head on the operation table, the robot arm is used to touch the pre-defined four markers on the patient's head. When robot arm's tip touches one marker, each joint's angle data is transferred into the computer. By calculating the joints' rotate angle, the system can get the tip location in robot arm's local reference system. Using the similar transform matrix as (2), we get the transform matrix \(T_2\) from the robot reference system to the patient system, then each point in the patient reference system \(P_{patient}\) can be mapped into the robot reference system by equation (4).

Combining equation (3) and (4), the link between the robot reference system and the model reference system is also established. The transform equation is:
\[
P_{robot} = (T_2 \cdot T_1^{-1}) \cdot P_{model}
\]
(5)
Thus the link among the patient, the model and the robot arm has been created. From now, any motion of the robot arm will be mapped into the model reference system in the computer, and any location of the model in the computer can be thought as the actual location on the patient's head (Fig. 6).

5. Surgery Navigation

5.1 Surgery Planning

As for a successful stereotactic surgery, the key issues are the correct location of the incisive site, the orientation and the depth of the medical instrument. The system provides surgeons with some metrical information such as the pathological tissue's volume, the long axis orientation and etc. This information gives the surgeon advice on the location of the incision site and the route by which the surgical instruments should be inserted into the brain. With the visualization of the brain model, the surgeon can define the route of the incision to avoid puncturing the critical vessel or nerves. The system will display the surgery plans designed by the surgeon repeatedly until they is complete and satisfied.

Fig. 6. The robot mapped on the model (The white line is the front arm of the robot arm)
5.2 Robot Arm

Our robot arm consists of six degrees of freedom and it is able to perform motions in the three-dimensional space (Fig. 7). Each axis contains an incremental encoder to determine its position. The encoder data are transformed into joint angles by corresponding transformations. Afterwards, with the help of the Denavit-Hartenberg-matrices, which respect the geometry of the robot arm, the cartesian coordinates are computed. Since the robot arm and the patient’s location can be mapped to the model in the computer, when the surgeon moves the robot arm around the patient’s head, the correct relative location can also be displayed on the screen.

The surgeon can modify the arm’s orientation so that the orientation matches the pre-designed orientation exactly (Fig. 6). Now the system can calculate the depth between the recent location and the destination and gives the surgeon precise information.

6. Experiments

Many simulation experiments and tests were conducted with the robotic system for stereotactic neurosurgery procedure. By experiments, we find that the needle tip could be a few millimeters off the specified target if without compensation for the inherent geometric errors of the robot arm. So we proposed the new compensation algorithm, which adjusts 24 link parameters. In addition, we did many experiments to test the location accuracy of the surgery planning system from about 60 samples of past slices in the hospital. After a lot of experiments, we proceeded closer to the actual surgical procedure. A skull of phantom embedded with a small lead landmark simulating a lesion in the human brain was placed in a frame and was CT scanned. After identifying the target on the CT picture, the robot arm swung to the desired position. A probe was inserted in the bushing and the probe tip hit the landmark. In its current form, the whole system is capable of accuracy less than 3-mm in finding or returning to a preprogrammed target.

Finally, the robotic system was successfully applied to clinical environments. A 40-year-old patient having a relapse of the brain tumor again was admitted to the hospital with a stereotactic neurosurgery, and the surgeons decided to use our robotic system. First, four markers were fixed on the patient’s head before the operation. Then the patient was put into the CT or MRI scanner. And the markers were visible in the CT or MRI images. When these images were input to our system, the surgeons identified them in the model of the brain. After the surgeons fixed the patient’s head on the operation table, the robot arm was used to touch the pre-defined four markers on the patient’s head (Fig. 4.), the system got the tip location in the robot arm’s local reference system. The surgeon made pre-operative plan on the model. Thus we used the robot arm to locate at the pre-defined incisive site with correct orientation. After the robot arm was moved to the pre-defined site, it was locked. Surgeons could use the probe installed on the robot arm to implement the operation (Fig. 8.). After operation, the patient’s symptom is disappeared. Up to now, six kinds of stereotactic operations was successfully performed in 106 cases with our system.

Figure 8. A biopsy probe is passed through the robotic hand on the trajectory predetermined by CT scan and robot positioning.
7. Conclusions

Our robotic stereotactic system has been successfully applied to the stereotactic neurosurgery clinical environment, the Naval Hospital, in China. The robotic system has several advantages over traditional stereotactic neurosurgery. First, the cumbersome frame in stereotactic neurosurgery is discarded. Second, adjustments in probe trajectory can be accomplished easily by manually activated robot arm. Third, there are no restrictions in access or proximity to the patient's skull. The six-jointed robot arm affords nearly unlimited access angles, so that the skull and brain can be approached easily from any direction. These advantages may be relatively minor, but potential uses of such a robotic system are exciting.

The present state of the technology and primary experiments show the exciting and encouraging improvement of surgical results. Our major contributions are

- Getting the patient’s CT and MRI scan images, the system reconstructs the 3D model of the critical anatomical tissue and pathological structure.
- Using visualization technology, the system makes the surgeons observing the inner structure of the patient's brain. The surgeon can make pre-operative plan on the model.
- The marker registration method is used in the system to construct the link among the patient, model and robot arm, thus surgeons discard the heavy head frame and use robot arm to locate at the pre-defined incisive site with correct orientation.
- The robot arm is also used as a platform to install medical instrument on it. After the robot arm is moved to the pre-defined site, it is locked. Surgeons can use the instrument installed on the robot arm to implement the operation.

References