Image-guided Positioning Robot for Single-port Brain Surgery Robotic Manipulator

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Abstract: The paper presents an image-guided positioning robot for a single-port brain surgery robotic manipulator. Due to its limited workspace, the robotic manipulator that performs a fine operation needs to be precisely and stably positioned near the target area. For this purpose, an accurate guidance of a positioning robot to the target position using CT images is developed. The developed brain surgery robot system consists of a single-port robotic manipulator, a positioning robot, an optical tracking system, a brain phantom, and an image model obtained from the pre-operative CT data of the brain phantom. The positioning robot supports the single-port robotic manipulator and positions it near a surgical site. To guide the surgical manipulator into a variety of positions and orientations, a 6-DOF serial robot is introduced as the positioning robot. The coordinate transformations among the image model, the brain phantom and the positioning robot and the single-port robotic manipulator are obtained to guide the positioning robot and to perform the registration between CT image of the phantom and the real phantom. The simple algorithm to specify the target location of the positioning robot in CT coordinate system is proposed. Using the coordinate transformations and the desired target location and orientation, it is possible to guide the positioning robot into the desired target position and orientation. The experimental result shows the targeting error of the proposed method is sufficiently small.

Keywords: robotic manipulator, single-port brain surgery, image-guided surgery

1. INTRODUCTION

Recently, various types of surgical robotic systems have been developed to achieve minimal invasiveness and to improve the maneuverability of surgical tools. Regarding a brain tumor surgery, many surgical treatment methods including an endoscopic resection of brain tumors using a slender conduit [1] have been proposed. For the endoscopic resection of brain tumor, we have developed a single-port multi-robotic arm manipulator system, which is composed of two small robotic arms and one stereo-endoscope in a long slender housing [2]. The robotic arms have been designed so that its workspace can cover the normal brain tumor size while minimizing its mechanical size and maximizing the tool’s accuracy. Since its workspace is limited, a positioning robotic system, which positions and supports the manipulator having small arms near the lesion’s position, is needed. Utilization of small robotic arms and external positioning robot makes it possible to achieve a large workspace and an accurate tool motion, at the same time [3].

There are a large number of existing surgical robotic systems which include the positioning robot system to support surgical manipulators. First, da Vinci system developed by Intuitive Surgical Inc., U.S.A is one of the successful surgery robots for a minimal invasive laparoscopic surgery. This system consists of 3 slave robots and each one has a 7-degree-of-freedom (DOF) manipulator. The system provides an immersive operating environment for surgeons by providing both high quality stereo visualization and a man-machine interface that transfers directly the surgeon’s hand motion to the motion of surgical tool tips inside the patient’s body [4]. Next is the NeuroMate, the first USA FDA-approved, image-guided and robotic-assisted system, which is used for stereotactic procedures in neurosurgery. It has been successfully used in frameless operations for movement disorder surgery. Its registration is performed using an ultrasound or X-rays images. The external positioning robot moves a probe autonomously along a predefined position before locking and powering off. The probe is then manually inserted into the brain [5]. The path finder is an image-guided frameless 6-DOF robot that provides a stable and accurate tool positioning for neurosurgery in the context of ROBOCAST project [6]. Fiducial markers are attached to the patient’s skin before acquiring the preoperative CT data for a registration.

Inspired by these surgical robotic systems, we developed a stable and accurate positioning robotic system which is guided automatically using CT data of a brain. We calculate the relative position between a patient and a surgical robot manipulator through coordinate transformation. The remainder of this paper is constructed as follows. Section II introduces an overview of the proposed image-guided robotic system.
Next, the control method for image-based guidance is described in Section III. Experiments and results are explained in Section IV. Finally, Section V concludes the paper with some list of the future work.

### 2. OVERVIEW OF PROPOSED SYSTEM

Since our single-port surgical manipulator has optimized workspace for the tumor size, it needs a positioning robotic system for moving it near the brain tumor. Therefore, the whole surgery system consists of a surgery robot system, which includes a small robotic manipulator and an external positioning robot carrying the manipulator, an optical tracking system to trace the positions of a patient and the robots, the patient that is replaced by a brain phantom in this work, and at last, the preoperative medical images that is converted into a virtual models as shown in Fig. 1.

2.1 Single-port Robotic Manipulator

As shown in Fig.1, the single-port robotic manipulator is inserted into slender hole in the brain and performs a surgical tumor removal procedure. Thus, the single-port robotic manipulator is designed so as to have several small robotic arms that have multiple DOFs in the limited workspace. The manipulator is also safe and precise, and able to provide a sufficient force and torque for grasping and incision of the soft tissue. As shown in Fig. 2, the developed manipulator consists of a gripping end-effector, a suction/injection end-effector and a stereo-endoscope in the trocar as explained in [2].

2.2 Positioning Robot System

A positioning robot supports the single-port robotic manipulator and positions it near a surgical site. To guide the surgical manipulator into various positions and orientations, a 6-DOF serial robot is introduced. In addition, we propose a method to calculate a trocar’s position using the patient's medical imaging i.e. CT data to guide the manipulator. The positioning robot is chosen as a 6-DOF articulated serial industrial robot Tx-90 manufactured by Stäubli international AG. Its repeatability is 0.03mm and its reach is 925mm.

Fig. 3 shows the overall surgical setup including the single-port robotic manipulator, the positioning robot on a flange of which the manipulator is mounted, a patient and the optical tracking system.

2.3 Optical Tracking System

To register the tumor’s location to the robotic system and to trace the position of the patient’s head relative to the robotic manipulator, we attach 3D markers on the patient’s head and the robotic manipulator to define the dynamic reference frames. To detect the frames, a three-dimensional (3D) optical tracking system (OTS), Polaris Spectra, manufactured by Northern Digital Inc. is adopted. The Polaris Spectra is selected since it uses passive-type probes to measure 6-DOF frames.
To identify the tumor’s location relative the patient coordinate system, fiducial markers are attached on the head and the bespoke software to identify the tumor location in preoperative CT images has also been developed.

3. Image-Guided Control Method

3.1 Coordinate Transformations

Fig. 4 shows coordinate transformations among an image model, a brain phantom, a positioning robot, a single-port robotic manipulator, and master devices. The registration between a CT image of the brain phantom and a real brain phantom is carried out first using point-to-point matching to find $CT_{OTS}$, the transformation matrix from the coordinate system of the CT image $\{CT\}$ to the coordinate system of OTS $\{OTS\}$, and then by measuring $OTS_{TP}$, the transformation matrix from OTS to the patient coordinate system $\{P\}$. Since we can also measure $OTS_{RO}$, the transformation matrix of the robotic manipulator’s base relative to OTS, it is possible to find the tumor’s location relative to the robotic manipulator. In addition, $CT_{GR}$ a transformation matrix from the coordinate system of CT image to the coordinate system of 3-D graphics is defined to visualize the 3D image properly. Using these transformation matrices, the positioning robot can be positioned properly if the targeting position/orientation is defined relative to $\{CT\}$.

Fig. 4 The coordinate transformations for image-based guidance.

3.2 Pre-operative Robot Planning Method

We define a desired targeting position and orientation of the positioning robot using a patient’s CT image. The targeting position is defined as the entry point $P_2$ of the trocar in CT image of the brain phantom. The targeting orientation is defined as the vector from a trocar’s entry point $P_2$ to a tumor’s center point $P_1$. Since, however, the vector from the entry point to tumor position is not sufficient to define a $3 \times 3$ rotational matrix, we define one more point $P_1$ to indicate $up$-direction. Fig. 5 visualizes the proposed method to define the targeting frame $\{O_t\}$ (position and orientation), along which the positioning robot will be inserted into the trocar.

First of all, $X_1$ the difference between $P_1$ and $P_2$ is obtained as in (1) and then its normalized vector $\bar{e}_1$ is calculated. $\bar{e}_1$ is defined as $x$-axis of the targeting frame $\{O_t\}$. To find $z$-axis, $X_2$ the difference between $P_3$ and $P_2$ is obtained as in (2) and then its normalized vector $\bar{e}_2$ is also calculated.

$$
X_1 = P_1 - P_2 \quad (1)
$$
$$
X_2 = P_3 - P_2 \quad (2)
$$

Since $\bar{e}_1$ and $\bar{e}_2$ are not orthogonal, however, $y$-axis is defined as $\bar{e}_3$ that is calculated by a cross product of $\bar{e}_1$ and $\bar{e}_2$ as in (3), and $z$-axis is defined by $\bar{e}_4$ that is calculated by a cross product of $\bar{e}_1$ and $\bar{e}_3$ as in (4).

$$
\bar{e}_2 \times \bar{e}_1 = \bar{e}_3 \quad (3)
$$
$$
\bar{e}_1 \times \bar{e}_2 = \bar{e}_4 \quad (4)
$$

The targeting rotational matrix and the transformation matrix are defined as in (5) and (6), respectively.

$$
R_t = \begin{bmatrix}
\bar{e}_1 & \bar{e}_3 & \bar{e}_4 \\
\end{bmatrix} \quad (5)
$$
$$
CT_{T_t} = \begin{bmatrix}
R_t & P_2 \\
0 & 1
\end{bmatrix} \quad (6)
$$

Fig. 5 The method to define the desired targeting position and orientation of the positioning robot

4. EXPERIMENT AND RESULT

Fig. 6 shows the experimental setup to evaluate the targeting accuracy. In order to protect the robotic arms
from crushing to the surrounding, a thin and flexible needle is attached instead of the robotic arms. We attach 3D marker to a 5mm grid paper to define the coordinate system of the real phantom. The plate with grid paper is also CT-scanned to define the targeting position precisely.

The positioning robot system is moved in order to reach the target position using the proposed image-based guiding method. We have calculated the measured position error from the target position to the actual position of the tip of the positioning robot. Targeting RMS error of the image-guided positioning robot is measured 2.2mm. The targeting error includes a robot calibration error, a model registration error and OTS error.

Fig. 6 Targeting setup: (a) The red circles indicate 3D reference frame’s marker, (b)(c) The green dots indicate target positions.

5. CONCLUSION

This paper proposes an image-based guidance of a positioning robot for a single-port robotic manipulator. Our brain surgery robotic system consists of a single-port robotic manipulator, a positioning robot, an optical tracking system, a patient, and a virtual patient model obtained from the pre-operative CT images.

The coordinate transformation among the frames attached to the aforementioned components is used to guide the positioning robot to the targeting frame, which is defined in patient’s CT image.

In the future, we will develop an image-guided force feedback algorithm for the single-port robotic manipulation.

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