Application of Robotic Stereotactic Assisted Brain Surgery: A Summary Analysis

Yixing Song*

College of Intelligent Equipment Engineering, School of Wuxi Taihu University, Jiangsu, China

*Corresponding author: songyixingbaiyuan@outlook.com

Abstract. Robots are used in various fields, and their accuracy can make brain surgery more successful. Developing robot-assisted surgery could also allow doctors to perform more difficult-to-perform operations. This thesis briefly describes the principle of stereotaxic directional robot in brain surgery. The lesions of patients are identified through digital images by means of medical imaging, then located by computer processing and planned trajectory. Finally, the operation is completed by robotic arm. In the following, this paper focuses on the differences in the characteristics of its own trajectory planning caused by the different algorithms and mathematical models used by Rosa robot, Neuromate robot and Remebot robot in trajectory planning through literature search and data search, and illustrates them with the latest clinical trials. The trajectory planning error of the three kinds of robots is small and does not affect the completion of the operation. The results show that the trajectory planning of the three kinds of robots has certain accuracy and flexibility. This paper aims to compare and analyze the different trajectory planning methods of three robots in order to study the possible development direction of trajectory planning.

Keywords: Surgical robotics; trajectory planning; Brain surgery.

1. Introduction

With the development of time and technology, robots have been used in neurosurgery. the concept of stereotactic localisation robots was introduced by H Fankhauser, D Glauser et al. in 1989, and in 1993 robots were used for biopsy surgery in patients with malignant cystic lesions in the brain [1]. The success of this procedure validated the feasibility of stereotactic robotic-assisted brain surgery. 2008 Reinhard E Wurm et al. used Novalis (BrainLAB, Heimstetten, Germany) to guide non-invasive radiosurgery, demonstrating the systematic accuracy of image-guided non-invasive radiosurgery using Novalis for the treatment of intracranial benign and malignant lesions and the feasibility [2]. Due to the complex structure of the brain, it is difficult to find the focal point in a simple two-dimensional image during robotic surgery. The robot needs a more detailed three-dimensional stereogram. Spiegel and Wycis solve the 3-D localization problem by connecting the stereotactic frame with the X-ray device [3]. Later, more and more accurate three-dimensional maps enabled doctors to more accurately and effectively determine the location of surgical incision, needle trajectory and the length of needles needed, but with the development of computers, this complex and time-consuming project was gradually solved by computers [4]. Computational path planning uses algorithms to automatically generate the best route based on the patient image. This method greatly reduces manpower requirements and facilitates the use of complex methods and multiple instruments. Robotic stereotactic surgery is of great significance in the field of brain surgery. The total incidence of perioperative ischemic stroke was 13.13%, including 23.64% in the intracranial group and 8.57% in the extracranial group. Intracranial hemorrhage is extremely common [5]. Reducing the operation time and the size of the surgical wound can effectively reduce infection, reduce the amount of bleeding, reduce the recovery time of patients after surgery, reduce secondary infection, and effectively improve the success rate of surgery. The stereotaxic directional surgical robot can accurately identify the location of the lesion and complete ultra-precision surgery with micro-instruments. The unusual precision reduces errors and thus reduces the damage to the surrounding tissue during surgery. This minimally invasive procedure could also make it possible to further advance the field of surgery that was previously difficult to perform due to the complex environment of the brain. In addition, robotic surgery can continuously complete high-intensity and complex operations. Compared with traditional surgery, robot-assisted surgery makes the operation more successful, reduces the burden of doctors, and improves the efficiency and safety of surgery. The procedure is also widely used for essential tremor, Parkinson's disease (PD), dystonia, obsessive-compulsive disorder (OCD), and epilepsy

Through systematic retrieval, this review introduces the surgical principle of stereotaxic directional surgical robot, including the localization of focal point trajectory planning technology, and focuses on the technical development of stereotaxic and navigation technology. In this paper, the trajectory planning method and the clinical research of the latest technology are introduced in detail. Finally, the development prospect and limitation of the current trajectory planning method are summarized.

2. Principles of robotic stereotactic surgery

Three-dimensional images of the patient's brain structure were obtained by CT, nuclear magnetic resonance(MRI) and other imaging techniques before surgery. After digitization of the images, computer software or doctors analyzed the images to determine the focal points (surgical targets), and obstacles (such as bones, nerves and other undamaged tissues) were avoided through software planning[4]. Before the operation of the robotic arm, the surgeon will confirm the path again, and the imaging technology will be used to match the surgical position of the patient. The robot will accurately and stably control the robotic arm probe instrument to move according to the path planned by the system, so as to achieve accurate operation in the location of intracranial lesions.

2.1. Computer digital image identification of lesions

Three-dimensional images of the patient's brain structure are obtained through imaging techniques such as CT or MRI. After digitization of the images, computer vision and deep learning technologies can automatically extract features from medical images and carry out accurate identification and classification of lesions. The computer will first preprocess the obtained images to make the subsequent lesion identification more accurate. In the preprocessing, the color correction makes the image color more consistent and improves the model recognition rate of the computer. The fusion method combining shallow and deep features is more accurate than the single method. After extracting information from 3D images using computer vision technology, the convolutional neural network (CNN) model and other representative models in deep learning technology can automatically extract the hidden features of medical images and carry out accurate classification and detection [5,6]. At the same time, computer transfer learning can improve the training effect of small-scale medical image data sets by using the model trained on large data sets and generating diversified training samples by data enhancement technology to accelerate the convergence speed and classification performance accuracy of the model.

2.2. Robot path analysis and planning

For path planning, if there are no obstacles in the path, only a straight line is needed to connect the start point and the end point. But the brain is a highly complex organ, involving numerous functions and structures. Surgery needs to be performed in a precise anatomical structure, and surgical errors can affect important nerve functions, so surgical precision is extremely important. However, the key to reduce the trajectory error lies in the accurate use of mathematical models and motion models of trajectory planning and the consideration of flexibility of surgical tools.

2.2.1 Neuromatede Trajectory Planning

Neuromatede 's trajectory planning mainly uses coordinate transformation and space mapping algorithms to convert the surgical path in the image coordinate system into the coordinates of the robot's operating space, ensuring the precise positioning of the robot during surgery. Fig. 1 shows Neurolocate machine being operated. This mapping is achieved through the calibration of visual sensors and marker points, allowing the robot to track and adjust the surgical path in real time. In order to optimize the smoothness and accuracy of robot movement, the system also uses NURBS curve and S-curve algorithms for interpolation in trajectory planning to ensure the stable and jitter free movement of the robot during surgery, which solves the stability of the robot arm during movement and reduces experimental errors [7]. The inverse kinematics solution and multi-layer vision sensor (MLP) neural network are also used to reduce the computational complexity and reduce the computer calculation error. The idea of linearization and the inverse Jacobian matrix are applied to map the Cartesian velocity to the joint velocity, which improves the accuracy and real-time of trajectory planning. Neuromatede robot is pictured at hand of the 24 cases of bilateral DBS electrode implantation reported by Raenette David et al., 62.5% used Neurolocate technology, of which 87.5% were delivered to GPi and the remaining 12.5% to STN. The mean age of patients was 11.0 (range 4-18) years, and 29.3% were female. The median absolute errors for the x, y and z axes using the Neurolocate module were 0.35, 0.75 and 0.9 mm, respectively, compared with 0.30, 0.95 and 1.1 mm using the technology based on the standard framework. Obviously, the coordinates error using Neurolicate technology is smaller. However, the median ED from the planned target to the actual electrode position using the Neurolocate module was 1.28 mm, compared to 1.69 mm using the standard framework-based technology. The average error reduction was 0.41mm [8]. The position error was significantly smaller and the patient experienced no major surgical complications after the operation using the Neurolocate technique.

Fig. 1 This is the Neurolocate machine being operated on

2.2.2 Rosa trajectory planning

ROSA can perform path planning on two-dimensional images and three-dimensional form data through Euler Angle transformation, which avoids the blind randomness of the previous surgical path determination process. It enables the doctor to determine the surgical path efficiently and quickly. In the coordinate calibration and conversion system, multiple coordinate systems (such as world coordinate system, patient coordinate system, robot coordinate system, etc.) are established [9], and the accurate mapping of surgical path is ensured through coordinate conversion, and the implementation of this algorithm reduces the error caused by the trajectory of Euler Angle transformation. The trajectory planning of the robot system also adopts Ruckig time-optimal trajectory generation algorithm, which is implemented in the Moveit! Realized in motion planning module. Moveit! The interior is divided into path planning module and trajectory generation module. The trajectory generation part implements Ruckig algorithm [10]. Ruckig algorithm divided the movement from the start to the end into seven stages, which was used to solve the problem of time-optimal online trajectory generation of finite acceleration and velocity under non-zero Jerk constraint. All possible configuration combinations were discussed, and the time-optimal scheme was selected from them. The numerical calculation method of kinematic state at any time between the starting point and the end point is given. In the course of trajectory planning, an improved fast random search tree (RRT) algorithm is applied to optimize the surgical path. The algorithm selects the final target point as the local target point with a certain probability to make the random tree grow towards the target point, thus effectively reducing the average search time and improving the real-time and path planning accuracy of the algorithm. Simulation experiment results show that the improved RRT algorithm has significant advantages in real-time performance and accuracy [7]. In addition, the optimization of the surgical path was also achieved by the double-target single-channel puncture Angle depth calculation method, which determined the target and the fixed Angle target in the lesion, brain sulci or non-functional cortex, so that the surgical path determined by the two-point connection was in line with the three principles of "nearest", "safest" and "most critical", thus reducing the difficulty and risk of surgery. Genetic algorithm is used to deal with complex path optimization problems, and the optimal solution is found by simulating natural selection process. Finally, the Denavit-Hartenberg (D-H) parameter method was used to establish the robot kinematics model, and the position and attitude of the robot end effector were calculated to ensure the motion accuracy of the robot arm [9,10]. Rosa ROs-based mobile robot trajectory planning software, steep learning curve can handle more complex surgical environments, and more suitable for complex and changeable environment. Hui-Tzung Luh et al. orally reported that a total of 7 patients received ROSA-guided ICH aspiration [11]. The robot under this system can effectively and safely reduce the volume of patients' hematoma by accurate aspiration of ICH and accurate placement of intra clot catheter, which proves that the robot can have a positive effect on the operation and the operation result is safe and effective. The diagnosis of diffuse pontine glioma - mutation H3K27ERM - was confirmed by Mathieu Lozouet [12]. using ROSA system biopsy in the cerebellar stem. As shown in Fig. 2, Rosa is undergoing surgery Due to the extremely complex relationship between blood vessels and nerves, robotic surgery must be used in order to obtain precise surgical operations. It proves the necessity of robot surgery in the field of brain surgery.

Fig. 2 ROSARobots are performing surgery

2.2.3 Remebot trajectory planning

Remebot uses the D-H parameter model to build kinematics equations, which helps solve forward and reverse kinematics by describing the relative positions and attitudes between robot joints [13]. The forward kinematics is used to calculate the position and attitude of the robot end based on the joint Angle, while the reverse kinematics is used to solve the joint Angle based on the desired end position and attitude. The establishment of this model is crucial for robot trajectory planning, as it ensures that the robot can accurately position and operate when performing surgical tasks. During surgery, Remebot uses a control model based on the input-output stability theory. By incorporating the dynamics of the robot into the closed-loop system equation, the model significantly improves the accuracy of trajectory tracking and position control. Specifically, the model uses nonlinear differential equations to describe the error dynamics, allowing for more precise position control. Simulation experiments show that compared with the traditional PD control with gravity compensation, the control model based on the input-output stability theory can control the deviation between the actual trajectory and the theoretical trajectory within 0.15mm, which provides higher position accuracy and adaptive control ability for surgical robots. To achieve accurate spatial positioning, Remebot relies on CT and MRI images for preoperative planning and surgical simulation. These imaging technologies reconstruct three-dimensional images of intracranial tissues and lesions through a computerized surgical planning platform, helping doctors to determine surgical targets and puncture paths, so as to realize the coordinate unification of medical image space and robotic surgical space [14]. This process not only improves the accuracy of the operation, but also enhances the safety of the operation. Chaoxi Li, Shiqiang Wu et al conducted a retrospective analysis of 33 patients with brain stem tumors who underwent stereotactic brain stem biopsies at the Department of Neurosurgery between January 2016 and January 2021. Remebot frameless stereotactic brain stem biopsy is as safe and effective as frame-based stereotactic biopsy [15]. However, Remebot frameless biopsy can reduce the total duration of surgery and has better applications in younger pediatric patients. It shows that Remebot frameless stereotactic biopsy is a better choice for safe and efficient treatment of brain stem tumors.

3. Conclusion

This paper summarises and analyses the advantages and disadvantages of trajectory planning in papers related to brain surgery collected in search engines and focuses on different or the same trajectory methods used in different robots to explain more clearly how trajectory planning is used in the Nike surgical robot. Previous experiments have proved that robot-assisted stereotaxic directed brain surgery is safe and effective. The development direction of robot surgical trajectory planning will tend to be flexible operational planning, which is used to adapt to the complex brain environment and complete the operation. The errors in the mathematical models and methods required for trajectory planning of various robotic surgeries will limit the help of robots in brain surgery, but the surgical errors have been reduced compared to conventional surgery. In the future, trajectory planning and robot-assisted brain stereotactic positioning surgery may also be more automated, in order to reduce the pressure on doctors and increase the efficiency of surgery.

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