An Automatic Calibration Method for Puncture Surgical Robot

H X Yuan, Q Q Li, H Zhao, L J Wang and R Song
School of Control Science and Engineering, Shandong University, Jinan 250061, China
rsong@sdu.edu.cn

Abstract. This paper proposes a rapid and automatic calibration method for puncture surgery robot, via which the hand-eye and tool calibration can be accomplished automatically in a short time. A new method for coordinate conversion between robot flange and needle tip is proposed, based on the method of spherical fitting and singular value decomposition. The experimental results show that the calibration accuracy and stability of this method can meet clinical requirements. There are good prospects for this method using in surgical calibration application.

1. Introduction

With the development of computer aided surgery (CAS) and robotic technologies, surgical robots are increasingly used in the clinical field, and show great advantages in terms of flexibility, stability and accuracy in the field of surgery [1-2]. The puncture procedure is a common and important operation in minimally invasive surgery, where the robot performed can improve the operating precision [3-4], reducing operator visual error and the elimination of the risk of radiation doctors.

At present, the image-guided surgical robot system has been widely used. It uses a six-degree-of-freedom lightweight robot arm as the actuator, the infrared stereo camera as the vision sensor for real-time intraoperative tracking and feedback, and the end flange is equipped with different surgical instruments as the tools of the robot system [5]. There are many researches on surgical robot system. Zeng [6] proposed a calibration method for the hand-eye of surgical robots, which can eliminate the data with large measurement error and improve the calibration accuracy, however it cannot avoid the human operation in the calibration process, and introduce a certain amount of human error. Liu [7] mentioned in the next phase of work to design an automatic calibration system. The latest research results of Niu [8] also emphasize the rapidity of self-calibration. Obviously, improving the automation of calibration is the main trend of current research. However, hand-eye calibration and tool calibration are usually carried out separately, and mass of data is needed to ensure the accuracy, which
will take up a lot of time. In order to make up for the complicated operation, long duration, and human intervention in the calibration process, this paper designs a set of automatic calibration system for puncture assisted surgical robot, which realizes the automation of hand-eye calibration and tool calibration of surgical robot system guided by infrared camera. It can not only ensure high accuracy of the system, but also improve calibration efficiency. The experimental results show that the repositioning precision of our method is $0.91 \pm 0.03$ mm, and the whole calibration process takes about one minute, so that, with the help of the new calibration system, the surgery robot can be better applied in clinic.

2. Calibration approach

2.1. System Establishment

The puncture surgical robot system usually consists of four parts: a workstation for multi-source data processing and robot control, a navigation system used for locating and tracking, an actuator served by a 6-DOF robot arm, and a customized needle equipped with infrared marker balls. In this paper, the mechanical arm uses UR5 (Universal Robots, Denmark), navigation camera uses NDI Polaris (Canada). The robotic surgical puncture system is shown in figure 1.

![Figure 1. Space axis of the robot system](image)

The role of the calibration can accomplish the unification of four parts coordinate system of the puncture surgical robot, especially the coordinate unification of the navigation camera, mechanical arm and the puncture needle. And this process is generally completed by two calibration methods, which the coordinate unification between the navigation system and the mechanical arm is defined as hand-eye calibration and the coordinate unification between the mechanical arm and the puncture needle is defined as tool calibration. In this paper, the main contribution is to realize the two calibration processes automatically through an operation process. It mainly includes locating the needle tip by the marker balls and using SVD (singular value decomposition) to solve the coordinate transformation.

2.2. Needle tip localization

The coordinate origin of reference frame \{D\} is obtained in real-time by four infrared reflective balls with relatively fixed positions in the optical camera coordinate system. Supposing that one of infrared reflective ball is the origin of coordinate, the camera can obtain the position and posture information of the reference frame through the information of these infrared balls.

The coordinate of Tip of Needle \{T\} is established with the probe tip as the coordinate origin, which the direction of the tip is determined by the reference frame. We use the spherical fitting method to locate the needle tip. The piercing tool rotates around its point, recording the position information of infrared ball on the puncture probe. Because of the unique positional relation between infrared ball and needle tip, these recording spots form a sphere. The core of this sphere is the end of the tool center, and its radius is the distance between
the origins of the coordinates. Supposing that the ball’s center in the optical locator coordinate system is (a,b,c) and its radius is R, the parametric equation for the sphere is:

\[ R^2 = (x - a)^2 + (y - b)^2 + (z - c)^2 \]  

(1)

In order to get the best fitting line experimentally, Equation (2) must be satisfied:

\[ \min f(x, y, z) = (x - a)^2 + (y - b)^2 + (z - c)^2 - R^2 \]  

(2)

By this method, the position and posture of the puncture tool tip in the optical camera system can be acquired. Changing the pose from Euler angle to the rotation matrix, we can obtain the transfer matrix \( R_T \) between tip of needle \( \{T\} \) and optical camera coordinate \( \{C\} \).

2.3. Calibration principle based on SVD

The automatic calibration process consists of hand-eye calibration and tool calibration. The hand-eye calibration needs to calculate the transfer matrix \( R_T \) between the optical camera coordinate system \( \{C\} \) and the robot coordinate system \( \{B\} \), and the tool calibration needs to calculate the transfer matrix \( E_T \) between the TCP (Tool Center Point) coordinate system \( \{E\} \) and the puncture tool coordinate system \( \{T\} \). To establish the transfer matrix between the camera coordinate system and the robot coordinate system, it is necessary to control the movement of the robot arm at least four different positions, recording the center point of the end of the arm \( \{P\} \) and the end point of the arm \( \{P\} \) directly acquired by the NDI camera at different positions. Set these two sets of three-dimensional point as \( \{P_1\} \) and \( \{P_2\} \). ARUN [9] present an algorithm for finding the least-squares solution of R and T, which is based on the SVD of a 3×3 matrix. By this method, it’s easy to find the transfer matrix \( R_T \).

Based on analysis positive and reversal motion of UR robot, we can derive the transfer matrix \( R_T \). Then we can get the transfer matrix \( B_T \) and \( E_T \) by equation (3) (4).

\[ \begin{align*}
    B_T^{-1} \times C_T &= B_T \times C_T = B_T \\
    E_T^{-1} \times B_T &= E_T \times B_T = E_T
\end{align*} \]  

(3) (4)

2.4. The optimized process

Figure 2. Calibration process

Calibration process steps as shown in figure 2. Before the beginning of automatic calibration, optical camera obtains the coordinates of infrared balls in real time, and the puncture tool rotates around its needle while recording the position of infrared sphere. Combined with the spherical fitting method to calculate the position and posture of the needle tip in the camera coordinate system. The hand-eye calibration process needs to control the robot arm to move three times in the camera space. When the robot moves to different locations, there will be a short pause. And we need to record the data from the robot and the optical camera about TCP location. Based on these data, we can obtain the hand-eye calibration transfer matrix by the method of SVD. Also, tool calibration needs to obtain the posture of the needle tip in the camera coordinate firstly. Then, converting the location information to a matrix and the tool calibration transfer matrix is derived by using the result of hand-eye calibration. Compared with the traditional mechanical calibration process, the system can be better integrated with the real scene. The tracking of the puncture tool and the TCP location of robot are
completed before calibration which could effectively reduce the operation time.

3. Experiments and results

3.1. Accuracy verification experiment

Accuracy experiment is to study the error change in the process of robot moving. The auxiliary probe is used to randomly take 25 consecutive points in the camera space as the moving target points of the puncture tool, and the robot arm is controlled to move to the points. According to hand-eye calibration matrix $\mathbf{T}_{b}^c$ and tool calibration matrix $\mathbf{T}_{P}^b$, the position of TCP in robot coordinate $\mathbf{P}$ can be converted into the position of needle tip in camera coordinate $\mathbf{P}$ by equation (5).

$$\mathbf{P} = \mathbf{T}_{b}^c \cdot \mathbf{P} \cdot \mathbf{T}_{P}^b$$

(5)

Compare the calculation results with the information tracked by the camera and the values recorded by the auxiliary probe, so the accuracy of the calibration method can be verified. The results are as follows:

![Figure 3. Accuracy verification experiment result](image)

In figure 3, expected value (E) is acquired by auxiliary probe in camera coordinate system, actual value (A) is the result calculated by equation (5), observed value (O) is the position of needle tip obtained by the camera. By analyzing the data, we can see the error range is around 0.1-0.3mm. And the expected value and the actual value are more similar and more stable.

3.2. Stability verification experiment

Stability experiments are designed to verify how the errors of the system will change after the repeated experiments. Coordinate (209.12, -108.63, -1413.97) is set as the target point. Then the robot repeats the automatic calibration process 10 times with different initial postures and control the puncture needle to reach the target point. Experimental data are as follows, where the error result is obtained by subtracting the target
position from the actual position. Each actual point is represented as $(x, y, z)$, the error is expressed as $(\delta_x, \delta_y, \delta_z)$ and $Err3d$ is the square root of the error.

| Table 1. Stability verification experiment data |
|-----------------------------------------------|
| $(x, y, z)$ | $(\delta_x, \delta_y, \delta_z)$ | $Err3d$ |
|----------------|---------------------------------|---------|
| 1 (209.89, -108.63, -1413.22) | (0.77, 0, 0.75) | 1.074 |
| 2 (209.48, -108.52, -1413.20) | (0.36, 0.11, 0.77) | 0.857 |
| 3 (208.99, -109.18, -1413.93) | (0.87, -0.55, 0.04) | 1.030 |
| 4 (209.34, -109.06, -1413.27) | (0.22, -0.43, 0.70) | 0.850 |
| 5 (209.14, -108.98, -1413.39) | (0.02, -0.35, 0.58) | 0.677 |
| 6 (209.70, -108.84, -1413.15) | (0.68, -0.21, 0.82) | 1.085 |
| 7 (209.63, -108.81, -1412.88) | (0.51, -0.18, 1.09) | 1.216 |
| 8 (209.26, -107.94, -1413.76) | (0.14, 0.69, 0.23) | 0.740 |
| 9 (209.32, -108.58, -1413.06) | (0.20, 0.05, 0.91) | 0.933 |
| 10 (209.03, -108.93, -1413.35) | (-0.08, -0.30, 0.62) | 0.693 |

It can be seen from the data in the table that the error between the actual coordinate point and the target coordinate point is within 1 mm, but the value of the 10 sets of results varies greatly. The main reasons for the large fluctuation of the value is that we can’t ensure that the puncture probe revolves accurately around the needle tip when using the sphere fitting method.

4. Conclusions
Considering the problems of complicated operation, long duration and human intervention, an automatic calibration method of puncture surgery robot based on optical navigation was proposed in this paper. Puncture tool with infrared ball is used to determine the position of the needle tip by using the principle of spherical center fitting. Then the singular value decomposition method of the given same position is used to control the movement of the robot arm and establish the hand-eye calibration equation matrix. Finally, tool calibration transfer matrix is derived by combining the known equations, and experiments are designed to verify the system. Experiments show the positioning accuracy of the puncture surgery robot system is controlled within 1 mm. And the calibration process only needs to control the robot arm to move three times and record coordinate information. Calibration time is controlled at about 1 minute.

5. References
[1] Kathryn G C, Tim F and Mehran A 2016 Medical Robotics & Computer Assisted Surgery 12 3
[2] Zhou Z, Wu B, Duan J, Zhang X, Zhang N and Liang Z 2017 Journal of Biomedical Optics 22 6
[3] Zhang Z, Zhang L and Yang G Z 2017 Computer Assisted Radiology and Surgery 12 10
[4] Jiang G W, Luo M Z, Lu L J, Bai K Q, Abdelaziz O and Chen S 2018 Applied Optics 57 8385
[5] Yang G Z, James C, Kevin C, Eric D, James D, Pierre E, Nobuhiko H 2017 Science Robotics 2 4
[6] Zeng B W, Meng F L, Ding H, Liu W B, Wu D 2017 Journal of Biomedical Engineering 34 2
[7] Liu G F, Yu X, Li C, Li G, Zhang X H and Li L Y 2016 Computer Assisted Surgery 21 55
[8] Niu J D, Luan N and Gui H J 2019 Machine Design & Research 35 3
[9] Arun K S 1987 IEEE transactions on pattern analysis and machine intelligence pami-9 5

Acknowledgements
Research supported by the Key Research and Development project of Shandong Province (2019GSF108032), Major Program of Shandong Province Natural Science Foundation (ZR2018ZCO437) and Key Research and Development Program of Shandong Province (2016ZDJS02A07).