Workspace Measurement and Calibration of a Parallel RCM Craniotomy Surgery Robot

Mohammadreza Dehghani, Majid M Moghaddam and Pourya Torabi
School of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

1 Corresponding Author: m.moghadam@modares.ac.ir

Abstract. This paper aims to improve the accuracy of a three degree-of-freedom surgery robot by means of calibration. The robot consists of a parallel Remote Center of Motion (RCM) mechanism which is designed for craniotomy surgery. The calibration method is based on the forward kinematic approach, which uses a nonlinear optimization model. The Levenberg-Marquardt method is used as the optimization technique and the loss function is defined by the least square definition. Sixty experimental data are used for the optimization process, the data are obtained using a Leica total station camera to measure the end-effector position, another sixty measurement data are also obtained to use in the evaluation process. Seven kinematic parameters are considered for the optimization process. After the optimization process the loss function reduced to 0.0002453 square millimeters.

1. Introduction

Robotic bone milling is not science fiction anymore. RIO by Mako Surgical Corp., Robodoc by Curexo Corp. are examples of commercialized systems for knee arthroplasty [1]. Moreover, there are several robotic systems for tooth bone milling and spine surgery [2]. Continuing on this trend, in recent years several studies are conducted on robotic systems for cranial bone milling [2]. Although the concept is the same as the previous systems, the crucial difference is the required high precision.

Pathfinder, RobaCKa and Cranio, are three robots designed and developed for assisting brain operations. The Pathfinder [3] uses CT scan images to find and mark the optimal points on the skull for bone removal and then uses some tools on the robot end effector, for its operations. RobaCka [4] is an industrial CASPAR robot, a 6-DOF serial robot. Cranio [5] has a C shaped arm which holds the tools for the cutting task and the arm is mounted on a Stewart-Gough platform. We [6] proposed a 2-DOF spherical parallel mechanism to keep the milling tool nearly perpendicular to skull surface. To achieve both stability and accuracy needed for bone removal task, this robot uses a parallel mechanism. The proposed design is discussed in the next section. For the skull bone removal task, positional performance is very important. The positional performance of a robot, can be described by three factors; resolution, accuracy and repeatability [7]. Fortunately, most industrial and medical robots have an acceptable repeatability and resolution but they sometimes, lack good accuracy. To improve accuracy, a good way is to use model-based calibration techniques. The calibration processes of parallel robot calibration methods are discussed in [8]. Model-based calibration consists of a step called Measurement [9], which actual end-effector positions must be measured. Different methods and tools are developed and used like cameras, laser trackers, coordinate measuring machines (CMM) and theodolites. In some non-contact methods, they use 2 cameras for position measurement [10]. These methods are based on binocular vision by which the distance can be measured but they lack high
accuracy. For enhancing accuracy, some use linear lasers which produce linear vertical and horizontal lines on the surface of the object to help the measurement.

For the present robot, position of the robot’s end effector is measured by a Leica TS06plus R1000 total station camera is used. This total station has the ability to measure the location of points from a predefined internal coordinate, by means of laser technology. The points are used during the optimization process of the calibration method. As the kinematic equations are non-linear, Levenberg-Marquardt is used for optimization process [11].

2. System Description
The Robot System (Figure 1) is a 3-DOF cable actuated mechanism which consists of a 2-DOF spherical parallel mechanism and a tool insertion interface. The active mechanism is installed on a C-shaped base manufactured from 10mm thick aluminum plate. The spherical mechanism has five motion axes, where three of them are dependant of the two actuation joints. The two required motors, control the two shoulder joints via a capstan mechanism with an 18.8:200 transmission ratio. The motors are AC servo drives (ASDA2 DELTA Electronics Inc.). Robot arms are manufactured with 4-axis CNC milling machine with 0.001 mm resolution. Considering the encoder output of 10000 pulse per revolution, the orientation resolution of the end effector is 1.2e-4 rad. The insertion degree is a cable driven rail and cart mechanism which moves a pneumatic drill along the tool joint axis. The theoretical resolution of insertion degree is 4.6e-3 millimeter.

3. Calibration
Accuracy of the robot, can be improved by working with the calibrated model of the robot. One way of finding this model, is to find an ideal robot kinematic equations and then change its parameters by calibration methods. This is called a model-based calibration. A model-based calibrations consists of four steps: Modeling, Measurement, Identification, Compensation[9].

3.1. Kinematic Modeling and Workspace Analysis
The kinematics of the parallel spherical mechanism is described in [12,13], utilizing appropriate coordinate systems according to Denavit-Hartenberg method (Figure 2). To validate the kinematic equations, data obtained from SOLIDWORKS model is compared with analytical equations’ output.

The Jacobian of the mechanism was calculated in [6] and used to optimize the mechanism for maximum workspace and isotropy. The optimized link lengths are as follows:

\[ \alpha_{13} = 61, \alpha_{35} = 66, \alpha_{24} = 61, \alpha_{46} = 66, \phi = 150 \]

To calculate the theoretical workspace of the mechanism, we introduced points covering a unit sphere into the inverse kinematic equations. Points corresponding to valid solutions are considered inside the mechanism workspace.

3.2. Measurement
Methods to measure EE position are different in application, accuracy and price. In this research, a total station camera, Leica TS06plus R1000, is used to measure points with 0.1 mm accuracy.

Figure 1. The robot prototype

Figure 2. Joints coordinate assignment
3.2.1. Actuation joint calibration

The control input to the mechanism is the motor rotations, while the kinematic equations relate the first link angle to the end-effector position. Therefore, we first need a relation between motor rotation and first link angle. We measured the position of three points (Figure 3) on each arm in four different orientations of the shoulder joints, so that we can pass a plane from each three points and then find the angle between the planes relative to the rotation of each shoulder joints.

We assigned the zero angle of the link to when the shoulder link is completely vertical. We used the Open Controller Z pulse (OCZ) of the controller to synchronize the motor with the zero position. The linear equations (1) and (2) are line fitting of the data of motor rotation vs. arm angle for the right and left motors respectively and equation (3) represents the relation between third motor rotation and tool insertion.

\[
\begin{align*}
\theta_1(r_1) &= 0.2785r_1 + 0.1332 \quad R^2 = 0.9999 \\
\theta_2(r_2) &= 0.2817r_2 - 0.188 \quad R^2 = 0.9998 \\
l(r_3) &= 3.917r_3 + 0.0998 \quad R^2 = 1
\end{align*}
\]

Here \( \theta_1 \) and \( \theta_2 \) are right and left arms’ angle, \( l \) is the amount of the tool insertion in meters and \( r_1, r_2 \) and \( r_3 \) are motor rotations. \( R^2 \) is the yielded Coefficient of determination.

3.2.2. Data acquisition and Workspace measurement

Robot was guided to 120 different actuation angles and the end-effector position is collected. Half of the data is used for calibration and the remaining is used for evaluation. The insertion mechanism was held still and the workspace over a constant radius sphere was covered. Figure 4 shows the recorded EE position alongside the theoretical workspace of the robot.

![Figure 3. Points of arms used for measurement](image1)

![Figure 4. Recorded EE position](image2)

3.3. Parameter Identification

7 parameters are chosen to be identified through an optimization technique. Optimization is used to minimize the error between the actual and nominal values. Vector \( \hat{V} \), shows the chosen parameters as:

\[
\hat{V} = [\alpha_{12}, \alpha_{13}, \alpha_{35}, \alpha_{24}, \alpha_{46}, \delta_1, \delta_2]
\]

Where \( \alpha_{12}, \alpha_{13}, \alpha_{35}, \alpha_{24} \) and \( \alpha_{46} \) are the base angle, the right shoulder arm’s angle, the right elbow arm’s angle, the left shoulder arm’s angle and the left elbow arm’s angle as shown in Figure 2. Since the kinematic equations are nonlinear, we use the Levenberg-Marquardt method [11]

\[
\dot{\theta}_k = \dot{\theta}_{k-1} - \eta_{k-1} \left( \hat{J}_{k-1}^T \hat{J}_{k-1} + \alpha_{k-1} D \right)^{-1} \hat{J}_{k-1}^T f_{k-1}
\]

Where \( \theta_k \) is the vector of robot parameters \( V \) in time “k”, and \( \dot{\theta}_{k-1} \) in time “k-1”, \( \alpha_{k-1} \) a positive non-zero constant and \( D \) is the diagonal value of the matrix \( \hat{J}_{k-1}^T \hat{J}_{k-1} \) where \( \hat{J} \) is Jacobian matrix. \( f \) is the error between nominal and measured parameters. We used least square method for the loss function as:

\[
I(\theta) = \sum_{i=1}^{N} f^2(i, \theta)
\]
Where, $I$ is the loss function. To achieve the inverse matrix in the Levenberg-Marquardt, we have:

$$\left(I_{k-1} + \alpha_{k-1}D\right)P_{k-1} = I_{k-1}f_{k-1}$$

(7)

So we can write:

$$\theta_k = \theta_{k-1} - P_{k-1}$$

(8)

We assume $\eta_{k-1} = 1$. The flowchart of this method is shown in Figure 5:

![Calibration Flowchart](image)

**Figure 5. Calibration Flowchart**

From [14], the convergence criteria is:

$$I_v = \frac{I}{n - \nu + 1} < \epsilon$$

(9)

Where $n$ is the number of data, $\nu$ the number of parameters and $\epsilon$ a positive value. We inserted 10, 30 and 60 data in the calibration algorithm respectively and the results are shown in Table 1.

| Number of points | Convergence value | $\alpha_{12}$ | $\alpha_{13}$ | $\alpha_{35}$ | $\alpha_{24}$ | $\alpha_{46}$ | $\delta_1$ | $\delta_2$ |
|------------------|-------------------|---------------|---------------|---------------|---------------|---------------|-------------|-------------|
| 10               | 0.0000447         | 144.25        | 63.05         | 68.08         | 55.82         | 67.02         | 0.041       | -3.360      |
| 30               | 0.0000920         | 146.03        | 62.09         | 67.47         | 57.21         | 65.02         | 0.149       | -2.156      |
| 60               | 0.0007577         | 146.68        | 61.48         | 67.31         | 58.36         | 63.81         | 0.190       | -2.036      |

3.4. Evaluation

For evaluation, first the motor rotations are used as input to the calibrated kinematic and then the output is compared to the relative measured position (Figure 6). The convergence value of the outputs generated using the calibrated kinematics is calculated to be 0.0002453.

![Comparison between the x, y and z of calibrated kinematic output and the measurement](image)

**Figure 6. Comparison between the x, y and z of calibrated kinematic output and the measurement**
4. Conclusion
To help surgeons in the craniotomy surgery, we developed a robot to ease the task of skull bone removal process. As the bone removing required a tough drilling process, we used a parallel mechanism for the robot and to have back-drivability, we used a capstan driving system. Since in the brain surgery operations, the accuracy is important, after the robot is manufactured and assembled, we used some calibration techniques to improve accuracy. For calibration process, first the kinematic equations were obtained. We considered 7 parameters to be calibrated. The kinematic equations were nonlinear so for the optimization process the Levenberg-Marquardt was used. With the help of a Leica total station camera, we measured 120 points of the robot end effector in different positions. 60 points were used in calibration and the others were used in evaluation process. Based on the defined convergence criteria, the convergence value of the calibrated kinematics outputs (for the same input points) is 0.0002453.

References
[1] Hoeckelmann, M. et al. 2015. Current capabilities and development potential in surgical robotics. *International Journal of Advanced Robotic Systems*. 12, 5 (2015), 61.

[2] Mattei, T.A. et al. 2014. Current state-of-the-art and future perspectives of robotic technology in neurosurgery. *Neurosurgical Review*.

[3] Deacon, G. et al. 2010. The Pathfinder image-guided surgical robot. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*. 224, 5 (2010), 691–713.

[4] Korb, W. et al. 2003. Development and first patient trial of a surgical robot for complex trajectory milling. *Computer Aided Surgery*. 8, 5 (2003), 247–256.

[5] Cunha-Cruz, V. et al. 2010. Robot-and computer-assisted craniotomy (CRANIO): From active systems to synergistic man—machine interaction. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*. 224, 3 (2010), 691–713.

[6] Shiakolas, P.S. et al. 2002. On the accuracy, repeatability, and degree of influence of kinematics parameters for industrial robots. *International journal of modelling and simulation*. 22, 4 (2002), 245–254.

[7] Majarena, A.C. et al. 2010. An overview of kinematic and calibration models using internal/external sensors or constraints to improve the behavior of spatial parallel mechanisms. *Sensors*. 10, 11 (2010), 10256–10297.

[8] Roth, Z. et al. 1987. An overview of robot calibration. *IEEE Journal on Robotics and Automation*. 3, 5 (1987), 377–385.

[9] Grosso, E. et al. 1996. Robust visual servoing in 3-D reaching tasks. *IEEE Transactions on Robotics and Automation*. 12, 5 (1996), 732–742.

[10] Shi, J. et al. 2011. Kinematic model identification of planar delta manipulator using Random Levenberg-Marquardt algorithm. *Intelligent Control and Automation (WCICA), 2011 9th World Congress on*. (2011), 1097–1102.

[11] Ouerfelli, M. and Kumar, V. 1994. Optimization of a spherical five-bar parallel drive linkage. *Journal of mechanical design*. 116, 1 (1994), 166–173.

[12] Wu, C. et al. 2010. Optimal design of spherical 5R parallel manipulators considering the motion/force transmissibility. *Journal of Mechanical Design*. 132, 3 (2010), 31002.

[13] Gavin, H. 2011. The Levenberg-Marquardt method for nonlinear least squares curve-fitting problems.