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# Kinematics Analysis and Trajectory Planning of a Multi-arm Medical Robot Assisted Maxillofacial Surgery

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***Abstract* – As the complex anatomical structure of the maxillofacial region, the surgery in this area is high risk and difficult to implement. Then, a multi-arm medical robot assisted maxillofacial surgery using optical navigation was proposed in this paper, which can improve surgical precision and make the doctors away from the heavy manual work. In this paper, the medical robot system and mechanical structure of the robot were introduced. Forward kinematics and inverse kinematics were analysed. Then trajectory planning using quintic polynomial interpolation for smoothly motion was adopted, and rectilinear motion in Cartesian space was adopted. The kinematics was validated and the workspace of the robot was calculated by simulations. Finally, the robot model was established and an experiment was carried out which proved the robot run smoothly and positioned accurately.**

***Index Terms* – *Multi-arm Robot, Maxillofacial Surgery, Kinematics, Trajectory Planning***

## I. INTRODUCTION

The accuracy and stability of a maxillofacial surgery is highly required, while the traditional maxillofacial surgery is hard to meet the operation requirements as there are various technical deficiencies. Meanwhile, maxillofacial surgery requires highly skilled surgeons with extensive knowledge about medicine and dentistry. So it is difficult to guarantee the treatment quality only with surgeons' manual operation [1-3].

With the development of computer science and navigation technology, medical robots assisted maxillofacial surgery have rose rapidly nowadays, and advanced industrial technology and computer advantages greatly satisfied the maxillofacial surgery as the anatomical structure is complex in this area, the individual treatment plan is strong and the operation requires highly accuracy. There are many advantages in a maxillofacial surgery with the robot assisted system [4-7].

*1)* The robot system can accurately positioning and avoid vascular and nerve injury of the base of skull and the neck region.

*2)* The minimally invasive operation can avoid large incision on the face.

*3)* The robot can accurately implement the preoperative virtual design, shorten the operative time and achieve precise treatment.

*4)* Surgeons with the help of robot could avoid the accidental damage caused by human factors as the high stability of the robot.

*5)* The robot assisted system provides a platform for multi-department collaboration and improves the therapeutic level.

This paper presents a medical robot owned three arms assisted maxillofacial surgery for improving the operation precision and reducing the labor intensity of the doctor, which can accurately complete the operation under the guidance of an optical navigation system. The robot system is introduced in section II. Forward kinematics and inverse kinematics are given in section III. The trajectory planning is introduced in section IV, and simulations by using Robot Toolbox in Matlab then experiments are introduced in section V. The last section is the conclusion.

## II. OVERVIEW OF MEDICAL ROBOT SYSTEM

### *A. System Overview*

Fig. 1 describes the overall structure of the medical robot system. The main components of the system are as the follows.

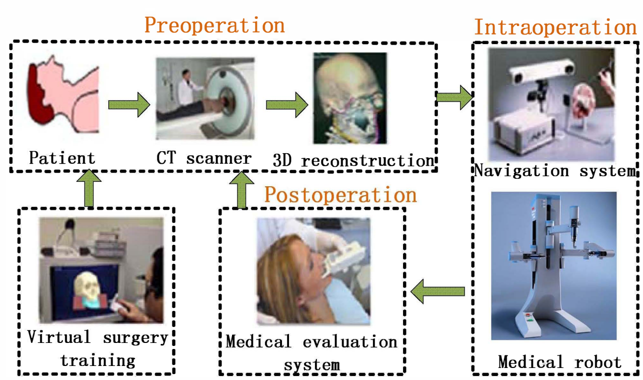


Fig. 1 Overall structure of the robot system

1) Collecting image data of the patient's head, establishing individual skull model, and then developing a surgical treatment with the help of computer aided technologies in preoperative stage.
2) In the preoperative stage, there is a virtual surgery training system for the training of surgical procedures.

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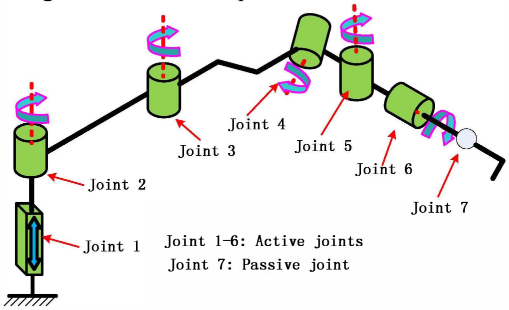
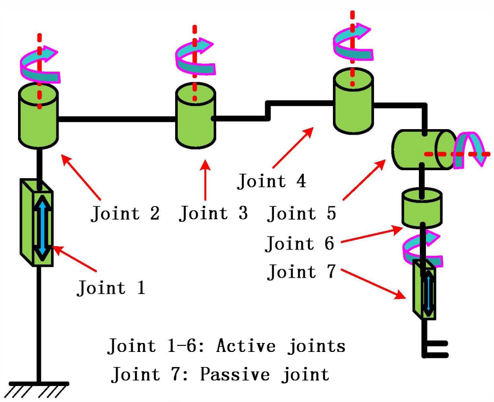
3) Updating the model of the patient and the plan if necessary by using optical navigation system, then doctors perform a specific surgical operation through multi-arm robot system in intraoperative stage.
4) Making a comprehensive assessment of the effect of the surgery by analysing preoperative design, data of intraoperative navigation and robotic operation, and postoperative equality of the actual status in postoperative stage.

*B. Multi-arm Medical Robot*

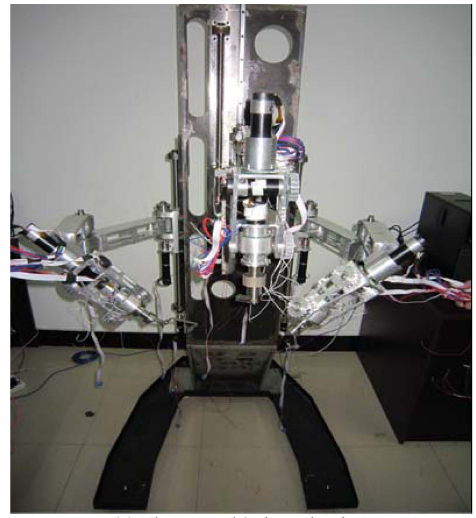
According to surgical requirements, we designed a multi-arm robot based on the structure of humanoid hand which two arms are used for supporting the ascending branch; while the other one is used for managing implant [8]. Each of the three arms has six active freedoms of degree and one passive freedom of degree. The 6-DOF active arm realises the position and posture, and the passive DOF grasps implant part. As shown in fig. 2. The first three DOFs compose robot arm and the remaining three DOFs compose robot wrist.




(a) The left arm




(b) The middle arm



(c) The assembled mechanism

Fig.2 Prototype and DOF arrangement of the medical manipulator

For minimally invasive surgery, cylindrical coordinate, SCARA-type and rectangular coordinate are considered a better structure [9]. We designed each arm by adopting the structure of one prismatic joint and five rotary joints. The left arm and the right arm have the same structure. And they both have a ball joint for facilitating the end-effector clamping the ascending branch. While the middle arm has a passive prismatic joint for clamping implant.

## III. KINEMATICS ANALYSIS

*A. Forward Kinematics*

Denavit-Hartenberg (D-H) parameters were employed to analysis the kinematics and establish the coordinate system of the medical robot. The kinematic chain configuration is shown in fig. 3, and the D-H parameters according to the configuration are presented in table I. The origins of each coordinate are fixed on the joint of each link. Forward kinematics is to calculate the position and orientation of end-effector in Cartesian space, given the joint angles in joint space. Inverse kinematics is to calculate the joint angles in joint space, given the position and orientation of end-effector in Cartesian space [10-13]. As the right arm and the left have the same structure, and the middle is similar with bilateral arms, so, we just discussed the middle arm.

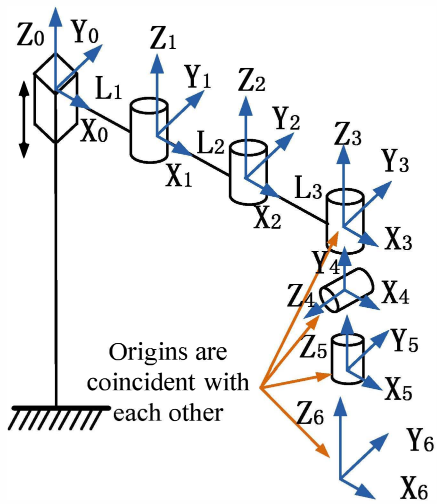



Fig.3 The kinematic chain configuration of the middle arm

TABLE I
D-H PARAMETERS OF MIDDLE ARM

| Link | $\theta_i$ | $d_i$ | $a_i$ | $\alpha_i$ | Range of joint |
|---|---|---|---|---|---|
| 1 | 0 | $d_1$ | $l_1$ | 0° | -600mm~0mm |
| 2 | $\theta_2$ | 0 | $l_2$ | 0° | -80°~45° |
| 3 | $\theta_3$ | $d_3$ | $l_3$ | 0° | -150°~150° |
| 4 | $\theta_4$ | 0 | 0 | 90° | -180°~180° |
| 5 | $\theta_5$ | 0 | 0 | -90° | -90°~90° |
| 6 | $\theta_6$ | 0 | 0 | 0° | -180°~180° |

According to the D-H coordinate system and D-H parameters, the homogeneous transformation matrix of link $i\,(i=1\ldots6)$ is

$$^{i-1}T_i = \begin{bmatrix} c\theta_i & -s\theta_i \times c\alpha_i & s\theta_i \times s\alpha_i & a_i \times c\theta_i \\ s\theta_i & c\theta_i \times c\alpha_i & -c\theta_i \times s\alpha_i & a_i \times s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Where, $s\theta_i = \sin\theta_i \quad c\theta_i = \cos\theta_i$

$s\alpha_i = \sin\alpha_i \quad c\alpha_i = \cos\alpha_i$

By multiplying rightward these transformation matrix one by one form the first to the sixth, the forward kinematic equations of the supporting manipulator is given as follow,

$$^0T_6 = {}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5\,{}^5T_6$$
$$= \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Where, for the middle arm:

$$n_x = c_{234}c_5c_6 - s_{234}s_6 \quad n_y = c_{234}s_6 + s_{234}c_5c_6 \quad n_z = s_5c_6$$
$$o_x = -s_{234}c_6 - c_{234}c_5s_6 \quad o_y = c_{234}c_6 - s_{234}c_5s_6 \quad o_z = -s_5s_6$$
$$a_x = -c_{234}s_5 \quad a_y = -s_{234}s_5 \quad a_z = c_5$$
$$p_x = l_1 + l_2c_2 + l_3c_{23} \quad p_y = l_2s_2 + l_3s_{23} \quad p_z = d_1 + d_3$$

*B. Inverse Kinematics*

Inverse kinematics is used to move the robot to an expected pose. The inverse kinematics equation is a nonlinear one due to nonlinear terms in equation. With the known position and orientation of the robot, the transformation matrix $^0T_6$ is given in (3)

$$^0T_6 = {}^{base}T_{end-effector} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

For the middle arm, combine the $^0T_6$ and multiplied individual matrices. We get $d_1$ via (4).

$$p_z = d_1 + d_3 \tag{4}$$

Though formula (5) we get $\theta_2$ and $\theta_3$.

$$\begin{cases} c_2p_y + s_2(l_1 - p_x) = l_3s_3 - d_4c_3 \\ c_2(p_x - l_1) + s_2p_y - l_2 = l_3c_3 + d_4s_3 \end{cases} \tag{5}$$

With computed $\theta_2$ and $\theta_3$, we can get $\theta_4$, $\theta_5$, $\theta_6$. Formula (6) presents all these 6 variables of left arm joints.

$$\begin{aligned} & d_1 = p_z - d_3 \\ & \theta_2 = 2A\tan u, \quad b = (l_1 - p_x) \\ & \frac{{p_y}^2 + b^2 - {l_3}^2 + {l_2}^2}{2l_2} = p_y\frac{2u}{1+u^2} - b\frac{1-u^2}{1+u^2} \\ & \theta_3 = A\tan(s_3, c_3) \\ & s_3 = \frac{(p_yl_3 - bd_4)c_2 + (bl_3 + p_yd_4)s_2 - d_4l_2}{{l_3}^2 + {d_4}^2} \\ & c_3 = \frac{-p_yc_2 - bs_2 + l_3s_3}{d_4} \\ & \theta_4 = \arctan\left(\frac{-a_xs_{23} + a_yc_{23}}{a_xc_{23} + a_ys_{23}}\right) \\ & \theta_5 = \arctan\left(\frac{n_z}{n_xc_{234} + n_ys_{234}}\right) \\ & \theta_6 = \arctan\left(\frac{n_xs_{234} - n_yc_{234}}{o_xs_{234} - o_yc_{234}}\right) \end{aligned} \tag{6}$$

## IV. TRAJECTORY PLANNING

*A. Trajectory Planning in Joint Space*

Polynomial interpolating algorithm was used for trajectory planning to ensure smooth movement and avoid sudden change of displacement, velocity and acceleration of each active joint, which mainly includes cubic polynomial function interpolation and quintic polynomial function interpolation. We planned trajectory conveniently with via points. The joint angle and angular velocity constraints of starting point A, via point B, and terminal point C were listed in table II. The characteristics of cubic and quintic polynomial function interpolation were contrasted by simulation in Matlab with one via point, as shown from fig. 4 to fig. 6. The angular velocity of via point was calculated by heuristic algorithm in joint space and the interval of interpolation points is 50ms [14-16].

TABLE II

D-H ParameterS

| Points | A | B | C |
|---|---|---|---|
| Angle values (rad) | 0 | $\pi/4$ | $\pi/2$ |
| Angular velocity (rad/s) | 0 | | 0 |
| Time (s) | 0 | 3 | 6 |

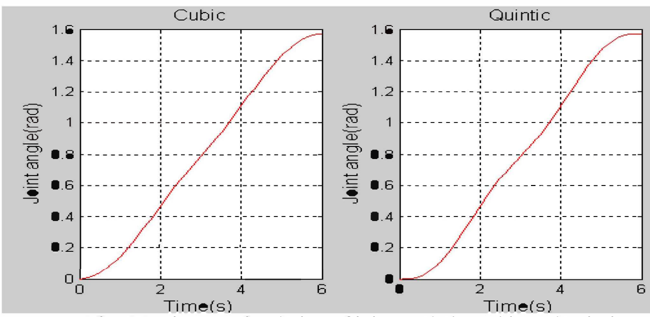



Fig. 4 Trajectory simulation of joint angle by cubic and quintic polynomial function interpolation

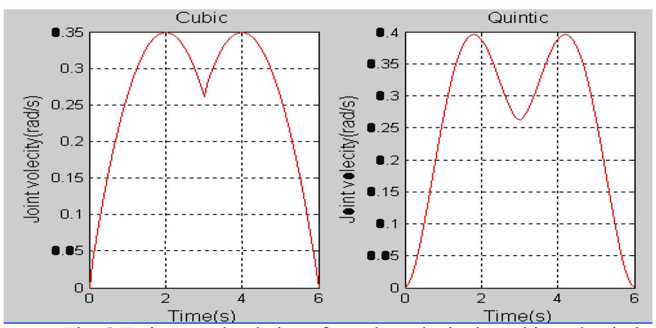



Fig. 5 Trajectory simulation of angular velocity by cubic and quintic polynomial function interpolation

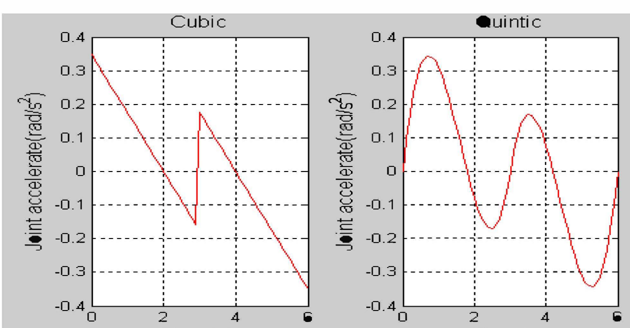



Fig. 6 Trajectory simulation of angular acceleration by cubic and quintic polynomial function interpolation

According to the simulation, we can see that the angular acceleration has a sudden change at via point by cubic polynomial function interpolation, while the trajectory with quintic polynomial function interpolation of joint angle, angular velocity and angular acceleration is continuous, which guarantees smooth motion of the robot from starting point to terminal point. So, quintic polynomial function interpolation was adopted for trajectory planning.

*B. Trajectory Planning in Cartesian space*

In order to ensure the end-effector of the robot motion along a given path, trajectory planning in Cartesian space is necessary. The planning of rectilinear motion was adopted. The approach of line interpolation for the position and posture of the manipulators was employed.

## V. Simulations and Experiments

Firstly, forward kinematics and inverse kinematics were validated by simulation in Matlab. Then the workspace of the middle arm was calculated in matlab. At last, a head model experiment of the optics-guiding robot was conducted.

*A. Kinematics verification in Matlab*

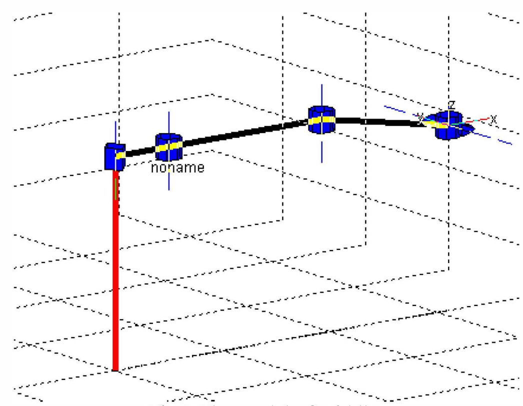



Fig.7 The model of middle arm

The middle arm model was established by using robot() function of Robot Toolbox in Matlab. As shown in fig. 7. We use a group of joint parameters matrix $q=[-60,-\pi/18,-\pi/9,\pi/18,\pi/9,0]$ to test the correctness of the kinematics. The matrix was computed by formula (2) and gets the result $\boldsymbol{n}$ = [0.8830, -0.3214, 0.3420, 0], $\boldsymbol{o}$ = [0.3420, 0.9397, 0, 0], $\boldsymbol{a}$ = [-0.3214, 0.1170, 0.9397, 0], $\boldsymbol{p}$ = [487.3202, -166.4897, -163.2800, 1] for the middle arm. By using the fkine() function of Robot Toolbox in Matlab, the results was

>>Tmiddle =

$$\begin{array}{cccc} 0.8830 & 0.3420 & -0.3214 & 483.3202 \\ -0.3214 & 0.9397 & 0.1170 & -166.4897 \\ 0.3420 & 0 & 0.9397 & -163.2800 \\ 0 & 0 & 0 & 1.0000 \end{array}$$

As Tmiddle was equal to the front, the analysis of forward kinematics is correct. By using ikine() function of Robot Toolbox in Matlab, the matrix of end-effector was given as follow.

$$
{}^{0}T_{6} = \begin{bmatrix} 1 & 0 & 0 & 519 \\ 0 & -0.7071 & -0.7071 & 0 \\ 0 & 0.7071 & -0.7071 & -200 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The inverse kinematics was calculated by using formula (6). The matrix was as follow.

q20=[-96.7200,0,0,1.5708,0.7854,1.5708]

By using ikine() function of Robot Toolbox in Matlab, the matrixes was gotten as follow.

q21=[-96.7210,0.0002,0.0004,1.5715,0.7866,1.5715]

As q20=q21 , the analysis of inverse kinematics was proved to be correct.

*B. Workspace in matlab*

The workspace of the robot was calculated according to the kinematics. According to the clinical requirements, the robot will work in a cube of $200mm \times 200mm \times 200mm$ .The workspace of the robot is represented in fig. 8 and fig. 9. The workspace of the surgical robot can easily cover the cube.

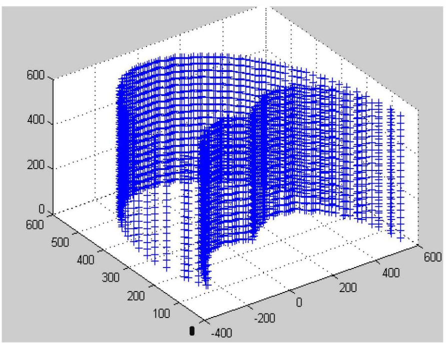


Fig.8 The workspace of middle arm

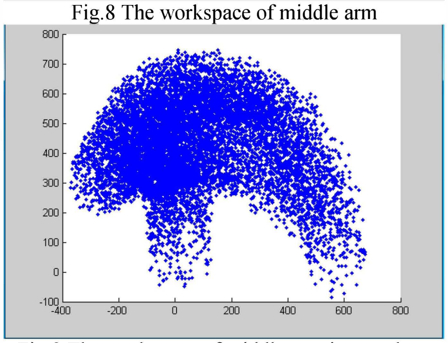


Fig.9 The workspace of middle arm in x-y plane

*C. Head model experiment*

The experiment was conducted with a human head model to test the feasibility of kinematics and trajectory planning of the robot, as shown in fig. 10.

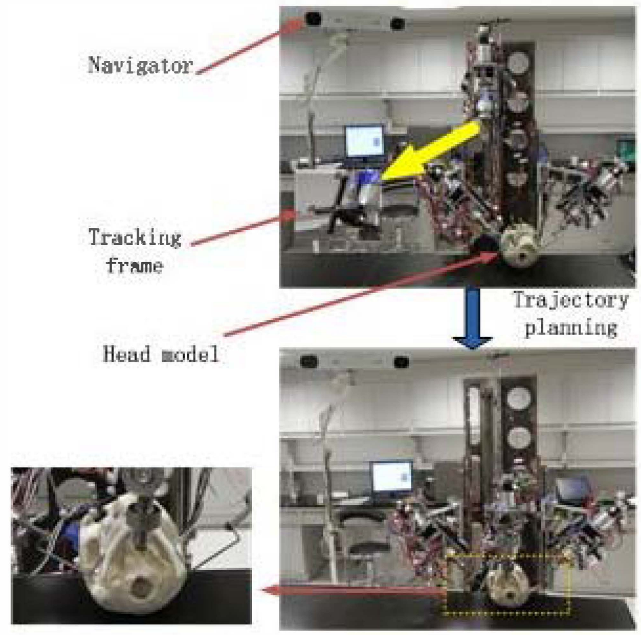



Fig.10 The head model experiment

During experiment, the robot arm was adjusted from starting point to desired point reposefully after kinematics solutions and trajectory planning. The position and orientation were given by optical navigation system. And the path of the tool of the robot was designed along a straight line. A tracking frame was fixed at the end of the arm. The tracking data of the frame was gotten by the navigator. By using plot3 () function in Matlab, the result is given as fig. 11. It approximates a straight line .

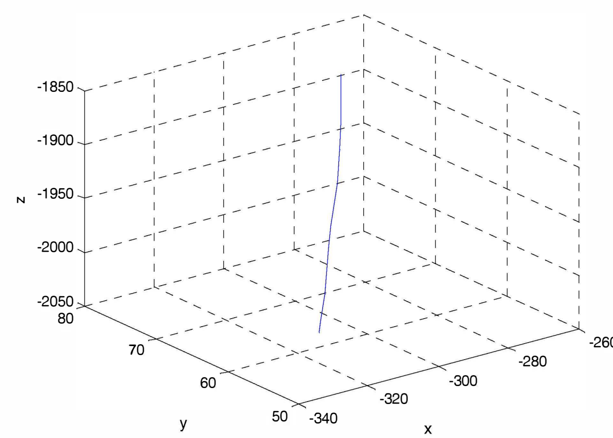


Fig.11 The straight path in Matlab

## VI. CONCLUSION

A multi-arm robot with optical navigation was developed to improve surgical precision. The structure design and working principle are introduced. Forward kinematics and inverse kinematics are solved and validated by simulation with Matlab. The continuity of trajectory functions in joint space is also validated, which is essential to smooth motion of joints. The workspace of the robot can easily cover the cube of

$200mm \times 200mm \times 200mm$. At last, the human head model experiment showed that the robot moved smoothly by trajectory planning with quintic polynomial function interpolation and positioned accurately

## ACKNOWLEDGMENT

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