Research Article

Autonomous Assembly Method of 3-Arm Robot to Fix the Multipin and Hole Load Plate on a Space Station

Zeyuan Sun, Hong Yang, Que Dong, Yang Mo, Hui Li, and Zhihong Jiang

1School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, China
2Institute of Manned Spacecraft System Engineering, China Academy of Space Technology (CAST), Beijing, China
3College of Electrical and Information Engineering, Hunan University, Changsha, China

Correspondence should be addressed to Hui Li; lihui2011@bit.edu.cn and Zhihong Jiang; jiangzhihong@bit.edu.cn

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Using space stations for a large number of observation, exploration, and research is a necessary way to fully develop space technology. It is a necessary means of space experiment to install the extravehicular experimental load by using the load plate. However, the extravehicular environment is full of danger, which poses a threat to the health and even safety of astronauts. Using robots to replace astronauts to complete this task can effectively reduce the threat to astronauts. Aiming at the problem that the configurations of existing space robots have difficulty in balancing the contradiction between complexity and dexterity, our previous work proposes a 12-DOF 3-arm robot and preliminarily explores the feasibility of its large-scale ability. This paper focus on the 8-DOF redundant dexterous manipulator composed of 2 of the robot arms. In view of the difficulties in solving the inverse kinematics of the redundant manipulator, the challenges of complex environmental lighting, and difficulties of matching multiple groups of holes and pins in the load plate assembly task, the research on the autonomous assembly of the load plate is carried out. The main work is as follows: (a) A variable D-H parameter inverse kinematics solution method is proposed, which lays a foundation for humanoid dexterous operation planning of the robot. (b) An autonomous operation method based on visual guidance and variable parameter admittance control is proposed. Finally, the safety and robustness of the robot in the autonomous assembly of the load plate with multipins and holes are successfully verified by experiments.

1. Introduction

Because robots are not limited by human physiological conditions, it is an inevitable choice for the development of space station automation technology to use them to assist or replace astronauts in space utilization and detection. Chinese astronauts entered the Tian He core module in June 2021 to carry out a three-month long-term residence experiment. It is expected that a large-scale and attended space station will be fully completed in 2022 [1]. The country needs a lot of observation, exploration, and research based on the space station [2] to fully develop space technology. At present, the tasks at the space station mostly depend on astronauts, which requires the space station to provide a complex life support system, and may lead to physiological and pathological phenomena of astronauts [3], even safety risks. Using robots to assist or replace astronauts can greatly improve the work efficiency of space missions and reduce risks, which is an inevitable choice for the development of space station technology in the future [4].

Many countries and regions have been actively carrying out research on space robot technology and gradually use space robots to assist or even replace astronauts to perform some space operations. The Canadarm II and Chinese robotic manipulator system on Tiangong 2 space station have played an important role in high-quality cabin capture, docking, and assembly, as well as assisting astronauts in extravehicular activities [5]. Aiming at the problem of insufficient dexterous operation ability of a large extravehicular manipulator, many dual-arm robots are developed, such as the dual-arm robot SPDM on the international space station [6], the Robonaut 2 humanoid robot developed by NASA [7], the German robot astronaut Justin [8] and Russia’s SAR-401 [9].

However, the large-scale autonomous mobility of the dual-arm robot still needs to be improved. In contrast, the
multiarm robot has the potential to solve this problem. The 3-arm crawling robot Eurobot developed under the auspices of ESA is a typical representative of a multiarm space crawling robot [10] [11]. Compared with the humanoid configuration, it has a lighter and smaller body. The Skywalker [12] and SpiderFab [13] space robots in the United States have the multiarm configuration. They can move with the help of the structure under construction to realize a wide range of mobile operations. The above robots have too many degrees of freedom redundancy; they do not fully tap the potential of each degree of freedom for robot movement and operation, which does not well meet the requirements of lightweight design [14]. Our previous work proposed a 3-arm robot whose configuration is simplified, which can still move in a large range with the help of handrails arranged inside and outside the space station, and has been preliminarily simulated and verified by the prototype [15, 16]. Based on this robot, aiming at the assembly task of a multipin and hole load plate, this paper deeply studies the operating control of the robot.

2. A Brief Introduction of the 3-Arm Robot

Figure 1 shows the ontology structure and control system architecture of the 3-arm robot. The 3-arm robot has three uniformly distributed 4-DOF arms. Each arm consists of a 3-DOF wrist joint and a 1-DOF elbow, totaling $3 \times 4 = 12$ DOFs. Each end of the arm is equipped with a gripper for movement and operation in the space station. In order to get environment information and ontology state, each arm of the robot is equipped with a monocular vision camera and a 6-dimensional F/T sensor. The basic motion mode of the robot has been verified by the principle prototype. This paper mainly studies the robot autonomous contact operation control.

3. Variable D-H Parameter Inverse Kinematics of Serial Redundant Manipulator

The common posture of robot operation is that the end of one arm grasps the handrail as the base and the end of the other arm operates the target. The 8-DOF manipulator composed of these two arms is used for flexible movement and dexterous operation, and applies the variable parameter admittance control algorithm to ensure that the robot can control the contact force within a safe range and effectively suppress the oscillation during assembling the load plate, so as to ensure the safety and reliability of the assembling task.

![Figure 1: Ontology structure and control system architecture of the 3-arm robot.](image)
improve the dexterity of robot operations. Inverse kinematics is an important basis for robot motion planning. By exploring the equivalent relationship between the 8-DOF manipulator and the 7-DOF humanoid manipulator, this paper establishes the humanoid kinematic model of the 8-DOF manipulator, which lays the foundation for the movement and operation planning of the 3-arm robot.

As shown in Figure 4, in the (a) 8-DOF manipulator, E is the midpoint of \( E_1 \) and \( E_2 \). The rotation of the joint at \( E_1 \) and \( E_2 \) leads to the change of \( \angle BEW \). In (b) 7-DOF manipulator, the joint rotation at E leads to the change of \( \angle BEW \). Therefore, it looks as if a virtual joint is configured at the point E in (a); the rotation of this virtual joint is the coupling of \( E_1 \) and \( E_2 \) rotation. The difference is that in (a), the rotation of point E changes the lengths of BE and EW, while in (b), the rotation of point E does not change their lengths. Therefore, each time (a) posture changes, the 7-DOF equivalent manipulator is reconstructed with its updated BE and EW. Based on this idea, this paper proposes a variable D-H parameter inverse kinematics method for redundant DOF serial manipulator. Specifically, we consider that the rotation of \( E_1 \) and \( E_2 \) joints determines the D-H parameters of the equivalent 7-DOF manipulator. Then, based on the D-H parameters, the 7-DOF kinematics model is established and the inverse kinematics can be calculated. Finally, the results are mapped back to the 8-DOF manipulator.

Based on the above equivalent method, the inverse kinematics of the 8-DOF manipulator can be solved according to the input end pose \( T \) and arm shape angle \( \beta \), and the specific process is as follows:

1. Use the solved D-H parameters according to the geometric relationship to construct the 7-DOF equivalent manipulator.
2. Obtain the inverse kinematics solution of the 7-DOF manipulator according to the solved D-H parameters.
3. Map the joint angle of the 7-DOF equivalent manipulator to the 8-DOF manipulator.

3.1. Construct the 7-DOF Equivalent Manipulator. We establish the coordinate system as shown in Figure 5 for the 8-DOF manipulator according to the D-H method. In order to simplify the calculation of the inverse kinematics solution without affecting the workspace of the manipulator, let \( \theta_4 = \theta_5 \), then the 8-DOF manipulator degenerates to a 7-DOF one. When the end pose is determined, the pose of the links in the plane where the torso is located is also determined, as shown in Figure 6. At this time, \( \theta_4 \) and \( \theta_5 \) can be solved directly according to the geometric relationship of the connecting rod in the torso plane.

It is easy to know from Figure 6 that when \( \theta_4 = \theta_5 \), MN is parallel to BW, then

\[
\theta_4 = \theta_5 = \angle MWP = \arccos \left( \frac{PW}{MW} \right) = \arccos \left( \frac{BW - MN}{2MW} \right),
\]

(1)

\[
BW = \sqrt{p_x^2 + p_y^2 + p_z^2},
\]

(2)

next,

\[
PW = \frac{1}{2} (BW - MN),
\]

(3)

\[
BW = \sqrt{MW^2 + PW^2},
\]

(4)

\[
EW = \sqrt{\left( \frac{1}{2} BW \right)^2 + MP^2},
\]

(5)

\[
CM = \frac{PN}{MW} \Rightarrow CM = \frac{1}{2} \frac{MN \cdot PW}{MW},
\]

(6)

\[
CW = |CM + MW| = DB,
\]

(7)

\[
CE = \sqrt{EW^2 - CW^2} = DE.
\]

(8)

We establish the coordinate system as shown in Figure 7 for the 7-DOF manipulator and use the CW and CE obtained as its D-H parameters, as shown in Table 1.
3.2. Solve the Inverse Kinematics of 7-DOF Equivalent Manipulator.

We set the given end pose as
\[ T_0^7 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x \\ r_{21} & r_{22} & r_{23} & y \\ r_{31} & r_{32} & r_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \] (9)

Then, \( \mathbf{BW} = (x, y, z) \).
We set the plane formed by \( \mathbf{BW} \) and \( \mathbf{X}_0 \) as the zero plane for angle \( \beta \). The normal vector of the zero plane is
\[ \mathbf{n} = \mathbf{BW} \times (1, 0, 0) = (0, z, -y). \] (10)

Normalization:
\[ \mathbf{n}_0 = \left( 0, \frac{z}{\sqrt{y^2 + z^2}}, \frac{-y}{\sqrt{y^2 + z^2}} \right). \] (11)

The structure of the manipulator determines that \( \mathbf{Z}_4 \) is always the normal vector of the plane BEW. The angle between \( \mathbf{Z}_4 \) and \( \mathbf{n}_0 \) is specified as arm angle \( \beta \). Then,
\[ \mathbf{Z}_4 = \mathbf{R}_{BW}(\beta) \times \mathbf{n}_0 = (x_4, y_4, z_4). \] (12)

As shown in Figure 8, a temporary coordinate system directly related to the plane BEW is established to describe the positions of points D and E, and the first four joint angles \( \theta_1 \sim \theta_4 \) that determine the position of point W can be obtained.

At point B, set \( \mathbf{BW} \) as the positive direction of the X axis, set \( \mathbf{Z}_4 \) as the positive direction of the Z axis, and establish coordinate system \( k \); set \( \mathbf{BE} \) as the positive direction of the X axis, set \( \mathbf{Z}_4 \) as the positive direction of the Z axis, and establish coordinate system \( k' \).

The following is easy to get from Figure 8:
\[ \hat{\mathbf{P}} = \mathbf{BE}, \mathbf{BD} \cdot \cos \angle \mathbf{DBE}, -\mathbf{BD} \cdot \sin \angle \mathbf{DBE}, 0 \) . BE, BD, and \( \Delta \mathbf{DBE} \) are the structural parameters of the manipulator and are known.

In addition,
\[ \hat{\mathbf{k}} \mathbf{R} = \begin{bmatrix} \cos \angle \mathbf{EBW} & -\sin \angle \mathbf{EBW} & 0 \\ \sin \angle \mathbf{EBW} & \cos \angle \mathbf{EBW} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \] (13)

\[ \mathbf{x}_k = \frac{\mathbf{BW}}{||\mathbf{BW}||}, \mathbf{z}_k = \mathbf{z}_4, \mathbf{y}_k = \mathbf{z}_4 \times \mathbf{x}_4, \] (14)

\[ \hat{\mathbf{x}}_k = \mathbf{R}[\mathbf{x}_k \mathbf{y}_k \mathbf{z}_k]. \]
Table 1: D-H parameters of 7-DOF equivalent manipulator.

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>$α_{i−1}$</th>
<th>$α_{i}$</th>
<th>$d_{i}$</th>
<th>$θ_{i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$θ_{1}$</td>
</tr>
<tr>
<td>2</td>
<td>90°</td>
<td>0</td>
<td>0</td>
<td>$θ_{2}$</td>
</tr>
<tr>
<td>3</td>
<td>-90°</td>
<td>0</td>
<td>CW</td>
<td>$θ_{3}$</td>
</tr>
<tr>
<td>4</td>
<td>90°</td>
<td>CE</td>
<td>0</td>
<td>$θ_{4}$</td>
</tr>
<tr>
<td>5</td>
<td>-90°</td>
<td>-CE</td>
<td>CW</td>
<td>$θ_{5}$</td>
</tr>
<tr>
<td>6</td>
<td>90°</td>
<td>0</td>
<td>0</td>
<td>$θ_{6}$</td>
</tr>
<tr>
<td>7</td>
<td>-90°</td>
<td>0</td>
<td>0</td>
<td>$θ_{7}$</td>
</tr>
</tbody>
</table>

And then,

$$0^T_k = 0^R_k R_k^T P = (x_E, y_E, z_E).$$

$$0^P_B = 0^R_B R_B^T P = (x_D, y_D, z_D).$$

(i) Get $θ_1$ and $θ_2$ according to the position of point D

From the forward kinematics,

$$0^T_3 = \begin{bmatrix} c_1c_2c_3 - s_1s_3 & -c_3s_1 - c_1c_2s_3 & -c_1s_2 & -BD \cdot c_1s_2 \\ c_1s_3c_2 - c_3s_1 & c_1c_3 - c_2s_3s_1 & -s_1s_2 & -BD \cdot s_1s_2 \\ s_2s_3 & s_2c_3 & c_2 & BD \cdot c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

That is, $x_D = -BD \cdot c_1s_2$, $y_D = -BD \cdot s_1s_2$, and $z_D = BD \cdot c_2$.

We get

$$θ_2 = \arccos \left( \frac{z_D}{BD} \right).$$

When $sin \ θ_2 \neq 0$,

$$θ_1 = a \tan \left( \frac{y_D}{x_D} \right).$$

When $θ_2 = 0$, due to the mechanical structure limitation of joint 2, it is only possible for $θ_2 = 0$. At this time, joints 1 and 3 are coaxial, and the shoulder joint is singular. In order to prevent the sudden change of joint motion from causing impact, make $θ_1$ take the value of the previous time.

(ii) Solve $θ_3$ by the direction of $Z_4$

From the forward kinematics,

$$0^T_4 = \begin{bmatrix} \cdots & c_3s_1 + c_1c_2s_3 & \cdots \\ \cdots & c_2s_1s_3 - c_1c_3 & \cdots \\ \cdots & s_2s_3 & \cdots \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$ (20)

The attitude information $0^T_4$ of $0^T_0$ describes the projections of the three coordinate axes of coordinate system 4 on coordinate system 0, so

$$z_4 = (c_3s_1 + c_1c_2s_3, c_2s_1s_3 - c_1c_3, s_2s_3) = (x_4, y_4, z_4).$$ (21)

When $sin \ θ_2 \neq 0$, $cos \ θ_1 \neq 0$,

$$θ_3 = a \tan \left( \frac{z_4}{x_4} \right).$$

When $θ_2 = 0$, $cos \ θ_1 = 0$, it has $sin \ θ_1 \neq 0$, then

$$θ_3 = a \tan \left( \frac{s_4}{s_2} \right).$$

When $θ_2 = 0$, according to the above, only $θ_2 = 0$ and joints 1 and 3 are coaxial and the shoulder joint is singular.

(iii) Solve $θ_4$ by $ΔBEW$
In space environment, the image acquisition system is seriously affected by the strong range change of light, stray light, and high-energy particles, which poses a challenge to the accurate and robust positioning of robot targets. Traditional image processing algorithms are often aimed at a specific environment, which is difficult for estimating the pose of targets in such a complex environment. Using a large number of data-driven deep learning algorithms is an effective way to solve such complex problems. Our previous work [22] proposed a triangulate geometric constraint combined with visual-flow fusion network for accurate 6-DOF pose estimation algorithm (TGCPose6D), as shown in Figure 9. Based on this algorithm, accurate and robust pose estimation of the target is realized using monocular vision in the environment of strong range variation of light, chaotic background, and occlusion.

4.2. Variable Parameter Admittance Control.

Safe and efficient autonomous operation ability is the basis for the space robot to assist or replace astronauts in-orbit operation, and it is an important research direction of space technology. In this paper, the robot completes autonomous target positioning and motion planning based on visual guidance and then ensures the safety during operating by compliance control.


When \( \theta_6 = 0 \), since joint angle are limited to \(-90^\circ \sim 90^\circ\), it is obvious that \( \theta_6 = 0^\circ \), causing a singularity, so we give it up.

When \( \theta_6 \neq 0 \),

\[
\theta_6 = \arccos (t_{23}),
\]

(iv) Solve \( \theta_5 \sim \theta_7 \) by the end pose

\[
^5T_s^7 = (^{0}T_s^{-1})^7.
\]
chain between the robot and the environment. If pure position control is adopted for the robot, it is easy for internal stress to occur in the closed chain under the combined action of high servo stiffness and positioning error of the robot, causing the operating object or the robot to be destroyed. In order to solve this problem, compliance control is usually added on the basis of position control to reduce the force generated during contact with the environment or the operating object. However, the traditional compliance control algorithms often aim at specific working conditions, so they have poor adaptability working in a complex environment [23]. In contrast, humans have excellent compliance performance in various assignments and have broad task adaptability. Based on the human compliant operation mechanism, this paper proposes a variable parameter admittance control algorithm in Cartesian space, so that the stiffness and damping of the controller can change dynamically with the contact situation, improving the safety and stable operation ability of the robot.

Our previous work [24] found that the end stiffness of human arm changes with the end movement. The stiffness increases in the main direction of movement and decreases in other directions. Inspired by this, we established the relationship between the stiffness and the velocity robot end, so it can be applied to the compliance control strategy of the robot arm. By changing the stiffness characteristics of the end of the robot, its motion performance is similar to that of a human.

\[ k = k_0 + \lambda \cdot \frac{\eta P_0 e^{\nu}}{\eta + P_0 (e^{\nu} - 1)} \]  

(34)

where \( k \) is the calculated stiffness, \( k_0 \) is the initial stiffness to avoid too small stiffness, \( \lambda \) is the oscillation coefficient of stiffness versus velocity, \( \nu \) is the normalized velocity, \( P_0 \) is the initial value, \( \eta \) is the end value, \( r \) represents the rate of curve variation, and \( e \) represents the exponent arithmetic.

In addition, the lightweight manipulator is prone to oscillation during operation [25]; in order to quickly absorb the system energy composed of the admittance controller and the environment, so as to prevent divergent oscillation caused by insufficient admittance control bandwidth, we make the damping term change dynamically with the contact force. Small contact force is generally generated by normal contact operation, and the damping should be small to release the motion speed of the robot so as to improve the operation efficiency. The larger contact force is likely to be the impact force. After the robot forms a closed chain with the environment, if the bandwidth or damping of the control system is insufficient, the impact force usually appears repeatedly in the closed chain and shows a divergent trend, which has a great impact on the safe operation of the robot. Therefore, the damping term is derived from the contact force at the end. The variation law of damping with contact force can be set as linear, exponential, or logarithmic, and the upper and lower limits can be set. The logarithmic variation law is conducive for the damping to enter the increased range from the lower amplitude limiting area as soon as possible, leading to strong adaptability to the rapidly changing impact force, and is conducive to oscillation suppression. It enters the upper limiting area later, which reduces the response time of the compliant contact force. So the damping term expression is constructed as

\[ c = \beta \ln (a|F| + 1). \]  

(35)

The variable parameter admittance controller based on the above concept is shown in Figure 10.

### 5. Autonomous Assembly Experiment of Load Plate

As shown in Figure 11, the device used to fix the experimental load outside the space station cabin is composed of two parts: one is the load chassis fixed outside the space station cabin and the other is the load tray for fixing the experimental articles. The load is installed and fixed by assembling these two parts. These two parts are generally positioned and installed by means of multipin and hole matching. The tolerance of mating parts is very small, and three groups of six pairs of pins and holes need to be matched at the same time, so the assembly is difficult, and the robot needs to operate with good compliance.

In the assembling experiment, according to the visual positioning results, the robot plans an end trajectory as the reference trajectory of the admittance controller and uses the inverse kinematics described in Section 3 to solve the joint trajectory. On this basis, the control strategy described in Section 4 is used to continuously modify the assembling trajectory according to the contact force and finally realize the safe assembly of the load tray and the load chassis. The visual recognition results are shown in Figure 12. The
Figure 11: Load chassis and load tray.

Figure 12: The pose estimation results of the load chassis.

Figure 13: Force and torque curve during assembling with fixed admittance controller. The numbers on the top of the figures are corresponding to those in Figure 14, the same as Figure 15.
recognition rate is not less than 93%, the position positioning error is within ±2.9 mm, the ADD in the attitude positioning accuracy evaluation index is not less than 88%, the 2D projection is not less than 92%, and the position and attitude estimation accuracy meets the tolerance of the guiding pin (±12 mm position, ±2° posture).

When the traditional fixed parameter admittance controller is used to complete the task, the force and torque curves measured by the six-dimensional force sensor at the end are shown in Figure 13, and the process of the task is shown in Figure 14. (The sensor is ATI’s six-dimensional force sensor Mini58. The existence of noise and the oscillation caused by flexibility make the data blur. The blur amplitude is small and does not affect the main signal.) Although the task was basically completed, there was obvious oscillation after some impacts.

When the variable parameter controller is used, the force and torque measured by the six-dimensional force sensor at the end are shown in Figure 15. The results show that the contact force and torque are controlled in a small range, and the oscillation is effectively suppressed.

6. Discussion

Base on the 12-DOF 3-arm robot developed in our previous work, aiming at the extravehicular load plate assembly task of space station, the operation control method of the robot is studied. The 8-DOF manipulator composed of two arms of the robot has the potential of humanoid dexterous operation, but it is difficult to solve the inverse kinematics. Therefore, this paper proposes a solution method of inverse kinematics with variable D-H parameters and deduces the solution process of equivalent 8-DOF manipulator to 7-DOF manipulator in detail, which lays a foundation for the dexterous operation of the 3-arm robot. Aiming at the interference of a space complex illumination environment on the
image acquisition system and the complex contact dynamic characteristics in the assembly process of a multipin and hole load plate, an operation control method is proposed in which the robot can automatically complete the target pose estimation and motion planning based on monocular vision and then ensure the operation safety with compliance control. A variable parameter admittance control strategy is used in the compliance control, which ensures that the contact force in the operation process is controlled in a small range and oscillation is effectively suppressed. Experiments show that the 3-arm robot can accurately estimate the pose of the load chassis and effectively suppress the oscillation in the assembly process, so that the robot can complete the autonomous assembly task of the load plate safely and reliably.

At present, the autonomous operation of the space station robot is still in the experimental exploration stage, and we did not get very clear application-oriented operation task and corresponding technical quantitative index requirements. However, improving the operation compliance of the space station robot is a certainly worth studying. In the future, we will further explore the quantitative relationship between operation contact force control requirements and controller parameters in combination with the specific tasks and index requirements of the space robot, so as to clarify the determination criteria of controller parameters.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Authors’ Contributions

Zeyuan Sun is responsible for overall coordination, manuscript writing, and data collection. Hong Yang is responsible for system design. Que Dong is responsible for motion control. Yang Mo is responsible for visual image processing. Hui Li and Zhihong Jiang provided administrative, technical, or supervisory support. Hui Li and Zhihong Jiang are the corresponding authors.

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