A study on large parts precision docking method based on 6-axis industrial robot

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Abstract. In view of the docking assembly difficulties of spacecraft large parts, resulting from the irregular contour and the inadequacy of process clamping points, this paper puts forward a method fitting the attitude relations of the docking parts based on the coordinates of the feature points, obtaining the target attitude of the docking parts based on the process constraints, and controlling 6-axis industrial robot achieves precise docking of large parts. Firstly, the composition of the large parts docking system is introduced, and the docking model is described by the selection of the measurement feature points and the establishment of the coordinate system. After that, a docking control algorithm based on the attitude constraints of large parts is established. Finally, In the RobotStudio and Matlab co-simulation environment, the attitude adjustment process of the large parts is simulated. The simulation results show that this study provides an effective method for precision docking of spacecraft engine large parts based on feature points, which is completed by 6-axis industrial robot.

1. Introduction

In the aerospace manufacturing industry, the size of the rockets and aircraft is extremely large, and the required manufacturing and assembly space is large as well. Usually, the main body is not processed as a whole, but fabricated by piecewise manufacturing, then assembled together in the assembly line. And the assembled parts often characterized as having various types, different material, different shapes, and compact space. It is similar to the traditional aircraft manufacturing process, the docking of rocket engine large parts mainly uses tools such as assembly frame, docking tooling, standard template, gauge, and etc. to ensure the coordination and docking of large parts. This kind of docking method based on analogy transfer is difficult to locate, difficult to adjust, low in precision and greatly influenced by human factors, which leads to long manufacturing cycle and poor reliability [1].

Since the rocket engine is a high precision product, its assembly process is almost completed by manual assembly. The technical literature which can be consulted through public information only involves the structure design of the engine parts, the reliability and stability analysis of engine running state, assembly processing exploration and other aspects, but for the rocket engine large parts automatic docking method is almost blank. The automatic docking method which can be used as a reference for large parts is most of designed for aircraft segment and cabin, wing and fuselage, such as flexible tooling system based on NC positioner, flexible tooling system based on parallel mechanism and so on [2-6]. The docking system is mostly using laser tracker or iGPS tracker as a measurement system. The computer control system plans the posture adjustment path and generates motion command by processing and analyzing the measured data, then drives the docking equipment to
complete the automatic docking. However, the above docking systems are only designed for a specific product. When the product or assembly processing changes, the flexibility and re-configurability of the system are poor.

A 6-axis industrial robot has many advantages, such as large load, high flexibility, high maturity, rapid reconstruction and so on. It has been widely used in many industrial applications, such as automatic welding, handling, assembly, spraying and so on. However, since rocket engine large parts have the characteristics of large welding deformation and many constraints, the docking process needs to be adjusted and positioned according to the initial relative attitude of the large parts, so it is difficult to use the conventional robot control method to realize the precision docking of the large parts. Abundant researches show that industrial robots have high repeatability positioning, but the absolute positioning accuracy is low. So robot absolute positioning accuracy and docking control algorithm are the keys to realize robot docking operation. To improve robot absolute positioning accuracy, scholars have carried out a lot of researches. Nubiola and Ginanni LS improved the absolute positioning accuracy of ABB robot by adopting optimizing D-H parameters, and satisfactory results have been achieved respectively [7, 8], but robot docking algorithm is relatively rare.

As for a series of requirements for rocket engine large parts docking, this paper characterizes the attitude relations by measuring the feature points of the large parts. Additionally, it calculates the target attitude of the large parts based on the coordinates of the feature points and the design constraints, establishes the BASE and TOOL coordinate systems of robot system to control the attitude of the end of robot, and realizes the attitude control of the parts. Finally, in the RobotStudio and Matlab co-simulation environment, the attitude adjustment process of the parts is simulated to verify the validity of this method.

![Figure 1. The docking system composition.](image)

2. Docking system design
The docking system for large parts is composed of 6-axis industrial robot, profiling clamping mechanism, measuring system and control system. The system composition is shown in Figure 1. Among them, the 6-axis industrial robot drives the profiling clamping mechanism to pick up and shift with 6 degrees of freedom. The profile clamping mechanism adopts the left and right separation form,
which is more conducive to the flexible and stable clamping part II. The measurement system adopts the laser tracker system to realize the accurate real-time measurement of each feature point, and transmits the measurement data to the control system. The control system can provide the functions of measuring data management and processing, motion control and docking process monitoring and so on. During the docking process, the measurement system measures the feature points of the docking parts I and II, firstly. After that, the control system calculates the relative attitude relation of the docking parts I and II according to the measurement data and converts to the robot control commands. At last, 6-axis industrial robot adjusts the position and posture of the part II to the target location.

3. Model description of large parts docking
In order to describe the docking model of large parts, the measurement feature points of large parts are selected according to the structural features, positioning requirements, high measurement consistency and excellent measurement accessibility principle, and the virtual axis are established based on the above feature points. Secondly, the BASE and TOOL coordinates are set up to describe the large parts based on the virtual axis.

3.1. The selection of feature points and the establishment of virtual axis
As shown in Figure 2, eight feature points A, B, C, D, E, F, G, H on docking parts I, II are selected to be measured by a laser tracker and stored in structured data.

\[
\begin{bmatrix}
A & B & C & D & E & F & G & H \\
ax & bx & cx & dx & ex & fx & gx & hx \\
ay & by & cy & dy & ey & fy & gy & hy \\
az & bz & cz & dz & ez & fz & gz & hz
\end{bmatrix}
\]  

(1)

At the same time, in order to clearly demonstrate the relative position and posture relation of the docking parts I and II, the virtual axis L1 which represents the vertical position and posture of the part I is composed by A and B, and the virtual axis L2 which represents the vertical position and posture of the part II is composed by C and D. The virtual axis L3 which represents the horizontal position and posture of the part I is composed by E and F. The virtual axis L4 and L5 which represent the horizontal position and posture of the part II are composed by G and C, H and C respectively.

3.2. Position and posture description of docking parts
In order to describe the position and posture of a rigid body in space, a coordinate system should be attached to the object and expressed in 6 degrees of freedom [9, 10]. Considering the actual situation of docking, the part I is fixed, the part II is driven by the robot to adjust the position and position. So the BASE coordinate system is established by virtual axis L1, the TOOL coordinate system is established by virtual-axis L2.

As shown in Figure 3, the BASE coordinate system is established by the following methods: A point is the origin of the coordinate system, the \overline{AB} is used as the unit vector of the \hat{Z}_b, and then using the default X direction of the robot system to calculate unit vector of \hat{Y}_b and unit vector of \hat{X}_b by 2 times cross-product, such as Formula (2) ~ (7):

\[
\hat{X} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}
\]  

(2)

\[
\overline{AB} = \begin{bmatrix} bx-ax & by-ay & bz-cz \end{bmatrix}
\]  

(3)

\[
\hat{Z}_b = \overline{AB} / |\overline{AB}|
\]  

(4)

\[
\hat{Y}_b = \hat{Z}_b \times \hat{X}
\]  

(5)

\[
\hat{X}_b = \hat{Y}_b \times \hat{Z}_b
\]  

(6)
4. Attitude control based on process constraint

The following process constraint are fulfilled for the docking of large parts: (1) L1 is parallel to the L2; (2) On the XOY plane, the actual angle between L3 and L4, and the actual angle between L3 and L5 are the smallest deviation from the designed value; (3) L1 and L2 distance is the designed value R and the angle between AC and L3 is the designed value λ; (4) In \( \hat{Z}_B \) direction, the actual height difference between L4 and L3, and the actual height difference between L5 and L3 are the smallest deviation from the designed value. Based on the position and posture constraints, the attitude adjustment adjusts the rotation posture step firstly, adjusts the translation position step secondly.

4.1. Posture adjustment of two parts

Because the Z axis direction of the BASE coordinate system and the TOOL coordinate system is respectively established in the direction of L1 and L2, the adjustment of the parallel posture of the two
parts is equivalent to the adjustment of the TOOL coordinate system from any posture to the target posture in the BASE coordinate system, therefore can calculate the Euler rotated by \( \hat{X}_b \) and \( \hat{Y}_b \). Specific solving process as shown in Formula (13) ~ (15)

\[
\begin{bmatrix}
\hat{X}_b \cdot \hat{X}_b, \\
\hat{Y}_b \cdot \hat{Y}_b, \\
\hat{Z}_b \cdot \hat{Z}_b
\end{bmatrix} =
\begin{bmatrix}
r_{11}, r_{12}, r_{13} \\
r_{21}, r_{22}, r_{23} \\
r_{31}, r_{32}, r_{33}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma \\
\sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma \\
-\sin \beta & \cos \beta \sin \gamma & \cos \beta \cos \gamma
\end{bmatrix}
\]

\( \beta = \arctan^{-1}(r_{21} / \sqrt{r_{11}^2 + r_{21}^2}) \)

\( \alpha = \arctan^{-1}(r_{21} / r_{31}) \)

\( \gamma = \arctan^{-1}(r_{32} / r_{33}) \)

As shown in Figure 4, the L1 and L2 have been adjusted to parallel state through preorder adjustment, the projection of the parts to the XOY plane can get the A and C points, and the L3, L4, L5 axis. The constraints of the large parts in the direction of the yaw are determined by the actual angle of L4 and L5 with L3 respectively. That is, the optimal \( \alpha \) is solved to minimize the deviation of the adjustment target angle \( \phi_1, \phi_1' \) with the designed value \( \phi, \varphi \).

**Figure 4.** The yaw posture adjustment of parts.

According to the geometric relationship, there is the following relationship among the adjusting angle of the target \( \phi_1, \phi_1' \), the yaw angle and the actual angle \( \phi_1, \phi_1' \):

\[\varphi_1 = \phi_1 + \alpha \quad \phi_1' = \phi_1 - \alpha\]

The following description function is constructed to solve the yaw angle \( \alpha \):

\[\min f(\alpha) = \min \left[ (\varphi - \phi_1) + (\phi - \phi_1') \right] = \min \left\{ (\varphi - (\phi_1 + \alpha)) + (\phi - (\phi_1 - \alpha)) \right\}\]

\[\alpha = \frac{(\varphi + \phi) - (\phi_1 - \phi_1')}{2}\]
\[
\phi_i = \cos^\dagger \overrightarrow{L_4 \cdot L_3} / \left| \overrightarrow{L_4} \right| \left| \overrightarrow{L_3} \right| \quad (19)
\]

\[
\phi_i = \cos^\dagger \overrightarrow{L_5 \cdot L_3} / \left| \overrightarrow{L_5} \right| \left| \overrightarrow{L_3} \right| \quad (20)
\]

Among them, \( \overrightarrow{L_4} \) is the projection of the L4 in the XOY plane, \( \overrightarrow{L_5} = [hx-cx \ hy-cy] \), \( \overrightarrow{L_5} \) is the projection of the L5 in the XOY plane, \( \overrightarrow{L_3} = [gx-cx \ gy-cy] \); \( \overrightarrow{L_3} \) is the projection of the L3 in the XOY plane, \( \overrightarrow{L_3} = [ex-fx \ ey-fy] \).

4.2. Adjustment of two parts translation

As shown in Figure 5, the horizontal position \( px \) and \( py \) are determined by the designed angle and the designed distance \( R \).

\[
px = R \sin \lambda
\]

\[
py = R \cos \lambda
\]  

![Figure 5. The horizontal position adjustment of parts.](image)

The vertical position \( pz \) is determined by the height of L4 and L5 to L3 respectively in the direction of the \( Z \) axis of BASE coordinate system. That is, the optimal \( pz \) is solved to adjust the actual value \( H_1', H_2' \) for the least deviation between actual value and designed value, and the following description function is constructed to solve vertical displacement.

\[
\min f (pz) = \min \left[ (H_i - H_i + pz) + (H_z - Hz + pz)^2 \right]
\]

\[
pz = \frac{(H_i + Hz) - (H_i' + Hz')}{2}
\]

Among them, \( H_1' = ez-gz \), \( H_2' = fz-hz \).
5. Simulation

Based on RobotStudio and Matlab software, a large parts docking simulation platform is established. RobotStudio software is used to realize the 3D simulation of the docking process. Matlab software is used to realize the calculation of robot control variables.

In order to verify the correctness of the docking method described in this paper, a simplified docking model, as shown in Figure 6, is designed in the RobotStudio software. The docking system selects the IRB8700 robot as the adjusting device, and designs a rod-shaped simulation model I and II, which can characterize the features of the docking parts. And in order to verify the docking algorithm in complicated work condition, the model I and II are biased. The simulation takes the robot foot as the original point of the global coordinate system. Through the software system, each feature point is measured, and the coordinate data of the simulation model I and II in a certain posture are obtained, as shown in Table 1.

![Figure 6](image)

**Figure 6.** Experiment in RobotStudio.

| Feature Points | X coordinate | Y coordinate | Z coordinate |
|----------------|--------------|--------------|--------------|
| A              | 2998.41      | 0.00         | 0.00         |
| B              | 3345.71      | -171.66      | 1962.12      |
| C              | 1888.69      | -128.51      | 1719.87      |
| D              | 2903.51      | 48.04        | 3196.01      |
| E              | 3258.88      | 668.21       | 1541.31      |
| F              | 3258.88      | -925.70      | 1401.87      |
| G              | 2844.44      | 466.48       | 2028.14      |
| H              | 2950.44      | -716.65      | 2645.50      |

The \(\overrightarrow{ab}\) and \(\overrightarrow{cd}\) vectors are used as the Z axis of the BASE and TOOL coordinate system of the robot system respectively. As shown in Figure 7, the left side is automatically generated by RobotStudio, and the right is the coordinate system established in Matlab by the method described in this paper.

Adjusts the models parallel posture with controlling the TOOL coordinate system to (0,0,0) state in the robot Base coordinate system, and adjusts the yaw angle of the models based on the updated dates, finally completes the adjustment of the rotating posture of the models as shown in Figure 8, and the coordinate data of each feature point, as shown in Table 2.
Figure 7. Establishment of Base and Tool coordinate systems for robot system.

Figure 8. Adjustment of rotating posture of parts.

Table 2. Coordinate data of feature points.

| Feature Points | X coordinate | Y coordinate | Z coordinate |
|----------------|--------------|--------------|--------------|
| A              | 2998.41      | 0.00         | 0.00         |
| B              | 3345.71      | -171.66      | 1962.12      |
| C              | 2290.30      | 48.88        | 588.57       |
| D              | 2616.31      | -109.77      | 2351.68      |
| E              | 3258.88      | 668.21       | 1541.31      |
| F              | 3258.88      | -925.70      | 1401.87      |
| G              | 2848.20      | 664.37       | 1408.58      |
| H              | 3083.12      | -618.86      | 1709.09      |

According to the coordinate data and constraint conditions, adjusts the horizontal and vertical positions of the models, and the completed attitude of the models is shown in Figure 9. The coordinate data of the feature points in completion status are obtained as shown in Table 3.

In order to examine the correctness of the docking control algorithm, according to the results of the simulation experiment, the relative position of the two parts are measured by using the A, E and F points as the reference point to measure the distance between the C, D, G and H points respectively. And then compared the distance between the measured value and the standard model, it can be seen in Table 4 that the desired position of the large parts based on the constraint can be obtained. The
accuracy of docking control algorithm better than 0.03mm, satisfying the overall docking accuracy of 0.5mm.

Table 3. Coordinate data of feature points.

| Feature Points | X coordinate | Y coordinate | Z coordinate |
|----------------|--------------|--------------|--------------|
| A              | 2998.41      | 0.00         | 0.00         |
| B              | 3345.71      | -171.66      | 1962.12      |
| C              | 2357.69      | 173.11       | 587.51       |
| D              | 2683.69      | 14.46        | 2350.62      |
| E              | 3258.88      | 668.21       | 1541.31      |
| F              | 3258.88      | -925.70      | 1401.87      |
| G              | 2915.59      | 788.60       | 1407.52      |
| H              | 3150.51      | -494.63      | 1708.03      |

Figure 9. Adjustment of the shift position of large parts.

Table 4. Feature points distance of actual posture and standard model.

| Feature Points | Experimental value | Designed value | Error |
|----------------|--------------------|----------------|-------|
| ac             | 790.69             | 790.71         | -0.02 |
| ec             | 1797.76            | 1797.78        | -0.02 |
| fc             | 1611.97            | 1611.96        | 0.01  |
| ad             | 2141.3             | 2141.31        | -0.01 |
| ed             | 1338.63            | 1338.66        | -0.03 |
| fd             | 1076.3             | 1076.3         | 0     |
| ag             | 1247.97            | 1247.97        | 0     |
| eg             | 66.98              | 66.70          | -0.02 |
| fg             | 1466.3             | 1466.28        | 0.02  |
| ah             | 1654.86            | 1654.87        | -0.01 |
| eh             | 1494.44            | 1494.47        | -0.03 |
| fh             | 154.15             | 154.15         | 0     |
6. Conclusions
In this paper, a method, based on the measurement of the feature points of the large parts and process constraint to control the 6-axis industrial robot realizing the precision docking of the rocket engine large parts, is proposed. Relying on the advantages of heavy load capacity, high flexibility and high maturity of industrial robot, the docking system has been developed rapidly. The docking process has been simulated in the RobotStudio and Matlab environment, under the arbitrary attitude of the large parts, the robot system can drive the large parts to the desired pose and position according to accurate measurement of the feature points. The simulation experiment shows that the method described in this paper can achieve accurate docking of large parts of the rocket engine, at the same time, this method can be used for the other docking of complex parts.

Acknowledgements
This work was financially supported by National Key R&D Program of China No. 2017YFB1303701, The Project of Intelligent Manufacturing Integrated Standardization and New Model Application 2017, Science and Technology Project of Shenyang (Z18-0-004).

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