An Autonomous Robotic Alignment Strategy Based on Visual Guidance

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Abstract. Aiming at the problem that the intelligent level of solid rocket motor production line depends on manual alignment is low, a control strategy of robot automatic alignment based on monocular vision guidance is proposed. Accurate position measurement is realized by monocular vision; the mapping relationship between vision space and robot space is obtained by hand-eye calibration technology; the motion path of the robot is planned by the probabilistic roadmap method, and the assembly process is optimized by using the results of visual feedback; finally, the alignment process is visualized by simulation. Experiments and results demonstrate the effectiveness of the proposed strategy, which can achieve high-precision positioning, visual detection, path planning and path adjustment. It can meet the accuracy requirements of the robot automatic alignment operation and complete the whole process automatically.

Key words: Robot Assembly; Vision-guided; Path Planning; Autonomous Alignment.

1. Introduction
The precision of solid rocket motor assembly affects the quality, performance and even success or failure of military products. At present, assembly mostly adopts manual assembly, supplemented by automation equipment, which requires high experience of skilled workers, and there is insufficient consistency and coherence in operation, which makes assembly quality difficult to guarantee [1]. Because of the large volume and mass of the equipment, it is not suitable for manual handling and alignment; and because of the high cost of the equipment, collision should be avoided completely in the assembly process. The traditional manual assembly method can no longer meet the accuracy requirements of assembly, so it is urgent to introduce intelligent assembly technology. With the continuous development of robotics technology, robots are gradually applied to assembly operations. Workers carry equipment by manipulating robotic arms instead of lifting weights by hand. However, they can not give full play to the characteristics of high accuracy, automation and intelligence of robots [2-4]. Alignment is an important part of assembly process and a prerequisite for complete assembly. Its accuracy has a great impact on subsequent assembly. Therefore, the combination of robot, machine vision technology and path planning technology is introduced into assembly field [5-6].
Song et al. [7] obtains the position and attitude information of the target through visual measurement, realizes the position and attitude alignment of complex geometric parts, which has a certain guiding role, but does not involve the control problem of the robot. Chang [8] realizes the assembly task by visual feature detection and attitude estimation and two-point path planning control of the manipulator. But it is essentially an open-loop control. Because of the accumulated error in the motion of the manipulator, the control accuracy is not high. Lu [9] proposed a method of automatic alignment based on vision sensor and multiple laser ranging sensors. However, the layout of sensors has a great impact on the system accuracy, and it needs to adjust position and posture several times, which is more cumbersome.

For a certain type of solid rocket motor, based on robot vision technology, path planning technology. This paper presents a vision-guided automatic alignment strategy for robots. The precise position measurement is realized by monocular vision, the mapping relationship between vision space and robot space is obtained by hand-eye calibration technology, and the experimental conditions are comprehensively analyzed. Probabilistic Roadmap Method (PRM) is used to plan the robot motion path, and the visual feedback results are used to adjust the path in real time to optimize the assembly process. Finally, the alignment is realized by simulation. Process visualization. The experimental results prove that the system has high precision positioning, visual detection function, and the ability of path planning and path adjustment. The whole alignment process can be completed automatically.

2. System Composition

![Figure 1. Schematic diagram of the overall system structure](image)

Based on industrial robots and monocular vision system, a visual control system platform is built as shown in Fig. 1. Industrial cameras are fixed at the end of the robot arm and move together with random manipulators. They are called Eye-in-hand structure. They have the advantages of non-occlusion of vision and simple operation. The end effector of the robot is a special fixture. Mobile platform plays the role of object transmission and fixing, and assists the smooth progress of assembly work. The industrial computer contains the software modules needed by the system, including the robot motion simulation module, image processing module and path planning module. It receives and sends instructions by communicating with robot controller and vision system via ethernet.
Figure 2. Unit Diagram of the Whole System

Image acquisition, feature extraction and path planning are all realized in computer. The control of the manipulator is completed by the robot controller. The data exchange between the robot and the robot controller is carried out by communication. The computer transmits the relative motion of the terminal in the basic coordinate system to the robot controller, and reads the current position and pose of the robot from the robot controller. The relationships among the units of the assembly system are shown in Fig.2.

3. Monocular Vision System

3.1. Camera Calibration

Camera calibration is the premise of guiding robot alignment. Zhang [10] proposed a calibration method based on plane target. According to the principle of camera pinhole imaging, the coordinates of a point on the calibration board mapped to the image plane can be expressed as:

$$
\begin{align*}
\begin{bmatrix}
    u_i \\
    v_i \\
    1
\end{bmatrix} = M_{in} \begin{bmatrix}
    R \\
    t
\end{bmatrix} \begin{bmatrix}
    x_{wi} \\
    y_{wi} \\
    z_{wi}
\end{bmatrix} = M_{in} M_{ei} \begin{bmatrix}
    x_{ei} \\
    y_{ei} \\
    z_{ei}
\end{bmatrix}
\end{align*}
$$

In the formula, \( s \) is the depth coefficient, \( M_{in} \) is the inner parameter matrix of the camera, \((k_x, k_y)\) is the distortion coefficient of the camera model, and \( (u_0, v_0) \) is the origin of the image coordinate system. The external parameter matrix of the camera is represented by rotation matrix \( R \) and translation vector \( t \). For any point on the calibration board, if the world coordinate of the point is set as \( x_w \), the camera coordinate is \( x_c \), then there are:

$$
\begin{align*}
x_c = Rx_w + t
\end{align*}
$$

3.2. Hand-eye Calibration

For Eye-in-hand system, hand-eye calibration is to obtain the pose relationship between camera and robot coordinate system. Usually, the end of the manipulator is controlled to observe the fixed target in different postures, and the external parameters of the camera relative to the robot coordinate system are
calculated according to the external parameters obtained from the calibration and the position and attitude information of the end of the robot.

![Diagram of hand-eye calibration of robot]

**Figure 3.** Hand-eye calibration of robot

\[ T_r = T_p T_m T_d \]  

Here, \( T_r \) is the pose matrix between the calibration board and the camera, which is obtained by camera calibration; the hand-eye relationship matrix \( T_m \) is to be evaluated; and \( T_d \) is the pose matrix of the end effector relative to the base of the robot, which can be obtained by reading out the information of robot controller. Therefore, the pose matrix \( T_r \) between the calibration board and the base of the robot is:

\[ T_r = T_p T_m T_d \]  

Fixed the position of calibration board and robot base, that is \( T_r \) unchanged. By changing the position of the manipulator several times and establishing the mathematical relationship, the hand-eye matrix can be obtained by the simultaneous equations.

### 3.3. Target Detection and Feature Point Location

In the alignment process, the mobile platform is driven to locate the target in the camera field of view and collect images. The quality of the original image affects the accuracy of image detection, and then affects the positioning accuracy. Under the condition of good light source in the experimental environment, target detection and positioning based on image processing technology, such as binarization, filtering and noise reduction, image segmentation, region of interest extraction, edge fitting and feature extraction, etc. For standard precise circles such as targets, the geometric center is chosen as the locating point.

The position of the feature point is known, then the position of the point in the robot base coordinate system can be expressed as:

\[ X_r = T_p T_m X_g \]  

### 4. Control strategy of manipulator

#### 4.1. Control System Structure

After image processing, the position and posture of the starting point and the end point can be obtained, and the motion of the manipulator can be controlled to achieve alignment. Because the assembly process has strict restrictions on the path, interference or collision between objects should be avoided; and there are structural errors in the process of manipulator motion, which will gradually increase with the accumulation of time, resulting in the decline of system accuracy. Therefore, online planning and real-time adjustment of the end path of the manipulator are needed to improve the accuracy of the system.
4.2. Path Planning of Probabilistic Roadmap Method

The purpose of the path planning is to obtain the optimal collision-free path from the initial pose point to the target pose point, according to the task requirements under the known environmental information [11-12]. Its specific form can be expressed as:

\[ T = (C, O, q_{\text{init}}, q_{\text{goal}}, f) \]  

(5)

In the formula, \( C \in \mathbb{R}^n \) is the N-dimensional posture space for the manipulator, \( O \) is the model of the obstacle in the space, \( q_{\text{init}} \) and \( q_{\text{goal}} \) represent the starting point position and the ending point position respectively, \( f \) is a function for detecting whether the collision occurs.

Collision detection is the basis of planning collision-free alignment path for robots. To judge whether collision occurs between two objects is to judge whether they have common points. In this paper, the method of collision detection is based on axis-aligned bounding box (AABB). Its core idea is to cover the manipulator and obstacles with larger geometry. The collision detection problem is transformed into a relative positional relationship between the bounding boxes. The mathematical expression is:

\[ \{(x, y, z) | x_l \leq x \leq x_u, y_l \leq y \leq y_u, z_l \leq z \leq z_u\} \]  

(6)

In the formula, \( x_l, x_u, y_l, y_u \) and \( z_l, z_u \) are the maximum and minimum coordinates of the bounding box projected on the axis, respectively. If two bounding boxes have overlapping projection areas on three axes simultaneously, they will be determined to intersect.

The core idea of the probabilistic roadmap method is random sampling. By randomly selecting some samples in the barrier free space \( C_{\text{free}} \) as the landmark nodes, and then connecting these nodes into an undirected feasible path probability road map in some way [13]. Finally, a heuristic search algorithm is used in the probability map to find a feasible path from the starting point to the end point. The algorithm of path planning mainly includes two stages: the learning stage and the query stage.

Firstly, the set \( G = (V, E) \) of random landmarks is constructed. \( V \) is a set of configurations that robots can achieve, \( E \) represents the feasible paths between nodes. The points sampled randomly in space \( C_{\text{free}} \) are put into \( V \), and the non-collision connection with the adjacent nodes is added into \( E \). The construction of the implementation.

Next comes the query phase, in the case of the known starting point pose \( q_{\text{init}} \) and the ending point pose \( q_{\text{goal}} \), the two neighboring nodes \( q'_{\text{init}} \) and \( q'_{\text{goal}} \) are respectively selected according to the selection rules, and then a feasible path between \( q'_{\text{init}} \) and \( q'_{\text{goal}} \) is found according to the search algorithm. The selection rules for neighboring nodes can be expressed as:

\[ V_q = \{q' \in V | D(q, q') \leq d\} \]  

(7)

In the formula, \( V \) is the set of sampling points, \( q' \) is the adjacent node of the node \( q \), and \( D(q, q') \) is the Euclidean distance of two vector nodes, \( d \) is the set distance threshold.

\[ D(q, q') = \sum_{i=1}^{n} |J_i(q) - J_i(q')| \]  

(8)

In the formula, \( J_i(q) \) is the position of the robot configuration \( q \) in the joint space.

4.3. Path Adjustment

The sampling points based on random landmark method are discrete sequence points. When the number of sampling points is insufficient or the distribution is not uniform, the movement path of the manipulator will jump, resulting in the increase of alignment error. In order to improve the alignment accuracy of the system, the current end position of the robot is read every other period, and a new path planning is carried out. Real-time path adjustment to reduce errors. Visual measurement consists of image acquisition, feature extraction and three-dimensional coordinate transformation. The position of vision measurement is used as a given position, and the motion posture of the robot in the next cycle is obtained by path planning algorithm. The joint position of six joints is given by inverse kinematics. Each joint is controlled by position closed loop and speed closed loop. The inner loop is speed loop and the...
outer loop is position loop. The position and posture of the end of the manipulator are read out at each sampling point, and then the path planning is carried out.

The planned path without path adjustment gradually deviates from the destination direction. Through repeated path planning and adjustment, new paths are obtained to reduce the deviation and gradually approach the end point to achieve the task requirements.

5. Alignment Simulation Test
This paper establishes the assembly system CAD model through SolidWorks, observes the target model using virtual reality tools and the model motion animation in the simulation process. Denavit-Hartenbe method can be used to model the joint angle information of the robot and the position and attitude relationship between the connecting rods, which can be solved by numerical calculation. In order to verify the effectiveness of the proposed strategy, a simulation experiment of alignment is designed and carried out. The test operating conditions are shown in Fig. 4.

Figure 4. Three-dimensional model diagram of test conditions

5.1. The Results of Target Detection and Location
Camera calibration test was carried out under OpenCV environment. The calibration board is the standard 9*7 checkerboard. In theory, it takes only six images to acquire camera parameters, but in order to get more accurate results, fifteen target images in different positions and postures are acquired. The camera internal parameter matrix is:

\[
A = \begin{bmatrix}
1647.74 & 0 & 959.35 \\
0 & 1641.94 & 721.18 \\
0 & 0 & 1
\end{bmatrix}
\]  

(9)

Distortion coefficient: \( k_1 = 0.09466, k_2 = -0.14784, k_3 = 0.0033, k_4 = 0.00124, k_5 = 0 \)

In the hand-eye calibration experiment, the calibration board is fixed, the position and posture of the robot are changed to collect 15 target images, and the first image coordinate system is taken as the global reference coordinate system. According to the method in reference [14], the hand-eye pose matrix \( T \) (mm) is obtained.

\[
T = \begin{bmatrix}
-0.0582 & 0.9803 & -0.1887 & 207.5204 \\
0.9980 & 0.0524 & 0.0371 & 219.4032 \\
-0.0266 & -0.1905 & -0.9813 & 23.8890 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]  

(10)

Since the solid rocket motor is a military product, a special model was used during the test phase. The obtained center coordinates are \([1858.5260 \ 586.0368 \ 1592.0514]\).
5.2. Simulation Results of Path Planning

After the visual processing, the coordinate transformation of image feature points has been completed, and then the virtual assembly environment has been constructed. Since the planning algorithm is implemented in the joint space, the initial pose and the goal pose of the robot should be inversely solved to make it become useful joint angle information. Initial posture \([36.500, -47.600, 79.150, -0.200, 69.300, 29.400]\); goal posture \([3.082, -25.788, 36.562, -5.890, -9.300, 5.215]\). Fig. 6 shows the joint variation curves of the manipulator, and Fig. 7 shows the simulation results of the assembly process.

![Figure 6. Variation curves of robot joints](image)

Figure 5. Experiment of image detection and location

(a) Original image  (b) Image preprocessing  (c) Location of the feature point
From the simulation results of path planning, it can be seen that the end-effector of the robot changes flexibly during the movement, and the curve of each joint changes continuously. It can meet the requirements of collision-free and smooth operation of robot assembly alignment. The assembly sequence animation observed in the visualization tool is as follows.

**Figure 7.** Simulation of robot assembly path

Group A adopts the online path planning and adjustment strategy proposed in this paper; Group B only uses online path planning. In order to compare the repetitive accuracy of alignment, ten alignment tests were carried out respectively, and the coaxiality was taken as the detection standard, and the data as shown in Table 1 were obtained. (Unit: mm)
Table 1. Contrast test results

| TEST NUMBER | A  | B  |
|-------------|----|----|
| 1           | 0.2| 0.25|
| 2           | 0.17| 0.35|
| 3           | 0.19| 0.19|
| 4           | 0.26| 0.28|
| 5           | 0.23| 0.26|
| 6           | 0.15| 0.17|
| 7           | 0.14| 0.23|
| 8           | 0.13| 0.28|
| 9           | 0.19| 0.33|
| 10          | 0.26| 0.46|

Std. Deviation 0.04 0.07

6. Conclusion
This paper proposed an industrial robot autonomous alignment control strategy based on monocular vision to improve the low intelligence level of artificial alignment in solid rocket motor production line. Based on robotic vision technology and image processing technology, the target is automatically detected, the precise positioning of feature points is realized, the path planning and real-time adjustment of the robot from the initial position to the terminal position and position are completed, and the alignment operation of the manipulator is controlled, and the simulation experiment is carried out. The simulation results prove the effectiveness of the strategy, which greatly improves the alignment accuracy compared with the traditional method. In order to achieve the smooth assembly of solid rocket motor, on the basis of solving the alignment problem, it is necessary to control the spinning and torque angle of the shell. How to achieve this is the next research focus.

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