Precision assembly method based on coaxial alignment and force control

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Abstract. To ensure the assembly performance of precision assembly system, a high-precision assembly system for gear-piece and gear-shaft is developed in this paper, which consists of a computer, two manipulators, a coaxial alignment module (CAM), a selective compliance assembly robot arm (SCARA), an adjusting platform and a force sensor. The CAM is used to calculate the position and angular deviation of gear-piece and gear-shaft. The force sensor is equipped to detect the contact force. In the stage of adjusting alignment, position-based visual servoing (PBVS) is adopted to ensure high precision alignment of parts. In the insertion stage, an impedance control method based on position is proposed to ensure the contact force. Experiments are carried out to demonstrate the validation of the proposed system and methods. Automated assembly of parts with a 5 μm gap is achieved.

1. Introduction

In the fields of aerospace, electronics and medical devices, precision assembly plays a very important role in the manufacturing process of micro-devices and directly determines the final quality of products. In the process of assembly, the control of assembly precision and assembly force is a difficult problem in the field of precision assembly. The force control of assembly system can not only ensure the good contact force and the assembly performance of the parts, but also play a role in collision detection.

In terms of visual alignment, Das [1] et al. put forward the multi-camera with inclined mode layout, which has the advantages of 3d pose measurement and accurate positioning, etc. The image jacobian matrix method is adopted for calibration, and PD controller is adopted for visual servo control. However, the disadvantages of this method are that image Jacobian matrix’s singularity may result in the object out of the view. Xu [2] et al. adopted the method of orthogonal vertical arrangement of multi-camera to achieve accurate positioning of position and Angle, and compared the methods of position based visual control and image based visual control. However, the calibration of multi-camera system is complex. Tamadazte [3] et al. used the two microscopes that arranged in horizontal 45°, and put forward a CAD model-based assembly system. However, this method is not high-efficiency. In [4], a automated microassembly workcell was developed assisted by virtual reality techniques, and a visually served position/force controller was designed. But they are not suitable for our work, because the image of the gear-shaft is clear, the image plane must be perpendicular to the gear axis.

In force control areas, the force/position hybrid control [5] and the impedance control [6] are widely used in the field of assembly. Takashi [7-8] et al. designed a flexible control manipulator based on model, proposed the target pose estimation method based on real-time model and the visual servo
control method based on position, and proposed the impedance controller based on model. The method based on c-space was used to self-set the impedance parameters. Chen [9] proposed a robust compliant control method based on dynamic model, which effectively controlled the contact force during insertion. Xie [10] et al. proposed a hybrid control method of vision and force, and adopted a fuzzy PID controller to control the contact force in the assembly process. In [11], a Hybrid Suppression Control (HSC) for a cooperative object manipulation task is proposed. It can effectively eliminate the vibration effect of flexible solar panels.

The motivation of this work is to develop an automatic precision assembly system to assemble gear-piece and gear-shaft. This paper presents a new assembly control method based on vision and force. In the position adjustment stage, the coaxial alignment system is adopted to obtain the position deviation of the basal part and the target part, and the precision micro-adjustment platform adjusts the deviation. This method is simple to calibrate and more efficient because the gear-piece and gear-shaft are imaged in the same image coordinate system. And the PBVS is adopted because it can achieve the non-difference control of the relative pose between two objects. In the insertion stage, an impedance control strategy is proposed to ensure the stability of contact force.

The rest of this paper is organized as follow. The second part introduces the configuration of the system and the characteristics of the assembled parts. The third part including coaxial alignment principle and pose adjustment method. Position-based impedance control is described in Section 4. The fifth part shows the experiment and result of the system and methods. Finally, the conclusion of this article is drawn in Part 6.

2. Components and system configuration

2.1. Components
The assembly objects of this paper are the gear-shaft and gear-piece, as shown in Figure 1. The outer diameter of the gear-piece is 9mm, and the middle is a spline hole with a diameter of 2mm, the thickness is 0.6mm. The length of the gear-shaft is 12.9mm, the outer diameter of the gear-shaft is 2mm, and the diameter of the stepped shaft is 1mm and 1.5mm. The assembly of the gear-shaft and the spline hole is clearance fit. To ensure accurate insertion, both position and angle must be ensured, and the dimensional error of gear-shaft and spline hole is less than 5 micrometers.

![Figure 1. Components of precision assembly.](image)

2.2. System configuration
The configuration of the assembly system mainly includes a computer, a CAM, a SCARA, two manipulators and an adjusting platform. The force sensor is mounted on the lower part of the adjusting platform, as shown in Figure 2. The CAM includes a CCD camera and two light sources, and has two degrees of freedom (DOF) in the X direction. The SCARA has 5 DOFs, 3 rotation and 2 translational
DOFs. The manipulators are controlled by air circuit, including vacuum adsorption type and rigid clamping type. The adjusting platform has three DOFs, namely vertical movement of X and Y and the rotation movement around Z.

![Assembly system](image)

**Figure 2.** Assembly system.

3. Visual alignment method
In order to achieve high-precision parts alignment, the system adopts coaxial alignment method, which is a PBVS control method. And the target parts images and the basal parts of the image are displayed in the same image plane. Alignment principle as shown in Figure 3. The focal length and object distance can be adjusted through the two moving axes, and the algorithm of image processing is template matching.

![Coaxial alignment module (CAM)](image)

**Figure 3.** Coaxial alignment module (CAM).

The position deviation of the base part and the target part in the cartesian coordinate system is represented by \( \Delta x \), \( \Delta y \), and the angle deviation is represented by \( \Delta \theta_z \). The unit is the number of pulses. The position deviation of the basal part and the target part in the image coordinate system is represented by \( \Delta u \), \( \Delta v \), and the angle deviation is represented \( \Delta w \). \( \Delta u \), \( \Delta v \) and \( \Delta w \) are subtracted from the image processing result of the target part and the image processing result of the base part. The unit
is pixel and degree. Without considering the angular deviation of the camera coordinate system from the world coordinate system, the relation between the deviation of the image coordinate system and the deviation of the cartesian coordinate system is expressed in (1).

\[
\begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta \theta_z
\end{bmatrix} =
\begin{bmatrix}
J_{11} & 0 & 0 \\
0 & J_{22} & 0 \\
0 & 0 & J_{33}
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta v \\
\Delta w
\end{bmatrix} = J
\begin{bmatrix}
\Delta u \\
\Delta v \\
\Delta w
\end{bmatrix}
\]

(1)

Where J is the proportional gain matrix. Part alignment can be done with three image processing and two adjustments. The three image processing includes image processing of one target part and image processing of two base parts. And the adjustment amount is calculated by Formula 1.

4. Impedance control of assembly force

In the insertion stage of a part, it is impossible to detect its relative pose. In order to realize flexible assembly, the force of assembly is achieved through the change of motion. A positional impedance control assembly method is proposed.

Before assembly by force feedback control, the target parts have been adsorbed on the vacuum adsorption head. The basal parts are fixed on the precision adjusting platform. The position of the two parts has been adjusted by the adjusting platform. The assembly manipulator performs z-direction vertical insertion operation. By judging the magnitude of the contact force and the calibrated threshold force, the positional impedance control is implemented to ensure that the assembly force does not overshoot greatly, as shown in Figure 4.

\[
F_e = F_r - F_c
\]

(2)

\[
M_d \Delta \dot{x} + B_d \Delta \dot{x} + K_d \Delta x = -F_e
\]

(3)

Where: \(F_e\) is used for deviation; \(F_r\) is the reference force; \(F_c\) is the contact force; \(M_d\) represents the inertia matrix of the impedance model; \(B_d\) represents the stiffness matrix of the impedance model; \(K_d\) represents the damping matrix of the impedance model; \(\Delta x\) said displacement deviation. The formula is transformed by Laplace as follow.

\[
\Delta x = \frac{F_e}{M_d \bar{s}^2 + B_d \bar{s} + K_d}
\]

(4)
\[ M_d = M_1 + M_2 \]  
\[ K_d = K_1 + K_2 \]  

Where, \( M_1 \) is the quality of the assembly execution manipulator; \( M_2 \) is the quality of the micro-adjustment platform; \( K_1 \) is the stiffness of the executing assembly manipulator; \( K_2 \) is the stiffness of supporting mechanism and force sensor.

The threshold of contact force has been determined through the calibration of force sensor. In the force feedback control, the goal of contact force control should be to make the interaction between vacuum adsorption head and fixture reach the threshold of contact force with a minimum overshoot. Ignore the positioning error of the manipulator and simplify it as an integral function for the input control speed. The step response curve of the controller is simulated by MATLAB, as shown in Figure 5.

**Figure 5.** Impedance control response curve.

5. **Experimental and result**

The CAM consists of a navitar lens, a prism, a Basler camera, two light sources and two high precision linear stage, and SCARA for parts loading and unloading and assembly. Image processing using template matching algorithm developed by Matrox. The proportional gain matrix calibration results are as follow.

\[
J = \begin{bmatrix}
-1073 & 0 & 0 \\
0 & -1073 & 0 \\
0 & 0 & -1002
\end{bmatrix}
\]  

The force sensor has a range of 100N, an elastic modulus of 2000mN/mm, a set contact force control goal \( F_r \) of 5N, a calibrated elastic modulus of \( 5 \times 10^4 \) mN/mm, and a damping coefficient of 1N\( \cdot \)(m\( \cdot \)s\(^{-1})\(^{-1}\). \( M_1 \) is 1Kg, \( M_2 \) is 0.32Kg. The relationship between the force sensor voltage and the force is calibrated with a weight, and the ratio of voltage to force is 4.98mv/N by least squares fitting.

Automated assembly control system consists of a computer and a controller, and the procedure is developed by c++ programming. Force sensor connected with the computer via USB port. The maximum output frequency of the controller is 5 MPPS. Template matching is achieved through Matrox’s development kit, MIL. The SCARA connect with computer using EtherCAT bus and automated assembly process as shown in Figure 6.
By gear-shaft and gear-piece assembly experiment, the actual assembly force results as shown in Figure 7 and Figure 8, when the reference input control for 5N. The error method is used to adjust impedance parameter. The results show that the force feedback control of the method ensures the amount of smaller overshoot, and the simulation results are basically identical, achieved good control effect. The actual measured response results of the system have certain deviation in the contact state, which is mainly caused by the friction during the contact process, the deviation of the perpendicularity, the change of stiffness and damping after the contact and the influence of signal interference.

**Figure 6.** Automatic assembly process.

![Diagram](image)

**Figure 7.** Assembly process: (a) The processing of alignment; (b) The processing of insertion; (c) Gear-piece image processing result; (d) Gear-shaft image processing result.
6. Conclusions
The main contribution of this work is the design of a high-precision automated assembly system and assembly strategy for gear-piece and gear-shaft. The assembly system achieves the precision automatic assembly of gear-shaft and gear-piece. The accuracy of the system achieves 5μm, and the contact force is stable. Through the template matching algorithm, PBVS and CAM, the alignment accuracy can reach micron level. The impedance control of single DOF is realized. The steady-state error is less than 1N. Finally, this assembly result of gear-piece and gear-shaft has been presented to illustrate and validate the performance of the method.

In the future, our work will be focus on the adaptive impedance control assembly method for different types of parts.

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