

# Study on Assembly State Identification and Automatic Assembly of Shaft Hole Parts

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**Abstract.** This paper constructed a shaft hole assembly model based on the C-space method, and analyzed the assembly contact state of shaft hole model. The assembly path of shaft hole parts was studied by exploring the disassembly sequence of parts. Eventually, an assembly production line was established to realize the fully-automatic assembly of shaft hole parts with the assistance of control system and software platform.

## 1. Introduction

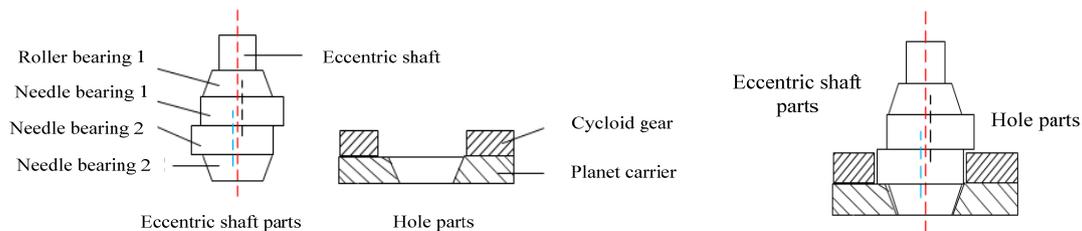
Owing to the progress of science and technology, it has been an inevitable trend to arrange robots in place of human beings for some tasks such as production of parts and assembly of products. Shaft hole assembly is the most common and typical kind of assembly related to mechanical parts. To study the shaft hole insertion assembly, Peng and Jin (1995) utilized the 2D images to describe the geometrical relationship between peg and hole in the process of assembly, and present the model of assembly force, but it appears very difficult to describe and analyze the abnormally shaped shaft hole or multiple shaft holes in this way. Ouyang et al. (2016) constructed a robot end effector rigidity model with two-dimensional images, and analyzed the state of force in the assembly process. Together with other scholars, Fei (2003; 2001; 2002) studied a variety of modeling methods. In one method, two-element approach was taken to describe the characteristics of the parts to be assembled. In the other method, C-space method was utilized to analyze the insertion assembly state of complex parts, and then boundary graph method was employed to study the insertion assembly search process of complex parts theoretically. Li (2001) put forward an active assembly approach featured by hole searching and lateral error compensation. Wu et al. (2005) designed the CMAC system of active-passive compound compliance, which took the input of assembly force signal. As precision machines are composed of multiple parts and have a compact structure. After it is assembled to the component, a part will become a constraint on the assembly of another part to be assembled subsequently, and such constraint is not static. For this reason, the existing achievements in the research of compliant assembly technology cannot satisfy the needs of assembly of complex and precision machines yet.

Considering the dynamic assembly environment formed in the assembly process of shaft hole parts, this paper intends to employ the C-space method for describing the insertion assembly state of complex parts. Based on the disassembly sequence of parts, the path of precision structure assembly is constructed to provide a theoretical approach for robot to enter the production line and assist the accurate assembly of precision machines.



## 2. Modeling with C-space Method

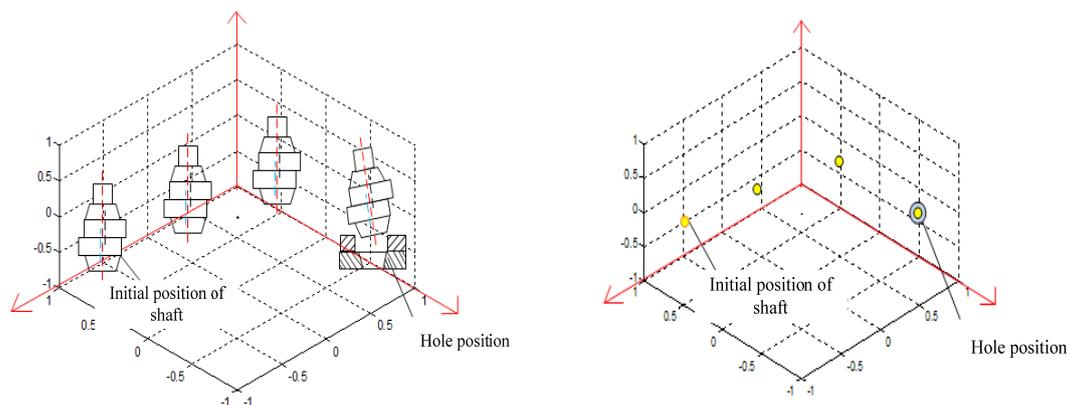
High-precision RV speed reducer consists of multiple shaft hole parts. Among them, eccentric shaft component is composed of an eccentric shaft, two needle bearings and two roller bearings, as shown in Fig. 1. The assembly of eccentric shaft hole involves many contact surfaces, so it has very complex features. For this reason, C-space method can be introduced to describe the relationship among the parts to be assembled.



**Figure 1.** Assembly sketch of eccentric shaft component

C-space, short for configuration space (Fei and Zhao, 2001), is essentially a generalized space, and a parameter space to indicate the degree of freedom of object (Chu and Ma, 1999). The C-space method can convert a rigid object that moves in the world coordinate space and has a certain size and shape into a point in the C-space, so as to significantly simplify the motion of the object.

Assuming that there is an object B in the  $k$ -dimension world coordinate system, the number of parameters used to determine the configuration of the object B is  $d = k + m$ ,  $m = k(k - 1) / 2$ ,  $k = 2, 3$ . Among  $d$  parameters,  $k$  parameters are used to determine the position of the reference point in the space  $R^k$ , while  $m$  parameters can help determine the pose of the object B in the space  $R^k$ . The above  $d$ -dimension space is defined as the C-space of the object B. When the object B has an initial configuration, it is represented by  $B_0$ , so there is a certain point  $B_i$  for any state of the object.



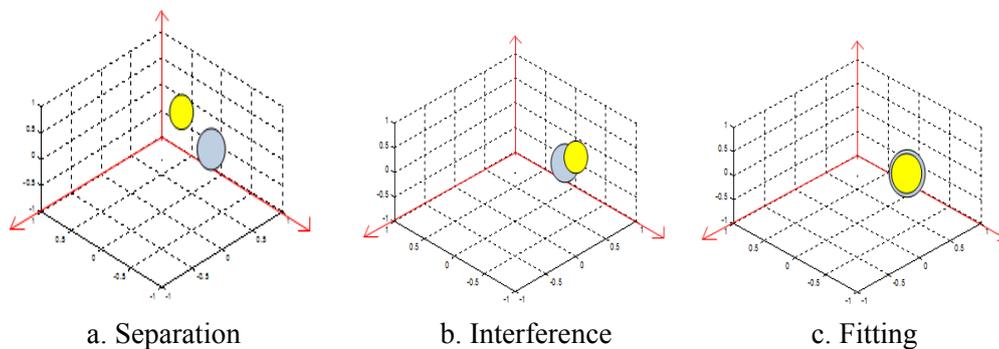
**Figure 2.** C-space model of eccentric shaft component

By utilizing the C-space method, 6 parameters  $(x, y, z, \alpha, \beta, \gamma)$  should be used to determine the configuration of eccentric shaft hole in the three-dimension world coordinate space. Among them,  $(x, y, z)$  defines the position of the eccentric shaft, while  $(\alpha, \beta, \gamma)$  can determine the angle that eccentric shaft turns relative to the initial configuration. A C-space model of eccentric shaft component is constructed as shown in Fig. 2. If eccentric shaft only moves horizontally,  $(x, y, z)$  can be used to determine the configuration of eccentric shaft alone. In this case, the eccentric shaft at any pose in the process assembly corresponds to a point in the C-space.

### 3. Analysis on Assembly State

After completing the model, the shaft hole is analyzed at different contact states. When the shaft is inserted into the hole from no contact to full insertion, the states can be divided into separation state, fitting state, and interference state in terms of the nature of contact.

Generally, the pose deviation in the shaft hole assembly process may happen to lateral position and shaft inclination. As there is clearance fit, the assembly error may exist within a range. It is assumed that  $S$  stands for the shaft;  $H$  stands for the hole;  $\Delta$  denotes the lateral clearance of shaft whole assembly;  $\theta$  denotes the inclination angle of shaft hole in any direction;  $\delta$  represents the depth error of insertion assembly. Hence, the shaft at any pose may be represented by  $S_i(x, y, z, \alpha, \beta, \gamma)$ . As the assembly hole is the target position, its pose does not vary in the process of assembly, so it can be represented at any time by  $H_0(x \pm \Delta, y \pm \Delta, z \pm \delta, \alpha \pm \theta, \beta \pm \theta, \gamma \pm \theta)$ . The  $S_i \cap H_0$  intersection operation is defined to have six quantities of shaft hole pose for operation separately.



**Figure 3.** Several different contact states

Separation state: When  $S_i \cap H_0 = \emptyset$ , there is no intersection between shaft and hole. In this case, the shaft and the hole are separated from and have no contact with each other.

Interference state: When  $S_i \cap H_0 \neq \emptyset$  and  $S_i \cap H_0 \neq S_i$ , there is contact between shaft and hole, but not full fitting. In this case, the shaft and the hole are at the stage of assembly.

Fitting state: When  $S_i \cap H_0 = S_i$ , i.e.  $x_i \in x \pm \Delta$ ,  $y_i \in y \pm \Delta$ ,  $z_i \in z \pm \delta$ ,  $\alpha \in \alpha \pm \theta$ ,  $\beta \in \beta \pm \theta$ , and  $\gamma \in \gamma \pm \theta$ , the lateral deviation and inclination angle of shaft exist within the assembly clearance, and the shaft is inserted to the required depth. In this case, the shaft is entirely inserted into the hole, and they are fully fit.

### 4. Motion Planning

In the process of shaft hole assembly, the C-space method is utilized to study the motion planning for effectively preventing any collision of robot against obstacle. In the path planning, it offers the satisfying abstraction and integrity, as it simplifies the pose of a moving object into a point in the C-space, and converts the obstacle into an obstacle point in the C-space as well.

#### 4.1. Model Description

The physical space in which robot arm and obstacle exist is called world space (Sun, 2008). The pose of an object can determine the position of each point in the space. The position available for assembly is a configuration in the free area. The assembly environment consists of the parts to be assembled, assembled parts, tools for assembly, assembling robot and operator, etc. The assembling robot moves the parts to be assembled along the assembly path, and install them onto the assembled parts.

In the process of automatic assembly, the robot must know about the positions of eccentric shaft component and assembly hole to realize the fitting and assembly between the eccentric shaft component and hole parts of RV speed reducer. The manipulator should first move to the position of eccentric shaft component and grip the eccentric shaft component. Subsequently, it moves the gripped part to the

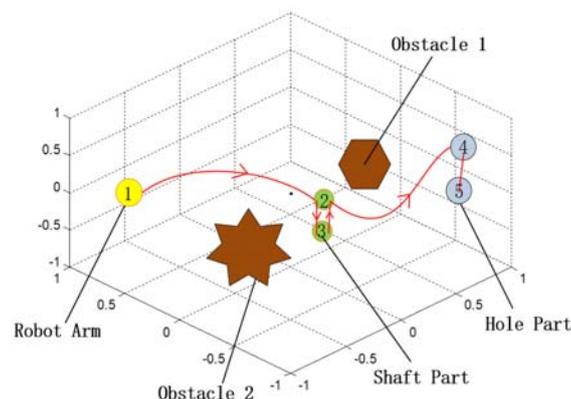
intended position for assembly. Hence, there are two target positions. On the assembly platform, a key factor to motion planning is to avoid obstacles. As three-dimensional obstacles normally have irregular geometrical shapes, it is very difficult to accurately obtain the obstacle domain by employing the C-space method. Generally, obstacles are indicated by taking such methods as grid/unit tree indication method, polyhedron indication method, and B-Spline method. In this paper, the enveloping of regular obstacles is conducted for approximation, which may expand the obstacle domain, but greatly simplifies the description of the obstacle domain, and effectively improves the efficiency of planning. Hence, it satisfies the requirements for safety.

#### 4.2. Path Planning Method

After building the model for robot arm, obstacle and target in the object space, the assembly path should be explored. The assembly process intends to realize the accuracy and rapidness of automatic assembly, so some unnecessary detours must be avoided to find the optimal path for assembly.

Based on the disassembly sequence of shaft hole parts, if robot arm needs to grip a shaft part, it must reach a certain target pose, which must be consistent with the pose of shaft part. Nevertheless, robot arm and shaft part must be the objects of certain size. In the practical process of gripping, robot arm moves first to right above the position of shaft part, and then downwards to grip it. In other words, there is a specific path point above the target position of shaft part. Similarly, there is also a specific path point above the hole part.

The position of robot arm is recorded as coordinate 1; the path point above the shaft part is coordinate 2; the position of shaft is coordinate 3; the path point above the hole part is coordinate 4; and the position of the hole part is coordinate 5. Then the assembly path is  $1 \rightarrow 2 \rightarrow 3 \rightarrow 2 \rightarrow 4 \rightarrow 5$ . In other words, robot arm departs coordinate 1, passes by coordinate 2, and arrives at coordinate 3 to grip the shaft component. After gripping, robot arm moves up and returns. After passing by coordinate 2, it moves towards the hole part, passes by coordinate 4 and gets close to coordinate 5. Eventually, the assembly is completed. During the process of moving from coordinate to coordinate 2 for gripping the shaft component, and the process of moving from coordinate 2 to coordinate 4 for installing the shaft component, robot arm moves in the form of interpolation and contour. The path planning is as shown in Fig. 4:



**Figure 4.** Path planning

## 5. Experimental Verification

### 5.1. Hardware Platform

To realize the automatic assembly of shaft hole parts, the experimental platform for assembly is constructed as shown in Fig. 5. The assembly production line consists of servo drive unit, synchronous belt conveyor unit, sensing & detection unit, assembly execution unit, and fixing support. Among them,

servo drive unit contains horizontal motor, drive wheel, driven wheel, sprocket, drive shaft, and bearing with vertical seat. Synchronous belt conveyor unit consists of conveying belt, guide rail, double plus chain drive wheel, and passive tensioning device. Sensing & detection unit is composed of stopper, four guide rod cylinder, and proximity switch. Assembly execution unit comprises three-coordinate straight line unit, sensor installation plate, six-axis force sensor, pneumatic three-jaw chuck, end gripper, and tool plate. The three-coordinate rectangular moving unit realizes the motion as the actuator, involving 3 degrees of freedom for motion. The motion range of each axis is 400mm travel for X and Y axes, and 200mm for Z axis.



**Figure 5.** Experimental platform for assembly

### 5.2. Control System

Control system consists of microscopic IPC, motion control card, drive, AC servo motor, encoder, limit switch, and six-axis force sensor. It can receive the commands from the host computer to drive and accurately control the robot. Information is exchanged between parts through certain communication protocols. IPC has full duplex communication with data collection card through RS232 serial port, and exchanges the data of command with motion control card through Ethernet protocol. Motion control card sends direction pulse and speed pulse to each drive through Ethernet bus protocol, so as to control the linkage of motor. During the operation of control system, the host computer plans the motion of motor, and sends the calculated amount of motion and speed commands to the control card. The control card converts the received motion command into pulse signal, and sends it to AC servo driver. At last, the drive controls the AC motor to move at the specified speed and amount of motion. Each motor is equipped with incremental encoder, and feeds back the information on the motion of motor to the drive, so that a closed-loop control system is formed. The force information collected by force sensor is fed back to the host computer in the form of voltage to provide the data of contact environment for the force-based compliant control.

Pneumatic control part has the air supply from air compressor, which is fixed at the leftmost end of the support in the production line. By regulating the filtration & relief valve, the compressor can automatically inflate and deflate. The filtration & relief valve is mounted in front of the support in the production line to monitor the information on air pressure. Then one-way relay is utilized to control the direction switching of two-position and five-pass directional valve for realizing the ascent and descent of cylinder, the blockage and release of horizontal bar, and the gripping and lowering of pneumatic chuck.

### 5.3. Automatic Assembly Process

After constructing the hardware platform and control system of the assembly robot, Qt Creator is employed to develop the software system, so as to realize the communication between PC and control card, communication with force sensor, motion control, force servo control and assembly strategy.

For convenience of monitoring the position of each workstation, the host computer program is developed, and the monitoring interface of the host computer is as shown in Fig. 6. By means of UDP wireless communication, the host computer controls three IPCs on the assembly production line by setting the IP and port on the host and slave computers. When each IPC is electrified and started, the



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