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ORIGINAL ARTICLE

A force/stiffness compensation method for precision multi-peg-hole assembly

Yi Luo · Xiaodong Wang · Mixin Wang · Debo Tan · Tao Zhang · Yuchun Yang

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Abstract In interference fit assembly, the magnitude and deviation of the assemble force are large so that it is hard to reach high accuracy of position for components of multiple parts stacked up. A force/stiffness compensation method is proposed to control the positioning accuracy in the interference fit assembly for multi-peg-hole components. Based on the force and displacement information measured in the assembly process, the position errors are acquired, and the stiffness of the assembly system under the exerted assemble force is calculated. According to the stiffness, the deviation from the target position is calculated and compensated. An experimental equipment based on this method was developed. As an example, assembly of rings, 6.2 mm in diameter and 0.25 mm in thickness, was carried out to demonstrate the feasibility of the proposed method. The assembly results show that high positioning accuracy of the assembled rings can be achieved with a large variation of assembly force. The presented method provides a simple, feasible, and efficient solution for interference fit assembly for multi-peg-hole components.

Keywords The force/stiffness compensation method · Interference fit assembly · Multi-peg-hole assembly · Force control · Position accuracy

1 Introduction

Interference fit assembly is widely used in the manufacturing industry because it is a simple manufacturing process. Peg-hole assembly is also a process frequently encountered in assembly, and two issues need to be focused on. The first one is the alignment of the parts and the second is how to reach high position accuracy. For the first issue, some methods have been proposed, such as compliant gripping mechanism [1–3], impedance control method [4–6], force/position constraint control method [7], and intelligent control method [8, 9]. In our previous research, a compliant gripper was developed to solve this issue [1].

The second issue is how to place the peg parts to the target position with high accuracy. Usually, the interference fit introduces a large assembly force, which causes the elastic deformation and deflection of the hardware of the assembly system and also causes hysteresis errors of the linear guides [10–12]. At the same time, the tolerance of the parts creates a large deviation of the assembly force, which makes the compensation amount different for each individual part [13]. All these cause poor position accuracy and consume much time in the assembly process. So the second issue is critical to a successful assembly. Since interference fit assembly for multiple parts is usually hand-manufactured, the position accuracy depends on the assembly mold. When one part stops at a wrong position, it cannot be realized until the mold is removed. Using automatic assembly can solve this problem but will introduce the problem of position accuracy control and compensation. There has been little research in this field; however, we can borrow research in the similar field of computer numerical control (CNC) machines to address the problem.

Some hardware, such as capacitance sensor integrated with the operational amplifier conditioning or a micro-platform based on PZT driven was added while hardware compensating method was taken to ensure the assembly precision in the assembly system for large

Y. Luo (✉) · X. Wang · M. Wang · D. Tan · T. Zhang · Y. Yang
Key Laboratory for Micro/Nano Technology and System of Liaoning Province, Dalian University of Technology, Dalian 116024, China
e-mail: luoy@dlut.edu.cn

assembly force [14]. The impedance control algorithm was proposed to compensate possible errors in the relative position of the peg with respect to the hole, improving the quality of the assembly process[15]; these methods will, to some extent, increase the cost and slow down the assembly efficiency, while it is hard to compensate the final position errors caused by a number of scattered error sources. Optimizing the structure of the parts to achieve a constant-force snap-fit to maintain a regular mating force against a range of interference uncertainty can also help improve the assembly accuracy [16], but in some cases, the mechanism of the part cannot be changed. Therefore, it is an efficient way to use the existing hardware and design a software compensation algorithm to make the system have enough precision for assembly [17, 18]. Usually, the CNC machines that work at high speeds and high accuracy are complex and thus have critical requirements for the microprocessor, sensors, and compensation algorithms. Fortunately, as specialized equipment for multiple parts interference fit assembly, the components are fewer than those of CNC machines, and the speed is lower, too. So, using the existing sensor and control computer, with an appropriated control method, real-time and effective compensation can be obtained.

The interference force in the peg-hole assembly causes the deformation to the hardware of the assembly system, including the mechanism deformation, connection errors, the hysteresis errors to the linear guides, and the pitch and roll errors of the guides. All these errors cause the total displacement error a nonlinear one that uses the common error propagation method to calculate the total displacement error will lead to large amounts of calculation and poor compensation results. At the same time, the interference fit causes large assembly force and large deviation of the force; the stiffness of the assembly system becomes an important factor which affected the assembly accuracy and must be taken into consideration in compensation.

In a common assembly system, force sensor and displacement sensor are usually used to control the assembly force and movement of the guide, respectively; thus a force/stiffness compensation method for multi-peg-hole assembly in an interference fit assembly is proposed. The assembly force deviation in the assembly process for a certain part is small, so the deformation characteristics are represented by the real-time system stiffness which is calculated by the assembly force and the displacement information of the guide. Using this stiffness to predict the displacement error for a certain part can achieve high accuracy as well as simple calculation algorithm.

2 Principles of the force/stiffness compensation method

2.1 Detailed description of the force/stiffness compensation method

In the assembly process, the errors are mainly introduced by the assembly force, and usually, the system meets the principle of elastic deformation, that is as far as the assembly force has disappeared, the system hardware errors can be eliminated. So, errors caused by assembly force can be detected and compensated as a whole. In the compensation for one part, the compensation process is divided into three stages, as shown in Fig. 1.

1. Pre-assembly: The interference assembly force causes the total displacement error. At this time, the linear guide stops at position D_0 in Fig. 1 while the tool that carries the assembled part stops at d_0 because of the existence of the total displacement error.
2. Searching for the actual location of the part: The linear guide moves backward to eliminate the deformation caused by the hardware of the assembly system. The assembly force becomes smaller and smaller while the total displacement error of the system is decreasing. When the error fully disappears, the tool just separates from the assembled part and the assembly force decreases to zero. Ideally, the tool is still at position d_0 when the linear guide moves from position D_0 to d_0, and the Z-axis distance between them is the assembling error ΔD_0.
3. Compensation: According to the reversed displacement of the guide and assembly force, the current system stiffness and compensation position D_1 is calculated. When the guide moves to compensation position D_1, the tool that carries assembled parts stops at position d_1 for the existence of the assembly error ΔD_1. The coordinate of the Z-axis of position d_1 equals D_0, which is the target position of the part.

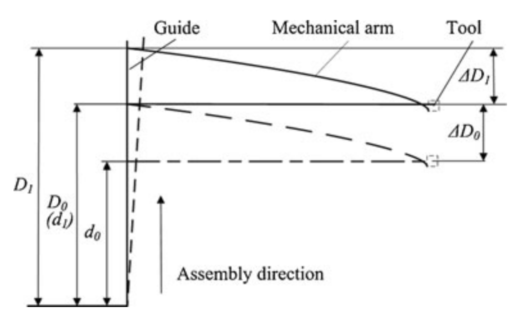

Fig. 1 Schematic of the position error for an interference fit assembly

But in a real assembly process, because of the precision of the position sensor and the force sensor, and considering the response of the sensors, the assembly force cannot decrease to zero to search the actual location of the part. It is more reasonable to use a force close to zero in a real assembly process. Figure 2 is the control algorithm flow chart of the force/stiffness compensation method in the actual assembly operation.

1. The tool is driven by the linear guide to the target location D_0 at a constant speed, but the tool actually stops at position d_0. The assembly force measured by the force sensor is F_0.
2. In order to detect the actual position d_0 of the tool, the linear guide moves backward at a low speed. Considering the response of the force sensor is not synchronic with the movement of the linear guide, the control value of F is chosen as $a_0F_0 \pm a$, where a_0 is the assembly force reduction factor, and a is the acceptable force error in an actual assembly process. Usually, $a_0 \leq 0.05$ and $a \leq 0.5$ N. As far as the force reaches the control value, the linear guide stops automatically. The position sensor detects the displacement in this backward movement which represents the positioning error ΔD_0.
3. According to the principle of elastic deformation, using the assembly force F_0 and the position error ΔD_0, the current stiffness of the system is calculated as $K_0 = F_0/\Delta D_0$.
4. The tool is driven along the assembly direction by the linear guide at a low speed. Based on the real-time location information D, the assembly force F and the system stiffness K_0, the actual position of the tool is calculated in real time with the equation $D_1 = D - F/K_0$. The linear guide automatically stops at position D_1 when it is in the range of $D \pm D'$, where D' is the acceptable motion error.
5. Repeat step 2; the assembly operation finishes if ΔD is in the range of $\pm D_0'$, where D_0' is the acceptable position error. Otherwise, repeat step 3 and step 4.

Considering the hardware response time, as well as the flexibility and robustness of the program, four parameter variables are set up in the assembly algorithm. There are assembly force reduction factor "a_0," acceptable force error "a," acceptable motion error "D'," and acceptable position error "D_0'," which could be adjusted by the program in the compensation process according to the hardware condition and precision requirements.

3 Experiments

To verify the feasibility of the force/stiffness compensation method, an experimental platform for precision assembly was set up and took the interference fit of the parts of ring as an example to do experiments.

The experimental platform is shown in Figs. 3 and 4, which includes: X-axis precision linear guide (Zolix

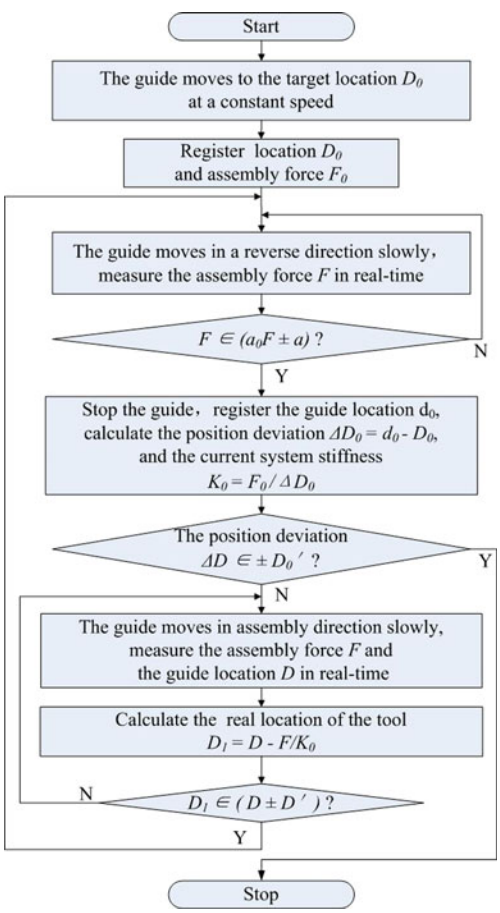

Fig. 2 Flow chart of compensation algorithm

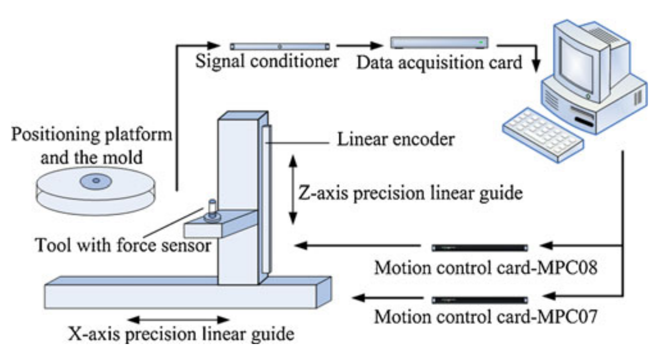

Fig. 3 Schematic of the experimental platform

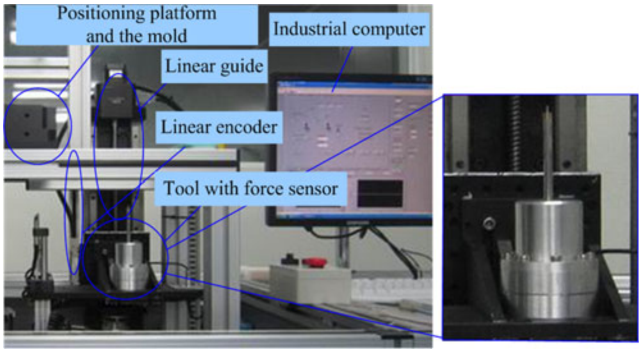

Fig. 4 The structure of the experimental platform

precision motorized position TSA-200), Z-axis precision linear guide with linear encoder (Zolix precision motorized position TSA-150), connecting rod and the tool with an force sensor (Lizhenxing XH32), positioning platform (Zolix precision motorized position RSA-200), industrial computer (Advantech industrial computer 610H), motion control card (Leetro MPC-07, MPC-08), and data acquisition card (Advantech PCL-711). The resolution of the linear guide is 1 μm, when the working length is less than 40 mm; using laser interferometer, the positioning accuracy and the repeatability accuracy is 1.8 and 0.7 μm, respectively. The range of the force sensor is 0–100 N; the linearity and repeatability is less than 0.1 % FS.

Assembly parts used in the experiment include: assembly mold with a hole of 6.2 mm in diameter and alloy rings of 6.2 mm in diameter, 0.25 mm in thickness. The interference of the ring and hole was between 0.005 and 0.010 mm, and the assembly force was between 5 and 40 N in this interference assembly with different rings. Five components each with 40 rings were assembled with a space of 0.1 mm.

The mold was fixed on the platform while the tool gripped one ring to accomplish the assembly operations in the experiment. The tool is driven by the X-axis and Z-axis linear guides.

Before pushing the ring into the mold, the center of the ring and the hole in the mold must be aligned. There are two steps to align the part before assembly. The first step is hardware alignment and the second step is compliant alignment. The procedure of the hardware alignment is shown in Fig. 5, and the position of the hardware will not change for parts of the same dimensions. The passive compliant mechanism is integrated into the tool to fix the tolerance of a model of parts and the grip error. The crucial point in this step is a new designed compliant gripper, which has the compliant

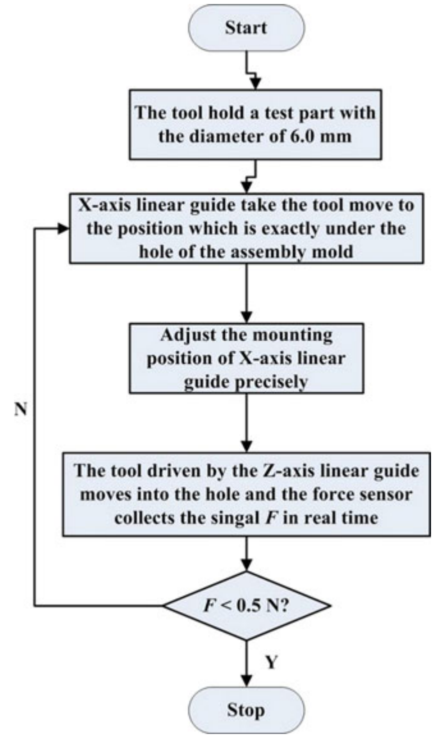

Fig. 5 The flowchart of the hardware alignment of the part and the assembly mold

both in X and Y directions (a detailed description is presented in the reference [1]).

In program design, taking the feedback time and the actual precision needs of the hardware in the system into account, parameters were optimized according to the experiments as follows: assembly force reduction factor a_0= 0.02, acceptable power error a=0.2 N, acceptable motion error D'=1 μm, and acceptable position error D_0'= 2 μm. To facilitate the experimental analysis, the location of the linear guide in the first forward movement was recorded as D_0, and the value of the decreased position was recorded as d_0, while the second location is recorded as D_1, the value of the decreased position is d_1, and so on. Figure 6 shows the assembly information of four sequential rings in one component. Figure 7 is the photograph of these rings.

The assembly forces were 22.6, 13.0, 23.4, and 25.1 N, respectively. From Fig. 4, the directly assembled position deviations ΔD_0 detected by linear encoder were −27, −13, −28, and −30 μm, respectively. With the force/stiffness compensation method, the position deviation ΔD_1 detected by linear encoder reduced to 0, −2, −1, and −2 μm, respectively.

In the experiments, more than 90 % of the assembly only needed to complete step 5 once in order to meet

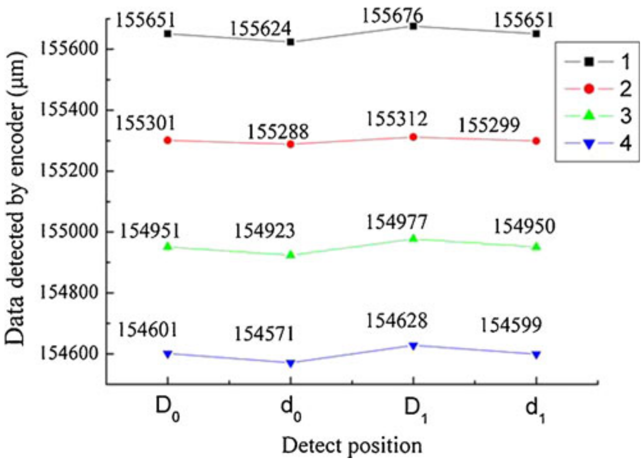

Fig. 6 Experimental data of the assembly

the requirements of the default precision, and the left experiments needed to repeat step 5 twice. The compensation process takes no more than 3 s because of short travel of linear guide and the total assembly time for one part is less than 100 s, so the real-time compensation method is feasible.

4 Results and discussion

To further validate the results of the experiments, the position deviation of the assembled rings was measured by a universal tool microscope (Olympus, STM6); the measurement accuracy of this microscope is less than 1 μm in the working length of 40 mm.

The mold with assembled rings was bonded together using epoxy resin glue to make the rings fixed, then the mold was opened to get the accomplished component. Table 1 shows the comparison of the detected results of the rings before and after compensation using the linear encoder as well as detected by the microscope.

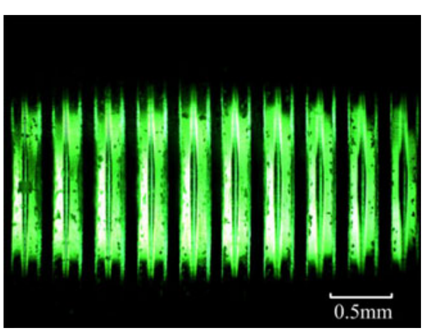

Fig. 7 The photo of the multi-ring component under a microscope (*light-colored stripes* are the assembled rings; *dark-colored stripes* are the solidification of epoxy resin)

Table 1 The position deviation of the rings

Types of deviation	The position deviation ΔD (μm)			
	1	2	3	4
Detected by linear encoder before compensation	−27	−13	−28	−30
Detected by linear encoder after compensation	0	−2	−1	−2
Detected by microscope after compensation	−4	−5	−2	−7

There is a deviation between the data detected by the universal tool microscope and linear encoder. The most important reason is that the microscope detected the components after the solidification of epoxy resin. In the process of solidification, the epoxy resin was contracted, which led to the shrinking of the whole components; thus, the value measured by microscope is smaller than the linear encoder. The other reason is the combination of the accuracy of force sensor, the feedback response time, and reading error by the naked eye. From Table 1, the accuracy of the assembled parts improved from 30 μm before compensation to less than 10 μm after compensation. By replacing the linear guide and the sensor with higher accuracy and sensitivity, and optimizing the control parameters in the compensation algorithm, the assembly accuracy of the components can be further improved.

5 Conclusions

A force/stiffness compensation method is proposed in this paper for multi-peg-hole interference assembly. The assembly system stiffness under a certain part was calculated in real time using the force sensor and the position sensor, and the compensation was made based on this stiffness. The experimental platform was set up, and the control algorithm of the compensation method was programmed. The size of the rings was 6.2 mm in diameter, and the interference ranged from 0.005 to 0.010 mm, which caused the assembly forces to range from 5 to 40 N. The component with 40 rings was assembled, and the assembly time for each ring was less than 100 s with a position error of less than 10 μm. This study provides a simple, feasible, and efficient solution for interference fit assembly for multi-peg-hole components.

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