Development of a High Precision Mounting Robot System With Fine Motion Mechanism (3rd Report)*

-Positioning Experiments of SCARA Robot with Fine Mechanism-

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In our previous work, robust control structure based on disturbance observer for a fast and precise fine motion mechanism has been proposed. The functionality of the controller was verified using one axis of precise X-Y table combined with one axis fine motion mechanism. As a further step in this paper, the approach is extended to two-axes fine motion mechanism with a SCARA robot as a real system to realize the final purpose, that is, the development of high-precision mounting robot. First, the paper introduces a high performance robot system based on a SCARA robot coupled with a fine motion mechanism which was developed in our laboratory. Second, the paper presents a control scheme that enables correction of possible offsets of the end-effector relative to the target and compensation of the oscillations at the end-point. Finally, experimental results show significant improvements in end-point accuracy and settling time achieved by the novel configuration of the coarse/fine robotic system. As a result, a repeatability (3σ) less than $2\text{ }\mu\text{m}$ and the CP positioning error (3σ) less than $4.0\text{ }\mu\text{m}$ were achieved by the coarse/fine robotic system.

Key words: coarse/fine manipulator, SCARA robot, vibration compensation, PTP positioning, CP positioning.

1. Introduction

For the purpose of rapid and accurate mounting of small electronic parts on printed circuit board, high-precision mounting robotic system incorporating a coarse manipulator and a fine motion mechanism has been developed¹⁾. The idea of applying Coarse/fine approach in robotics is not new²⁾, but here another practical implementation is proposed. Our coarse-fine approach uses an ordinary industrial SCARA type robot for coarse positioning which carries a precise fine motion mechanism used for fine positioning. The coarse robot can access a large workspace needed for parts feeders, but it is not sufficiently accurate to align and place the components during the assembly. The fine motion mechanism, however, is more precise than the coarse robot carrying it, and it is capable of rapid motion at the sub-micrometer order. For most pick-and-place operations, high accuracy is only required within the target area. Therefore, local sensing and local micro-actuation take place only within the target area. The coarse manipulator carries the micro-manipulator to the vicinity of the target, and the micro-manipulator corrects the misalignments between the end-effector and the target using end-point position feedback. Unlike other coarse/fine manipulator model based approach³⁾, we propose a coarse/fine architecture that utilizes the existing control system of the coarse manipulator, which is considered as a black

box, and implements an additional controller for the fine motion mechanism to make the necessary adjustment for the whole system. In this coarse/fine control algorithm, absolute end-point position is used to derive the position of the coarse manipulator that serves to control the fine motion mechanism. This enables the fine motion mechanism to be combined with different types of coarse positioner.

The micro-manipulator compensates also for vibrations occurring at the tip of the macro-manipulator. This idea of using a micro-manipulator mounted at the tip of a large and elastic arm for vibration control has been reported in the literature mainly in the robotic space field. Cannon⁴⁾ and Lew⁵⁾ have considered active damping of the macro-manipulator with the micro-manipulator using a flexible motion compensator based on measurements of the flexibility of the macro-manipulator. The control algorithm in our work is developed with no knowledge of the model of the macro-manipulator. Disturbance observer is used to damp out the interaction between the coarse manipulator and the fine motion mechanism. Our previous work⁶⁾ has shown the functionality of the control system using one axis of precise X-Y table having a repeatability of $\pm 2\text{ }\mu\text{m}$. In this paper, the approach is extended to the case of two axes fine motion mechanism combined with a SCARA type robot, having large amplitude of vibration and less accuracy.

SCARA robot and the fine motion mechanism are combined to realize the final purpose, that is, the development of high-precision mounting robot system. The paper is organized as follows. Section 2 describes the coarse/fine robotic system. The control strat-

* Received October 31, 2000

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Fig.1 Coarse/fine robotic system

egy for the coarse/fine manipulator, including the end-point vibration issue, is presented in Section 3. The experimental results in Section 4 show the performance improvements successfully achieved.

2. Description of the coarse/fine manipulator

The coarse/fine manipulator is a precise mounting robot incorporating a coarse manipulator and a fine motion mechanism. This high-precision mounting robotic system consists of a SCARA robot fitted with an X-axis fine motion mechanism and a Y-axis fine motion mechanism below the X-stage. The coarse/fine manipulator is shown in Fig.1.

The SCARA robot has 4 DOF, three revolute joints and one prismatic joint. Because of its wide workspace and high speed, this type of robot is widely used in assembly tasks.

The developed fine motion mechanism for this purpose¹⁾, is attached to the end-effector of the SCARA robot to compensate for its undesired vibrations and possible offsets.

2.1 Coarse stage characteristics

First an analysis of the dynamic characteristics of the coarse manipulator gives design requirements for the controller of the fine mechanism.

In this section, we deal with the dynamic characteristics of the SCARA robot. The position of the end-effector, when the robot moves from an initial posture to a final assigned posture, is measured using a capacitive type position sensor. The robot performs some vibrations before and after reaching the assigned final posture. The former vibrations are the transient vibrations in the frequency range from 15Hz to 25Hz with an amplitude of 20 μm .

The latter are residual vibrations in the frequency range from 45Hz to 55Hz with an amplitude of 5 μm . This poor time response and low precision can be attributed to the low dynamic characteristics of the coarse manipulator such as low stiffness and semi-closed loop control. A fine motion mechanism with wide bandwidth and enough stroke is needed to

Fig.2 Two-axes fine motion mechanism

compensate for undesirable vibrations of our coarse manipulator.

2.2 Fine motion mechanism

The fine motion mechanism used in this experiment is a general purpose XY robotic fine positioner. Its design analysis and performances have been already described in Refs. 1) and 6).

The fine positioner is a fast, small and precise positioner which can be attached to the terminal link of a general purpose robot for assembly tasks. The developed fine motion mechanism is shown in Fig.2.

Piezo-electric actuator featuring excellent resolution and fast response has been selected to actuate the fine motion mechanism. Since the piezo-electric device has a small stroke, a displacement magnifying mechanism with elastic hinge is used.

An internal position sensor, namely a strain gage sensor is located in the hinge part to measure the largest distortion that occurs when the stage moves.

The effective mass (mass of the movable part) of each axis of the fine motion mechanism and some of the fine positioner specifications are shown in Table 1.

Based on the dynamic characteristics of the coarse manipulator, the controller of the fine positioner is designed. Our primary emphasis has been on using the device attached to a general purpose robot as a high-precision positioner. Lag-lead phase compensator is designed, in frequency domain, as a feedback controller.

Table 1 Specifications of the fine motion mechanism

	X-axis	Y-axis
Effective mass	0.97 kg	0.17 kg
Stroke	139.8 μm	145.8 μm
Repeatability (3 σ)	0.18 μm	0.19 μm

The feed-forward compensation is added to improve

Fig.3 Control strategy for X-axis coarse/fine manipulator

tracking ability of the fine positioner. When a fine mechanism is attached to the coarse manipulator, dynamic interactions exist between them. Therefore, a disturbance observer is needed to damp out the effect of the coarse manipulator on the fine positioner, considered as a disturbance, for such case. This robust controller⁶⁾ based on disturbance observer is designed with no knowledge of the coarse manipulator model.

3. Coarse/fine manipulation

3.1 Positioning control method

Figure 3 shows the block diagram of the control strategy adopted for X-axis coarse/fine manipulator system. The same control structure is used for Y-axis coarse/fine manipulator, although different controller parameters were used.

For practical considerations, the existing control system of the coarse manipulator was not altered, and an additional controller for the fine motion mechanism was implemented to make the necessary adjustments for the coarse/fine robotic system.

The coarse manipulator is position-controlled to follow a reference input.

In the target area, the end-point position information is used to derive the position of the coarse manipulator. The latter serves to control the fine motion mechanism which compensates for vibrations and corrects positioning errors due to the coarse manipulator's inaccuracy. The controller of the fine motion mechanism is composed by a Lag-lead-phase feedback controller G_c , a unit gain feed-forward compensation G_{ff} and a disturbance observer.

3.2 Compensation of vibrations

To achieve fast and precise positioning, the first challenge is to damp out the transient and residual vibrations of the coarse manipulator. A robust controller algorithm is implemented so that the fine motion mechanism is moved to counteract the vibrations

of the coarse manipulator. In presence of vibrations, both coarse/fine and fine positions are measured and then the coarse position is derived. the latter is used to control the fine motion mechanism. Therefore, the vibrations of the coarse manipulator are compensated. As an ideal result, the tip stays in a fixed position relative to the absolute frame.

4. Experiments

4.1 Setup of the positioning experiment

The experimental system consists of a general purpose SCARA type robot combined with the developed piezo-electric based fine motion mechanism. Experiments were done on two axes positioning by the coarse-fine robotic system. The system control of the fine mechanism is implemented in digital form, and the calculations are performed in software. A sampling rate of 5 kHz is used. Figure 4 shows the configuration of the combined coarse/fine stage and Figure 5 shows the initial and the final positions of the SCARA robot represented by the points M1, M2,..., M6 on the workspace table. The absolute end-point position was measured using non-contact capacitive type displacement sensor (from PHOTONICS, model AY30-200) which has a working range of 200 μm and a resolution of 0.1 μm . Two sensors of this type have been placed to measure positions in both X and Y directions. The control voltage, computed by the control program running on an AMD-K6 based computer, is fed into the actuator through a 16-bit DA board and the power amplifier. The displacement output signal of the movable stage is sent back to the computer through a 12-bit AD board.

4.2 PTP positioning

4.2.1 PTP time response

The coarse robot moves to the target positions (M1,..., M6) from the start position (position S), and

Fig.4 Experimental setup for the coarse/fine manipulation

Fig.5 Initial and final postures of the robot

the fine stage starts to move when the robot reaches its movable range of $\pm 50 \mu\text{m}$. Since the frequency varies with the position and the orientation of the robot (point dependent), six final postures, namely M1,...M6, are considered to evaluate the performance of the system in the whole workspace. For the coarse/fine manipulator, measurements corresponding to the target position are represented by 0. On the other hand, the position commands for the fine mechanism are in the range of $\pm 50 \mu\text{m}$ around the position 0. The mid-point of the working range of the capacitive type sensor is considered as a reference position (position 0). Measurements of the end-point position in both X direction and Y direction are presented in order to compare the performance of the SCARA manipulator alone and the combined coarse/fine manipulator. As an example, the positioning performance results obtained for the final posture M1 in X and Y directions are shown in Fig.6 and Fig.7 respectively.

Figures 6 and 7 show the position measurements of the coarse manipulator, fine motion mechanism and the combined coarse-fine manipulator for the target

Fig.6 Time response in X direction at M1

position 0. The combined coarse/fine manipulator exhibits some vibrations at the beginning, resulting from the simultaneous displacements of the coarse manipulator and the fine motion mechanism. These results show that the coarse/fine manipulator demonstrates significantly higher performances of accuracy and speed than the coarse manipulator alone. Therefore, it can be said that the fine motion mechanism improves the positioning performance of the coarse/fine manipulator by compensating for the vibrations of the coarse manipulator besides the steady error of positioning.

4.2.2 PTP repeatability of the coarse/fine manipulator

To evaluate the positioning performance of the two-axes coarse/fine manipulator, repetitive positioning is considered. The coarse/fine manipulator moves to the final posture from a start position thirty times. The same experiment has been carried out for the six final postures shown in Fig.5. The positioning deviations for both X and Y axes are shown in Fig.8.

Fig.7 Time response in Y direction at M1

The evaluation tests fully corroborate that the repeatability (3σ) was $1.5 \mu\text{m}$ for X-axis and $2.0 \mu\text{m}$ for Y-axis. As shown in Fig.8, the repeatability of the system in Y direction is larger than the repeatability

Fig.8 Positioning deviations

in X direction. This result is due to the periodic vibrations with large amplitude of the Y-axis coarse/fine system after its settlement. These vibrations are not observed in the case of X-axis. Furthermore, **Figure 8** shows larger differences between repeatabilities of X-axis and Y-axis for $M_4 - M_6$ comparing to $M_1 - M_3$. This is because the differences between the experimental positioning errors of SCARA robot in X and Y directions for $M_4 - M_6$ are larger than those for $M_1 - M_3$. And these differences between positioning errors of X and Y axes are caused by the differences between the manipulabilities of SCARA robot in X and Y directions.

4.3 CP positioning

4.3.1 Line trajectory tracking

In this section, tracking performance of the coarse/fine manipulator is considered. Both coarse manipulator and fine motion mechanism move simultaneously to track a line trajectory from M1 to M2 in the workspace of the robot system (see **Fig.5**). Capacitive type sensor is used to measure the end-point position. **Figure 9** shows the displacements of the coarse manipulator, fine motion mechanism and coarse/fine manipulator. Tracking error (3σ) less than $4.0 \mu\text{m}$ along the line was achieved by the combined coarse/fine manipulator.

4.3.2 Circle trajectory motion

For some purpose, it is necessary for the fine motion mechanism to perform a micro continuous path motion in many local areas within the workspace of the robot. Two experiments involving a circular trajectory were carried out. First, the coarse/fine manipulator is considered in open-loop and the fine motion mechanism performs a desired trajectory motion. In the second experiment, the coarse/fine manipulator is considered in closed-loop. Capacitive type sensors are used to measure the end-point positions in both X and Y directions for both cases. **Figures 10 and 11** show the position response and the radial error of the end-point when the coarse/fine manipulator is in open-

Fig.9 Experimental coarse/fine manipulator line tracking

loop. **Figures 12 and 13** show the position response and the radial error when the coarse/fine manipulator is in full closed-loop. The trajectory is a circle of diameter $A = 40 \mu\text{m}$, and centered at $(x_c, y_c) = (20, 0)$. In this experiment, the time duration is 1 s, that is $\omega = 2\pi$.

The radial tracking error is defined as

$$e_{rt} = \frac{\sqrt{(x_d - x_c)^2 + (y_d - y_c)^2}}{\sqrt{(x - x_c)^2 + (y - y_c)^2}} \quad (1)$$

where x_d and y_d are the coordinates of the desired trajectory, x and y are those of the actual trajectory and x_c and y_c are the coordinates of the center of the circle. From **Fig.11**, it can be seen that the radial error is $6.2 \mu\text{m}$ when the system is in open-loop. This can be attributed to the effect of disturbances from the external environment, mainly from the coarse manipulator. This effect is damped out when the system is in full closed-loop.

Fig.10 Experimental open-loop circle trajectory

Fig.11 Experimental open-loop radial error

Fig.12 Experimental closed-loop circle trajectory

Fig.13 Experimental closed-loop radial error

As a result, a maximum radial error less than $3.0\mu\text{m}$ along the circle was obtained by the full closed-loop. These results confirm the ability of the fine motion mechanism to perform a desired trajectory. Furthermore, the obtained results exhibit the aptitude of the fine motion mechanism to reject disturbances from the external environment, namely from the coarse manipulator, when full closed-loop is used.

5. Discussion about the experimental results

By analyzing the experimental results, we know that the capacitive type sensor noise is a main factor for affecting the response of the system, and thus deteriorates its performance. The standard deviation of the positioning errors for the X and Y axes were $0.5\mu\text{m}$ and $0.66\mu\text{m}$ respectively. However, they were limited by the capacitive type sensor noise which was approximately $6\mu\text{m}$ peak to peak with a standard deviation of $0.22\mu\text{m}$. In this section, by simulation, we show the relation between the positioning error and the sensor noise in quantity. Figure 14 shows the block diagram used in the simulation. The same controller shown in Fig.3 is used here. The measured noise signal of the capacitive type sensor used in the experiment is shown in Fig.15.

Fig.14 Simulation block diagram

The result of the position response obtained by simulation is shown in Fig. 16.

From Fig.16, it can be seen that the positioning error is within the range of $\pm 2.0\mu\text{m}$. This result is close to the experimental one obtained with the Y-axis. The same result was obtained for X-axis. Therefore, we can say that with such sensor noise level (see Fig.15), the result cannot be better than the obtained one.

Next, a simulation to a noise signal having half amplitude of the real one has been conducted to show the improvement of the response. The simulation result in this case is shown in Fig.17.

As shown in this figure, the positioning error is within a range of $\pm 1.0\mu\text{m}$. Therefore, the use of a sensor

Fig.15 Measured sensor noise signal

Fig.16 Simulated position response with real noise

Fig.17 Simulated position response to half amplitude of the real noise

with noise amplitude half of the one used in the experiment can lead to a result which satisfies the design specifications, and thus a repeatability of $1\text{ }\mu\text{m}$ or less can be obtained.

6. Conclusion

A coarse-fine manipulator, for the purpose of precise mounting electronic components, has been described. Experimental positioning performance of two-axes coarse/fine manipulator was presented. The following results are obtained.

- Using only the control of the fine motion mechanism, transient and residual vibrations of the coarse manipulator have been successfully compensated besides the steady error of positioning.
- Experimental results have shown high performance for the coarse/fine manipulator. Repeatability was $1.5\text{ }\mu\text{m}$ for X-axis and $2.0\text{ }\mu\text{m}$ for Y-axis, also CP positioning error (3σ) less than $4.0\text{ }\mu\text{m}$ was obtained as well.
- It is found out that the noise of the capacitive type sensor affects the response of the system. A positioning error of $\pm 1\text{ }\mu\text{m}$ can be expected by a sensor with noise amplitude half the one used in the experiment, with the same controller.

Also, it should be mentioned that the proposed approach can be utilized for different types of coarse positioner mechanism.

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