Task Analysis of Ultra-Precision Assembly Processes for Automation of Human Skills

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March 1, 2001

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ABSTRACT
A lot of research efforts on assembly automation problems have been given by many researchers from a variety of communities, e.g., manufacturing, artificial intelligence and so on. They mostly focused on the geometric constraints related to a considered task, e.g., relative configuration change between the peg and the hole. Such an approach, however, seems valid only when the dimensional tolerance is fairly large so that it allows to change the relative configuration of the two mating parts in an obvious fashion. This paper investigates how highly precise assembly tasks can be automated. Tolerance considered in the present study is in the range of $3 \mu m \sim 9 \mu m$. Currently the assembly task is being operated by skilled human workers. In order to analyze the insertion task, we focus on force sensory information and attitude measurements involved in high-precision peg-in-hole task of a polygon mirror unit because a position-based analysis under such a narrow dimensional tolerance seems inappropriate. A variety of insertion experiments are conducted by skilled and unskilled subjects for comparison purposes.

1 Introduction
Recent advance of Information Technology (IT) has brought a lot of things that once used to be shear dreams within everybody’s reach. There is no doubt that the main driving force for the trend is the rapid growth in photonic and semiconductor technology. Individual electronic or mechanical components can be built very small, e.g., sometimes in nanometer scale, owing to the recent uprise of micro electromagnetic systems (MEMS) technology. However, for those components to be able to function to their full extent with high reliability, of equal or even higher importance is packaging and assembly technologies. It is no exaggeration to say that, without synchronous development of the packaging and assembly technologies, most MEMS will be of no use. That is why there have been great demands on sophisticated manufacturing and assembly technologies for IT-related products.

Since the invention of industrial robots, a lot of research efforts have been given to the assembly tasks using the robot arms, e.g., SCARA-type robot, due to its industrial importance. As a result, a variety of assembly tasks have been automated, e.g., print circuit board. However, most of such tasks do not involve many constraints. Typically the motion of the robot’s end effector is restricted only by a wall type of constraint, e.g., placing electronic components on a PCB and is free of constraints otherwise. Practical use of robot manipulators in more constrained environments is yet to come and still a peg-in-hole problem is considered as a demonstrative example of such cases.

In this paper, we deal with an ultra-precision peg insertion task using polygon mirrors. It should be noted that there are different types of technologies required according to the dimensions and tolerances of the products to be handled. When they are large enough to be handled with no special care, there are a variety of tools available such as robot hands or specialized assembly machines. If they are extremely small such as micro machines in micrometer or nanometer scale, then van der Waals force will take effect while
the gravity factor becomes negligible. Typically static electricity forces can be utilized for handling purposes under such circumstances. On the other hand, if the size of a product is sufficiently large but the assembly tolerance is in the order of a few microns, neither of the above technologies can be used because they are not meant to accommodate such situations. In order to handle those cases, the fine motion and the gross motion have to be decoupled and be accommodated by separate means. Assembly process of the polygon mirrors exactly falls in such a category. Namely, the dimension of the mirror is a few 10 millimeters in diameter while the fit tolerance of the rotation axis is less than 5 microns. Such a tight tolerance is needed in order to ensure the stable rotation of the mirror.

Primary objective of this research is to automate the ultra-precision assembly task which is a peg insertion with a narrow tolerance, i.e., less than 5 \( \mu \text{m} \). Currently the task has been being performed by skilled workers because there is no robot or assembly machine available at this moment that can accomplish the task with the same accuracy and efficiency as the skilled workers do. As the first step to achieve the goal, we measure reaction forces as well as attitude changes while the insertion task is being executed. The purpose of the experiments is not only to measure how a skilled worker executes the task from the viewpoint of physical information associated with the task, but also to compare their ways of doing with those of unskilled subjects. For this particular insertion task, the relative configuration of the peg and the hole is completely blocked from the worker’s view. Therefore, he/she must base his/her judgment mostly on haptic information. Several experimental results are presented, followed by in-depth analyses of the observed patterns.

2 Related Previous Work

Peg insertion task has a long history in the field of robotics and automation research\[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13\]. It is one of the most commonly used goal tasks. Part of the reason is that the shape of the mating parts is very simple and geometrically well-defined, and that many practical assembly tasks include such insertion tasks. This section reviews some of the previous work.

Dakin and Popplestone [7] presented a technique for modelling the 6-dimensional contact space of an assembly with narrow insertion clearance. They proposed two-phase approach; a gross-motion planner and a fine-motion planner. The former deals with a nominal motion plan based on kinematic constraints while the latter resolves uncertainty caused by various factors such as modelling errors or control errors. When an insertion clearance becomes extremely narrow, e.g., a few microns, since everything is position-controlled, this kind of strategy is unlikely to work unless the manipulation hardware is able to provide with much higher positional resolution, e.g., less than one micron say.

Badano et al. [5] introduced random motion to the work-table in order to absorb the positioning error between parts to be inserted. The clearance they use is about 15 \( \mu \text{m} \). They succeeded in compensating large positioning errors for chamferless insertions. This type of random motion can be used when a possible damage to the contact surface can be tolerated or the parts are well lubricated so that no contact surfaces are damaged. In our goal task, neither can be tolerated.

What makes this research unique is twofold. First, our approach is quite different from others in the sense that we do not pay much attentions to kinematic constraints as others do. The constraints, however, can be used to estimate the current status while the task is being performed. We primarily focus on the force and moment information and use the position information as a secondary means. Secondly, an insertion clearance that we deal with comes from a real-world product and is as narrow as 3 \( \mu \text{m} \). To our best knowledge, no previous work considered such a narrow clearance.

3 Task Description

The task goal is to collect and analyze the physical data associated with the peg-in-hole insertion task in view of automatization of the task. The schematic of the parts used is shown in Fig. 1. The nominal dimension of the parts is 10 mm in diameter. They are both made of ceramics and the gap clearance is less than 5 \( \mu \text{m} \). The clearance is determined from the viewpoint of quality assurance. Since the mirror surface of the
polygon (hole) cannot be touched for an obvious reason, an insertion jig to which the mirror is magnetically attached is used for holding purpose as shown in Fig. 2.

When an assembly worker undertakes the insertion task, he/she first makes a rough alignment of the center of the polygon mirror with the center of the peg by visual information. It is, however, impossible to complete the task solely based on the visual information, because the peg becomes completely occluded as the mirror gets close to it before they makes a contact with each other. Even if he/she takes a close look at the insertion point, it is still very hard to visually adjust the position and orientation of the mirror because of such a narrow clearance. Therefore, he/she has to rely on some other means to finish the task. A typical solution to this is to use haptic information. It is not easy to make a quantitative prediction through the haptic information. Nonetheless, it is able to provide with a robust sensory signal in many occasions.

4 Experiments

We conducted experiments with three different kinds of clearance; 3, 5 and 9 µm. For each clearance choice, four different people performed the insertion task three times. Two of them are considered to be skillful subjects who are engaged in the task on regular basis in the assembly plant of a polygon mirror manufacturer, and the other two are considered as unskilled subjects who are students involved in this study. Let us name the former skilled subjects A and B and the latter C and D.

4.1 Experimental setup

Fig. 3 displays the experimental setup which consists of three measuring instruments: force sensor, autocollimator and laser pointer with CCD video camera. The polygon motor unit with the peg on it is mounted on a 6-axis force sensor (Nitta, IFS-70M35A25-M50B). The nominal force ranges are 100 N along X and Y directions and 200 N along Z direction. The nominal moment ranges are 10 Nm about all three axes. Autocollimator (Nikon) is set downright above the motor unit, which has ± five minutes of measuring angle range. The autocollimator is employed to obtain a direct, precise measurement of the attitude of the insertion jig. Laser pointer with CCD video camera is used to measure the same physical data as the autocollimator, but over a much wider range and in indirect manner. The laser pointer is attached to the side of the insertion jig and pointing upward. A screen with 5mm mesh grid is placed about 2m above the pointer. The CCD video camera records the movement of the projected laser point at the rate of 30 frames per second. The signals from the force sensor and the autocollimator are acquired by C program on PC and stored for further data processing and analysis by MATLAB. Locations of the laser point in the video images are represented in terms of XY coordinates of the grid. Each data acquisition session takes less than 10 seconds, which varies depending on how skillful the subject may be.

4.2 Results

Typical observations for skilled and unskilled subjects are shown in Fig.4-7. Fig. 4 and 5 are from subject A (skilled) and a gap clearance is 3 µm and 9 µm, respectively. Similarly Fig. 6 and 7 are from subject C (unskilled) with 3 µm and 9 µm, respectively. Two sessions are shown in each figure. All the force measurements are given in Newton. We also measured three moment values throughout the experiments and attempted to compute the contact points from three forces and three moments. However, the sensitivity of the moments was so poor that no meaningful, quanti-
tative analysis could be conducted.

In plotting these figures, sensor drifts have been already eliminated. As shown in Fig. 3, X and Y correspond to horizontal components and Z force is set downward positive. All these figures represent successful insertion although there were cases in which the parts got stuck with each other, hence unsuccessful attempt. Such failures occurred mostly to unskilled subjects (C and D).

Discrepancies between the skilled subjects and the unskilled subjects distinctly appear in those figures. One of the most significant differences is the subject A’s consistency. Observing X and Y components Fig. 4 and 5, it can be seen that both X and Y fall within a narrow range around zero. These horizontal components should be kept near zero because an ideal insertion only involves a vertical force along Z axis. On the other hand, the subject C exerts fairly large horizontal forces as shown in Fig. 6 and 7. This implies that the subject C had a great difficulty in making an initial alignment before the peg started being inserted.

Not only the consistency in the subject A is noticed in Z component as well, but also the Z force never exceeds 1 Newton which is the self-weight of polygon mirror plus the insertion jig. This is another outstanding feature of the skilled subject. Again, an ideal insertion process never requires a vertical force more than the self weight. As seen in Fig. 6 and 7, the subject C exerts Z force more than 1 Newton here and there, sometimes impulsive. Also it is noteworthy in Fig. 6 and 7 that the subject C keeps exerting horizontal forces even after the insertion process is completed. This implies
the importance of haptic sensitivity. Without such sensitivity, one can hardly recognize when the insertion is done.

Another interesting observation in Fig. 4 and 5 is that the Z component changes stepwise for a large clearance (Fig. 5) while it gradually increases for a small clearance (Fig. 6). This illustrates that the insertion process tends to be subject to larger sliding resistance as the clearance becomes smaller such as 3 µm.

As far as the execution time is concerned, the subject A takes about 3 seconds for 9 µm and 4 seconds for 3 µm while the subject C takes 5 to 6 seconds for either case.

4.3 Analyses

Fig. 8 shows an example of the test results given by the subject B with 5 µm clearance. The figure, especially Z component, displays how the insertion proceeds. It turns out that the process can be divided to a few phases. The insertion starts near the mark a. From a to b, a rough alignment is being made without exerting a significant force in any direction. It then begins a fine alignment motion at the mark b. The fine alignment involves a search motion for the two center axes to coincide. Between b and c, such a motion is illustrated by a large wavy horizontal force, especially X component. It is worth noting that such a wavy motion does not show in Z component. This seems another characteristic that a skilled subject displays but a unskilled does not, i.e., decoupled fine alignment motion. From c to d, it is seen that Z force gradually decreases to almost zero at d. This proves that the fine alignment motion is achieved at c. Once the two axes of the peg and the hole become coincident, there exists no source causing a vertical force unless they starts a relative motion such as sliding. Then a downward insertion motion commences at d. From d to e, Z component proportionally increases until it reaches the self weight at e where the insertion process completes. Small force values in horizontal components observed in d to e also manifests a well decoupled motion of the skilled subject.

Fig. 9 shows an example in which all three measurements are successfully captured. From the top to the bottom, horizontal force (X), vertical force (Z), Y-axis inclination by laser pointer, and Y-axis inclination by autocollimator. Note that the inclination in (c) and (d) is represented in minute, not degree. The maximum inclination is about 100 minutes. It is seen that the axes of the two parts are aligned with each other.

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1 Note that X and Y components use a different force scale from Z component does
around 4 second in time. This is verified by the fact that the Z force component drops around 4 second and that the inclination approaches to zero after 4 second in which the inclination comes to fall within the measuring range of autocollimator.

5 Concluding Remarks

Ultra-precision insertion task of a polygon mirror was investigated from the physical information point of view. Force sensory information was obtained by using a 6-axis force sensor while the inclination of the insertion jig was measured by two different methods, i.e., laser pointer with CCD video camera for a coarse range and autocollimator for a smaller range. Measurement of the force signals was conducted at two different levels of skill, namely skilled and unskilled. It was found that not only skilled subjects can finish the task faster than the unskilled, but also the former tends to minimize unnecessary forces while the latter rather blindly searches for an incidental insertion. The way the skilled subjects approach the task is highly consistent and efficient. Such consistency and efficiency must be related with haptic sensitivity which they possess. Inclination of the insertion jig was kept within 1 degree for most of the insertion period except the initial stage. However, the method using the laser pointer is a little too coarse to give us details of the final stage of insertion. On the other hand, the measuring range of autocollimator is so small that it is often hard to find connections between the two methods.

It is expected that this kind of study potentially serves the foundations of automation of human tasks, and that it can be used for education and training purposes of unskilled people.

As future work, there are two issues to be resolved. One is to measure the moment information, which should not be achieved this time due to the limited resolution of the force sensor used. A possible solution to this is to develop a new moment sensor with a sufficient resolution. With such a sensor, even a transition of the contact point would be able to be estimated as the task proceeds. Second is to collect not only inclination data in detail but also the position information. By combining all the information, further accurate analyses are expected to be achieved. As a result, a robust, physical model of the insertion task which will serve a basis for task automation will be obtained.

References


