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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, robotics, 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 the mechanism of a high-precision insertion process from the viewpoint of sensory information. Tolerance considered in the present study is approximately 5 µm. Currently the assembly task is being conducted by skilled human workers. In order to analyze the insertion task, we focus on force and moment information and inclination measurements. Conventional approach, i.e., a position-based analysis, is not appropriate for such a narrow dimensional tolerance because it is unlikely that human operators conduct the task based on position information. This paper presents a newly developed, high-sensitivity moment sensor and experimental results in high-precision insertion tasks.

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 photoelectronic 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 electromechanical 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.

Primary objective of this research is to thoroughly analyze a high-precision assembly task which is a peg insertion with a very narrow tolerance, *i.e.*, 5 µm or less. 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 a sufficient accuracy and efficiency that the skilled workers can deliver.

As the first step, we measured reaction forces with a commercially available force sensor and did comparisons between skilled workers and unskilled workers [1] . There were a lot of distinctions observed between the skilled and the unskilled in terms of the force patterns and the magnitude of the forces they exerted. However, the force sensor used was not sensitive enough to give us all the information we needed, *i.e.,* the resolution of moments was so low that any meaningful information could not be extracted. Therefore, a primary purpose of the present paper is to enhance the measurement system by designing a new moment sensor which has a sufficient sensitivity, to collect necessary force and moment information, and to analyze the insertion task based on the obtained data. In addition to the force-related measurements, the inclination of the polygon mirror is also measured.

2 Related Previous Work

Peg insertion task has a long history in the field of robotics and automation research[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. 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.
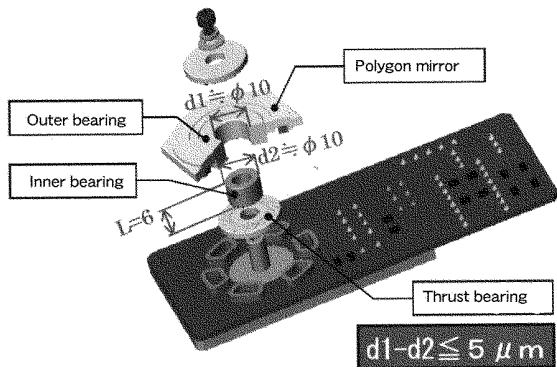
Fig 1: Schematic of the polygon motor unit

Dakin and Popplestone [8] 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 a 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. [6] 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 μm. 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 μm. 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 insertion task in view of automatization of the task. The schematic of the polygon motor unit is shown in Fig. 1. The nominal di-
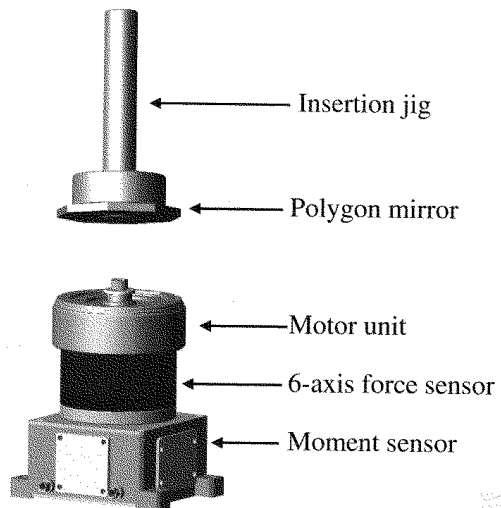

Fig 2: Experimental apparatus

mension of the bearings is 10 mm in diameter. They are both made of ceramics and the gap clearance between the two parts is 5 μm or less. 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 newly designed a 2-axis moment sensor for the current study. This section presents the details of the sensor as well as the entire experimental setup.

4.1 2-axis moment sensor

As mentioned earlier, there is no commercial sensor which can provide a sufficient sensitivity in terms of moment measurements. Therefore, we have designed a 2-axis moment sensor which suits our needs. It measures moments about X-axis and Y-axis. A

moment about Z-axis is omitted because it is considered to bear less importance than the other two components. Fig. 3 displays the outlook of the sensor. What is shown in the figure is one integral piece except strain gauges and cables attached to it. Each axial moment is measured by means of a set of four semiconductor strain gauges which form a wheatstone bridge circuit.
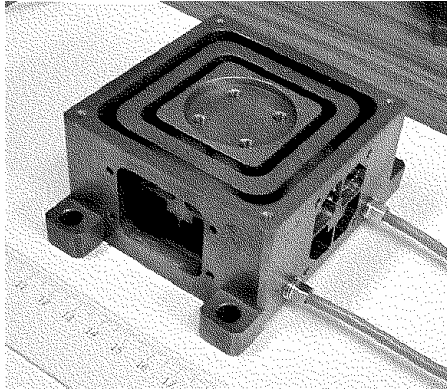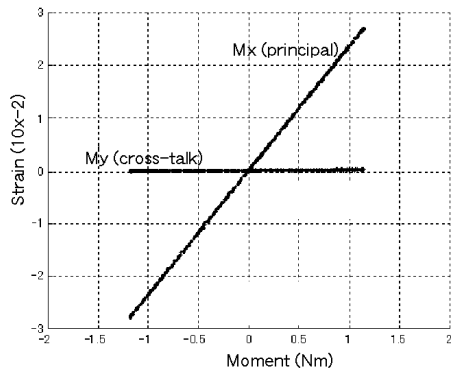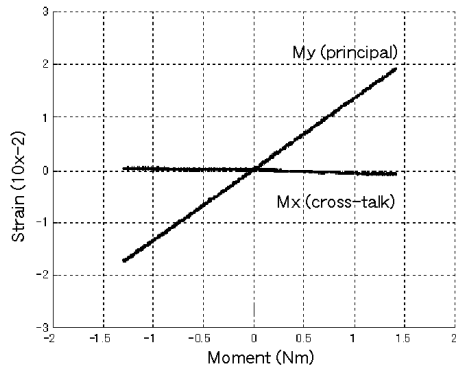

Fig 3: Outlook of the moment sensor

(a) X-axis moment

(b) Y-axis moment

Fig 4: Calibration curves of the moment sensor

Calibration curves of the moments about X-axis and Y-axis are depicted in Fig. 4. It is seen from the figure that the sensor is very good in linearity, hysteresis and cross talk. Its sensitivity is 0.0043Nm
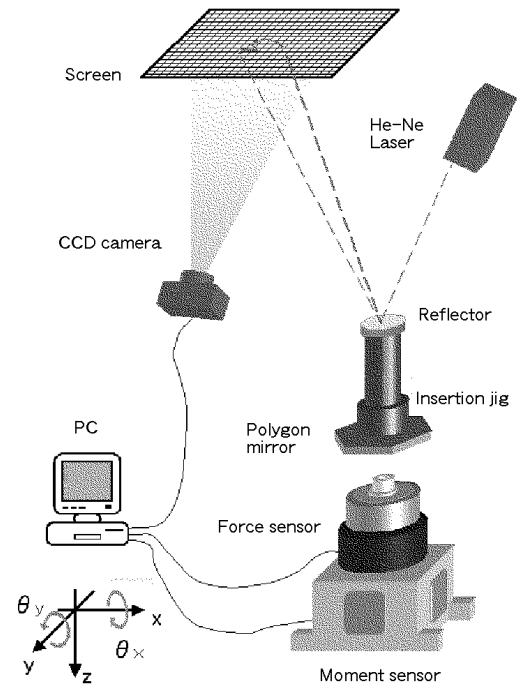

Fig 5: Experimental setup

per 100μst for X-axis moment and 0.0074 for Y-axis moment. The cross talk/principal ratio is 1.2% and 1.4% for Y/X and X/Y, respectively. There is virtually no hysteresis observed.

4.2 Experimental setup

Fig. 5 displays the experimental setup which consists of three measuring instruments: a force sensor, a moment sensor and a inclination sensing system with a He-Ne laser and 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 force sensor is placed atop the aforementioned moment sensor. A He-Ne laser beam is projected to the head of the insertion jig where an optical mirror is placed and the laser beam is reflected by the mirror surface. The reflected beam then is projected to the screen which is deployed about 2.8 meters away. A CCD video camera records the trajectory of the laser beam projected on the screen at the frame rate of 30 Hz. A real-time image processing program computes the XY coordinates of the gravity center of the projected point which are then converted to the inclination of the insertion jig. Conversion from the XY coordinates to the angles is done afterwards with zero reference angles when an insertion is completed. With this method, a resolution of the inclination measurement is 0.0205^{o}.

The signals from the force sensor and the moment sensor are acquired by C program on PC and stored for further data processing and analysis by MAT-
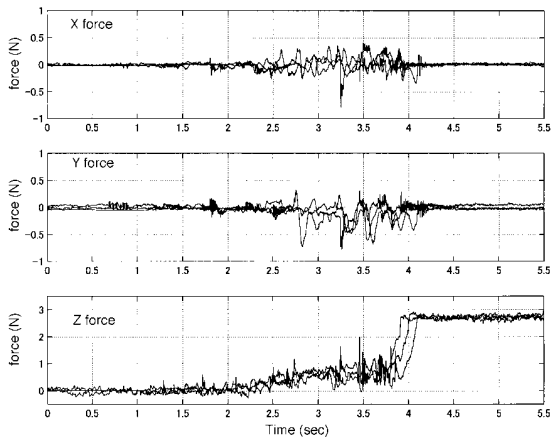
(a) Forces (top: X, middle: Y, bottom: Z)
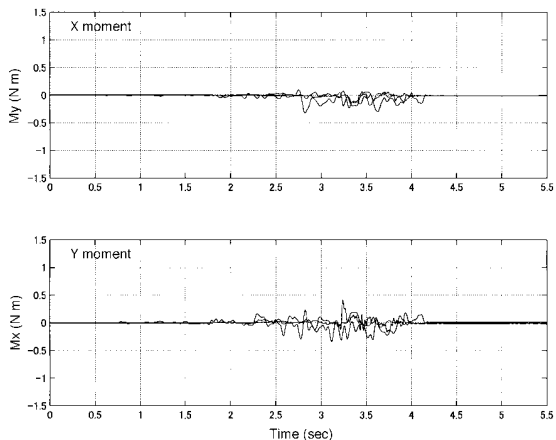
(b) Moments (top: X, bottom: Y)

Fig 6: Force and moment measurements (skilled)

(a) Forces (top: X, middle: Y, bottom: Z)

(b) Moments (top: X, bottom: Y)
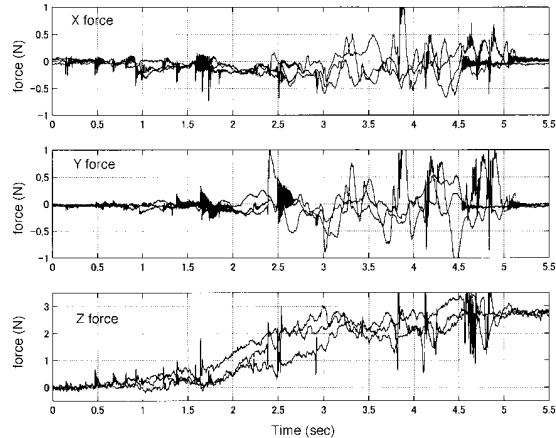
Fig 7: Force and moment measurements (unskilled)

LAB. Each data acquisition session takes less than 10 seconds, which varies depending on how skillful the subject may be.

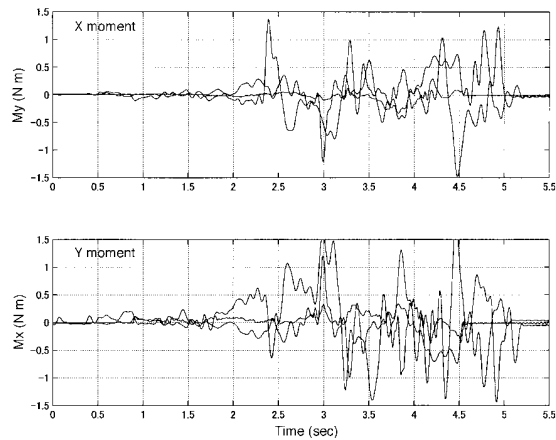We conducted insertion experiments with skilled subjects and unskilled subjects.

4.3 Results

Typical observations of forces and moments for skilled and unskilled subjects are shown in Fig.6 and Fig.7, respectively. All the force measurements are given in Newton while the moments are in Newton meter. Each figure contains measurements from three different attempts by a same subject.

Discrepancies between the skilled subject and the unskilled subject distinctively appear in those figures. One of the most significant differences is the consistency of the skilled subject. Observing X and Y components in Fig. 6, it can be seen that both X and Y fall within a narrow range around zero. These horizontal components should be kept near zero be-

cause an ideal insertion only involves a vertical force along Z axis. On the other hand, the unskilled subject exerts fairly large horizontal forces as shown in Fig. 7. It seems that the unskilled subject is having a great difficulty in finding a clue of what kind of situations he/she is in. It can be seen from Fig. 7 (a) that he/she somewhat places the polygon mirror atop the mating part and makes a precessing motion to do a final alignment,[1] which can be inferred from the fact that Z component reaches about the self weight of the jig and the mirror even before large horizontal forces start being exerted. By contrast, Fig. 6 (a) clearly shows that the skilled subject sustains the part's self weight until he/she becomes certain that the exact alignment is almost made and it is ready for a inserting motion to take place. It is also seen that he/she ceases exerting a force immediately after the insertion is done while the unskilled subject

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[1] This is supported by the observation of the inclination data, which will be discussed in the following section.
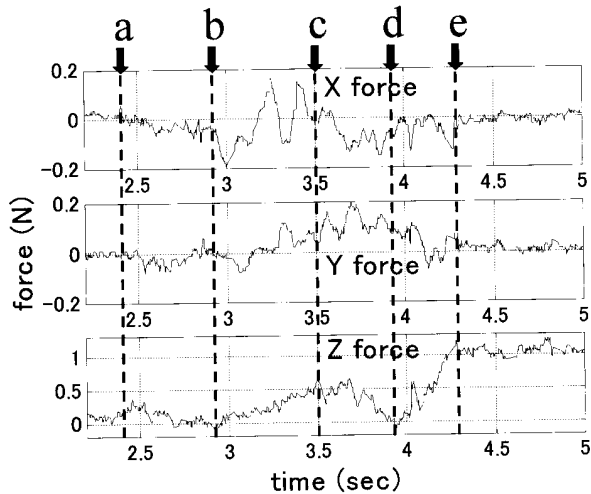
Fig 8: Interpretation of observed pattern (skilled)
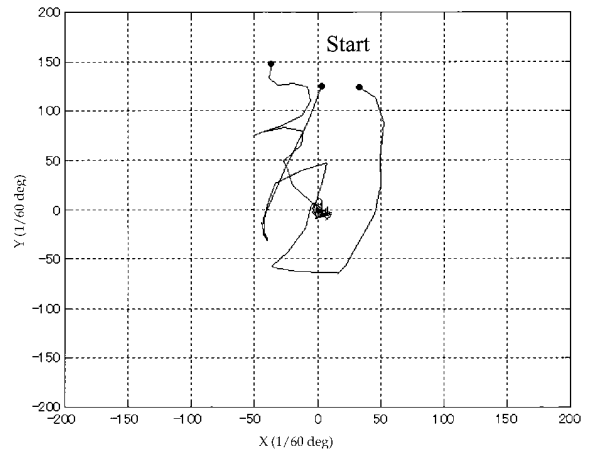

Fig 9: Inclination of the polygon mirror (skilled)

Fig 10: Inclination of the polygon mirror (unskilled)

tends to fail to do so.

As far as the execution time is concerned, the skilled subject takes about 2 seconds and the unskilled one takes approximately 5 seconds.

4.4 Analyses

Fig. 8 shows an example of the test results given by the subject B with 5 μm clearance[2] . 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 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 and Fig. 10 illustrates what kind of motion sequences the skilled subject and the unskilled subject undertake during the insertion process, respectively.[3] In both figures, the abscissa and the ordinate represent the inclinations of the insertion jig, *i.e.*, the polygon mirror, about X-axis and Y-axis, respectively.

There are two noteworthy observations. First, there is a clear difference in terms of the shape of the trajectories. Namely, the trajectories of the skilled subject tend to be more or less minimal, *i.e.*, only a few switching motions, and their motions mainly take place as an adjustment of the inclination about Y-axis alone. On the other hand, the trajectories of the unskilled subject illustrate a presence of precessing motions instead of directly moving toward the origin.

Second, it is seen that both skilled and unskilled subjects tend to start from a similar orientation for every attempt.

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[2] Note that X and Y force components use a different force scale from Z component does.

[3] Note that these figures are not the trace of the laser beam.

5 Concluding Remarks

High-precision insertion process using a polygon mirror was investigated from the physical information point of view. Force and moment information was obtained by using a force sensor and a newly developed moment sensor while the inclination of the polygon mirror was measured by a laser and a CCD video camera. Measurement of the force and moment data 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 poorly searches for an incidental insertion. This observation is supported by the fact that the inclination change of a skilled subject more or less directly converge to a goal while an unskilled subject tends to do a precessing motion in order to find an exact alignment, which in general takes more time and is less energy efficient. 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.

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, we plan to conduct extensive insertion experiments using the current system and to make further in-depth analyses. As a result, a robust, physical task model of the insertion process will be obtained which will serve a basis for the process automation in the future.

Acknowledgment

References

[1] Y. Yamamoto and T. Hashimoto and T. Okubo and T. Itoh. Measurement of Force Sensory Information for the Automation of Ultra-Precision Assembly Tasks. In *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, (2001), 395–400.

[2] K. Takeyasu, T. Goto and T. Inoyama. Precise Insertion Control Robot and its Application. *Trans. ASME, Journal of Engineering for Industry*, 98(4), (1976), 1313–1318.

[3] D.E. Whitney. Quasi-Static Assembly of Compliantly Supported Rigid Parts. *Trans. ASME, Journal of Dynamic Systems, Measurement, and Control*, 104, (1982), 65–77.

[4] J. Simons, H.V. Brussel, J.D. Schutter, and J. Verhaert. A Self-learning Automaton with Variable Resolution for High Precision Assembly by Industrial Robots. *IEEE Trans. on Automatic Control*, 27(5), (1982), 1109–1113.

[5] E. Vaaler and W. Seering. Automated Assembly with Systems Having Significant Manipulator and Part Location Errors. In *Proceedings of IEEE International Conference on Robotics and Automation*, (1987), 1357–1360.

[6] F. Badano, M. Betemps, T. Redarce, and A. Jutard. Robotic Assembly by Slight Random Movements. *Robotica*, 9(1), (1991), 23–29.

[7] J.M. Schimmels and M.A. Peshkin. Admittance Matrix Design for Force-guided Assembly. *IEEE Trans. on Robotics and Automation*, 8(2), (1992), 213–227.

[8] G. Dakin and R. Popplestone. Contact Space Analysis for Narrow-clearance Assemblies. In *Proceedings of IEEE International Symposium on Intelligent Control*, (1993), 542–547.

[9] V. Gullapalli, A.G. Barto and R.A. Grupen. Learning Admittance Mappings for Force-guided Assembly. In *Proceedings of IEEE International Conference on Robotics and Automation*, (1994), 2633–2638.

[10] H. Nakagaki, K. Kitagaki and H. Tsukune. Study of Insertion Task of a Flexible Beam into a Hole. In *Proceedings of IEEE International Conference on Robotics and Automation*, (1995), 330–335.

[11] H. Qiao, B.S. Dalay and R.M. Parkin. Fine Motion Strategies for Robotic Peg-hole Insertion. In *Proceedings of Institution for Mechanical Engineers*, 209(C),(1995), 429–448.

[12] K. Hara, R. Yokogawa and Y. Kai. Evaluation of Task Performace of a Manipulator for a Peg-in-hole Task. In *Proceedings of IEEE International Conference on Robotics and Automation*, (1997), 600–605.

[13] Y. Li. Hybrid Control Approach to the Peg-in-Hole Problem. In *IEEE Robotics and Automation Magazine*, (1997) June, 52–60.

[14] G. C. Pettinaro. Behavopr-based Peg-in-Hole. In *Robotica*, 17, (1999), 189–201.