Development of an Intelligent Power Module Inserter

Junya Sato∗ Member, Yoshiaki Ichikawa∗ Non-member
Takayoshi Yamada∗ Non-member, Kazuaki Ito∗ Senior Member
Hidetoshi Yamamoto∗ Non-member, Motoharu Fujihara** Non-member
Satoshi Kawaguchi** Non-member, Takehiko Suzuki** Non-member
Jin Izawa** Non-member

(Manuscript received May 8, 2019, revised Oct. 17, 2019)

In this research, we developed a system to insert an intelligent power module (IPM) in a circuit board automatically. The pin row spacing of a target IPM is not reformed in advance and is not the same as the hole row spacing of the board. Hence, after the pin row of one side is inserted, the opposite side must be inserted while applying a force to the already inserted pin row in order to reform the spacing. To this end, a parallel link robot consisting of servo motors was developed. Also, visual feedback control using two webcams is utilized for the alignment and insertion. Moreover, by using the information obtained from a six-axis force sensor installed on the motion base of the robot, it is possible to confirm the grasping IPM and prevent the damage. In the experiment, the developed system was used to perform insertion 100 times, and a 100% success rate was achieved. The average insertion time was 29 seconds.

Keywords: intelligent power module (IPM), parallel link robot, visual feedback control, six-axis force sensor, peg-in-hole

1. Introduction

Numerous industrial assembly tasks have been automated. However, it remains challenging to robotically insert parts with complex shapes such as coils and switches or with many pins such as integrated circuits and intelligent power modules (IPMs). This is because they require precise alignment. Delicate handling is also necessary if the inserted parts are deformable. Therefore, robotic automation is difficult and many processes still depend on human labor. This remains problematic long working periods decrease the concentration and productivity of workers. Also, the increase in labor costs and decreasing working population make 24-hour production difficult. To address this problem, this study focused on automating the insertion of IPMs and the development of an inserter.

Figure 1(a) shows the IPM used in this study. The number of pins and the pin pitch are asymmetrical. This IPM is inserted into the circuit board as shown in Fig. 1(b). The pin row spacing is greater than the hole row spacing (Fig. 1(c)). Hence, it is necessary to address this problem. To conceptualize a solution, we observed a worker during the insertion routine. After the worker had inserted the pin row on one side, the opposite side was inserted. More specifically, the insertion was completed by applying force to the already inserted pin row to adjust the spacing. This resolves the spacing differential between the IPM and the board’s receiver holes. To this end, a parallel link robot, which consists of servo motors, was developed. As the robot operates like a human using force, relevant data are necessary to manage the process. For data gathering purposes, a six-axis force sensor was installed on the robot’s motion base. These details are explained in Sect. 3. The worker correctly aligns the IPM and board using visual recognition. To mimic this, two webcams were installed on the inserter. As 3D robot control is essential for the insertion, the webcams were arranged to capture both the front and side of the IPM being grasped (Fig. 1(d)). The positions of the IPM pins and board holes are identified by processing the captured images. Correct alignment is
possible by minimizing the distance between the pin tips and the board holes. The details of the visual feedback control are explained in Sect. 3.3.

In experiments, the proposed inserter attempted the insertion process 100 times. The success rate was 100%. The average time to complete an insertion was 29 s. Hence, our system is effective.

2. Related Works

The action of inserting a pin into a hole is known as a peg-in-hole or peg-and-hole. Many methods have been proposed to automate this task using a robot. The related works mainly can be categorized into two main approaches. The first is the utilization of force information. For example, automatic insertion of a peg-and-hole is made possible by sensing their contact information using a force-torque sensor installed on the robot (10). However, searching for the hole based on contact information is time-consuming. Kronander et al. propose a method where a human directly teaches a robot (11). After the robot fails the insertion, the human completes the insertion by operating the robot arm directly. The wrench and angular velocity during the direct teaching are measured using a sensor attached to the robot, and the sensed information is transferred to the robot. Then, the robot can achieve the insertion itself. Tang et al. propose a method by which the insertion is completed even though the initial position of the peg is significantly misaligned (12). This method constructs a three-point contact model that overcomes the large misalignment by estimating the positions of the peg and hole using force and geometric analysis. Inoue et al. propose a deep learning-based method (13). They achieve precise peg-in-hole by combining long short-term memory (LSTM) and reinforce learning using image information measured by force and position sensors. This approach achieves robust assembly with common force and position sensors, thereby dispensing with ultra-precise sensors.

The second approach is a visual-based method. Ho et al. researched automatic insertion of an LED tip with 10 pins into a PCB board (14). The objectives of their research and ours are similar. After a delta robot with an arm grasps the tip, it is aligned by utilizing the two cameras. To acquire the positions of the tip and the PCB board correctly by image processing, a white ring light, blue ring light, and back light are installed. As several devices are used, the system is expensive. Huan et al. use a commercial parallel link robot and propose a method that can achieve high-speed peg-in-hole, although there is uncertainty about the hole position (15). The system consists of a six-axis force sensor, servo motor, aluminum arm of off-set type (G-ROBOTS), and a gripper fabricated using a 3D printer. The 3D model is shown in Fig. 4(a). There is a docking space for the IPM next to the board (Fig. 4(b)), and this was also fabricated using the 3D printer.

Figure 5 shows the surface on which to place the IPM and circuit board. They are adjacent to each other and attached for every experiment. As the IPM dock was based on the IPM’s shape, as shown in Fig. 4, the position and orientation of the IPM placement are always identical. Hence, the yaw angle between the pin row and board holes is always the same.
Development of an Intelligent Power Module Inserter (Junya Sato et al.)

Fig. 4. Parts fabricated using a 3D printer; a) gripper; b) IPM docking site

Fig. 5. IPM and circuit board docking site

Algorithm 1 Process flow of the insertion.
1: Grasp the IPM
2: Move to the initial position
3: Insert pin row on one side using the visual feedback
4: if Failed then
5: Try again from the initial position until success
6: Insert pin row on the opposite side by the visual feedback
7: if Failed then
8: Insert using grope motion until success
9: Push the IPM to complete the insertion

when the robot hand moves parallel to the circuit board from the IPM dock. As the positions of the IPM, circuit board, and cameras are fixed, it is not necessary to adjust the yaw angle when grasping the IPM.

Next, each coordinate system of our inserter is shown in Fig. 6. (a) and (b) are the coordinate systems of the robot, cameras, and captured image. As OpenCV is used for image processing, the point of origin is at the top left.

3.2 Grasping the IPM In this section, the IPM insertion algorithm is explained. Algorithm 1 describes the process flow. First, the gripper moves above the IPM to initiate grasping. Next, while opening, the gripper moves down until it makes contact with the IPM (Fig. 7(a)). After this step, the gripper moves parallel until it contacts the side of the IPM (Fig. 7(b)). Then, once the IPM is grasped (Fig. 7(c)), the gripper moves to the initial position to start insertion. The contact judgement utilize information obtained from the force sensor.

3.3 Inserting One Side of the Pin Array using Visual Feedback Once the gripper reaches the initial position, insertion, guided by visual feedback, begins. As explained in Sect. 1, the pin row spacing of the IPM is wider than the circuit board’s array of holes. To address this problem, the left pin row, as shown in in Fig. 8(a), is inserted first. The positions of both the pins and the holes must be acquired. To this end, images captured by the two webcams are utilized as shown in Fig. 1(d). Three-dimensional control of the robot during insertion necessitates the use of two webcams. They capture images of the front and side of the IPM to achieve the desired precision of movement. Figure 8 shows the images captured by the webcams. These images also show how the pin tips and target holes are located and matched. To reduce the calculation overhead, not all the pin tips and holes are factored; however, adequate data are produced to ensure alignment. The process of locating the board holes and pin tips using OpenCV for image processing is explained in the next section.

3.3.1 Locating the Board Holes The process flow to locate the board holes is described in Algorithm 2. As shown in Fig. 9(a), the edges of the holes have a golden color. Hence, locating the holes is possible once this color is recognized. To do so, the RGB image is converted to an HSV image. This is because this color system is more robust to illumination changes than the RGB color system. Each channel of the RGB image includes an intensity component. On the other hand, HSV color system consists of hue, saturation, and brightness. Simply, the color components and intensity are separated. Therefore, more robust color extraction to the illumination change than RGB color system is possible. Next, by thresholding each HSV component, hole candidates are acquired (Fig. 9(b)). The settings are $H \in [0,180]$ for hue, $S \in [68,255]$ for saturation, and $V \in [115,255]$ for brightness. These values are empirically determined. Automatic determination of these setting is a project to be undertaken in the next section.
Development of an Intelligent Power Module Inserter (Junya Sato et al.)

Fig. 9. Identification of the hole candidates from the front: a) target image; b) binarization result by thresholding HSV components; c) hole areas; d) final candidates

Fig. 10. Identification of the hole candidates from the side: a) target image; b) binarization result by thresholding HSV components; c) hole areas; d) final result

the future. After that, the position and bounding box of the candidates are obtained by the labeling. Undesirable candidates are excluded by applying a set of criteria. As the positions of the board and webcams are fixed, the relative size and position of the holes in the images are always constant. Therefore, extracted candidates, whose bounding box is less or equal to 60, or greater or equal to 500 pixels, are inappropriate. Also, since the areas, where the hole rows exist, are always the same as shown in Fig. 9(c), the candidates, which locates outside of this area, can be removed. The green area on the left is \((x, y, \text{width}, \text{height}) = (100, 0, 220, 480)\). The red area on the right is \((320, 0, 230, 480)\). The remaining candidates are shown in Fig. 9(d). In Fig. 9(c), the candidates with the largest \(y\) coordinate is the closest to the webcam and is marked with light blue circles. These two holes are utilized for visual feedback.

The same algorithm is used to identify the holes from Fig. 10(a). However, different thresholds are adopted for color extraction. This is because a different type of webcam is used. The setting for this thresholds are \(\text{Hr}[0,50], \text{Sr}[56,255]\), and \(\text{Vr}[48,255]\). The result of applying these settings are shown in Fig. 10(b). The thresholds, less than or equal to 150 pixels and greater than or equal to 400 pixels, are used to eliminate the unsuitable candidates after they have been identified. Also, the candidates, whose central coordinate of the bounding box \((x_{\text{center}}, y_{\text{center}})\) is not in \(50 \leq x_{\text{center}} \leq 600\) and \(250 \leq y_{\text{center}} \leq 400\) (the red rectangle in Fig. 10(c)), are removed. Figure 10(d) shows the final result. The leftmost and rightmost candidates (light blue in Fig. 10(c)) are utilized for the visual feedback.

3.3.2 Locating the Pin Tips

Next, the algorithm used for locating the pin tips of the IPM is explained (Algorithm 3). Firstly, Sobel filters for \(x\) and \(y\)-directions are applied to a target image (Fig. 11(a)). Then, the results images are binarized using Otsu method (Figs. 11(b) and (c)). Next, straight lines of the pins are obtained by applying Hough transform to Fig. 11(b) (Fig. 11(d)). The parameters used for the Hough transform are 50 for the voting threshold, 50 for the minimum length of the line to acquire, and 7 for maximum distance to judge that two points are the same line. Also, the line width to draw the acquired lines is 5. These parameters are empirically determined. Automatic determination of these settings is a project to be undertaken in the future. Finally, by applying the AND operation to Figs. 11(c) and (d), the candidate areas of the pin tips are acquired (Fig. 11(e)). The left and right candidates, whose \(y\)

\textbf{Algorithm 3} Locating the pin tips.

1. Convert RGB image to grayscale
2. Apply Sobel filters for \(x\) and \(y\)-directions (IMG1 and IMG2)
3. Binarize IMG1 and IMG2 using Otsu method
4. Apply Hough transform to IMG1 to acquire straight lines (IMG3)
5. Apply AND operator to IMG2 and IMG3
coordinates are the largest, are the pin tips closest to the webacam. Figure 11(f) shows the result of matching the pin tips to the holes.

Algorithm 3 is also applied to the side view, as shown in Fig. 8(b), to match the pin tips and the board holes. The parameters applied for the Hough transform are 60 for the voting threshold, 20 for the minimum length of line to acquire, and 20 for the maximum distance to judge that two points are the same line. Automatic insertion is possible by aligning the pin tips and the holes using visual feedback.

In the system we developed, the size (mm) of one pixel is 0.15 mm in the front camera and 0.088 mm in the side camera as calculated using the board holes. Hence, the image processing acquires the positions of the pin tips and board holes at these resolutions. As shown in Fig. 1(b), because the board holes consist of φ1.05 mm and φ1.15 mm, the precision of the visual system of the developed inserter is enough for the IPM insertion. As described in Sect. 4.1, the inserter achieved a success rate of 100%, thereby proving its capabilities to be sufficient for the task.

3.3.3 Visual Feedback Control 

After the positions of a pin tip and board hole are acquired by image processing, the pin row is inserted using visual feedback. Figure 12 shows the visual feedback process flow. The equations to convert the error ($e_{pix}$) [pixel] between the pin tip and board hole in the image coordinate system to the error in real space ($e_{mm}$) [mm] are:

$$e_{mm} = e_{pix} \times c + 0.1 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ Quad

Fig. 12. Visual feedback control
Development of an Intelligent Power Module Inserter  (Junya Sato et al.)

---

zero until $e_{\text{mm}}$ exceeds the hysteresis zone ($|e_{\text{mm}}| > r_\text{h}$).

As the servo bandwidth of the parallel link robot is wider than the sampling frequency of the vision camera ($f = 60$ Hz), the transfer function of the current coordinate ($P_0$) for the target coordinate ($P'_0$) is assumed as unity. To compensate for steady state error of visual feedback, proportional (P) and integral (I) controllers are adopted to obtain the target coordinate from the modified distance error as follows:

$$u(s) = \left( K_p + \frac{1}{s} K_i \right) e_{\text{hyst}}(s),$$

where, $K_p$ and $K_i$ are proportional and integral, gains tuned to 0.1 and 3.0, respectively, allow the parallel link robot to achieve a smooth settling motion. motion of the parallel link robot.

As the PI controller is discretized using Tustin transform with the sampling time of vision camera $T = 1/f$, the target displacement $u_k$ at each sampling is determined as follows:

$$u_k = u_{k-1} + \left( K_p + \frac{K_i T}{2} \right) e_{\text{hyst},k} + \left( K_p - \frac{K_i T}{2} \right) e_{\text{hyst},k-1}$$

After the moving amount $u$ is obtained, this is added to the current position ($P_0$) to calculate the target position ($P'_0$), and each servo of the parallel link is activated. The current coordinate after the movement is $P$ as shown in Fig. 12. By repeating this process, the IPM is aligned. The insertion process is judged by $z$ coordinate of the robot in the robot coordinate system. If the insertion succeeds, the opposite side is inserted. Otherwise, the gripper goes back to the initial position, and the insertion restarts.

3.4 Insert Pin Row of the Opposite Side  After the insertion of the first side is completed, the insertion of the opposite side starts. During this insertion, the visual feedback process acquires only the front view of the IPM (Fig. 8(a)). By manipulating it into the horizontal position, pressure is placed on the inserted pin row and it is reformed. After this step, the other pin row can be inserted. The success of the insertion is decided based on the sensing of force. If the insertion succeeds, the robot finally pushes the IPM to complete the process. If it fails, a grope motion using the force sense is initiated.

3.4.1 Grope Motion  The grope motion initially raises the pin row that has not yet been inserted. Next, after the gripper horizontally moves to the opposite side, the IPM is rotated so that it is in position to insert. Then, the result is decided based on the force sense. If it fails, the grope motion is repeated until the procedure is successful.

This movement is not initiated at the attempted insertion of the first pin row, but at the insertion attempt on the opposing side. As described in the abstract and Sect. 1, the pin rows of the IPM are not reformed in advance to facilitate insertion. While yet to be reshaped, the first pin row insertion is completed because of the visual feedback from the front and side cameras, and therefore 3D alignment is possible. However, the opposing insertion is difficult. As described in Sect. 3.3.3, only the front camera is used to insert the pin row on the opposite side. This is because the alignment of $x$-direction in the robot’s coordinate system (Fig. 6(a)) is necessary. Nevertheless, during this insertion, only the right pin, which is the closest to the front camera (as shown in Fig. 8(a)), is used for visual feedback. The farthest pin is not used because it cannot be captured by the front camera. In this condition, inserting the not reformed pin row using only the visual feedback is difficult. To address this problem, we implemented grope motion.

3.5 Final Push to Complete the Insertion  After both pin rows are successfully inserted, the insertion is completed by pressing on the IPM (Fig. 14). When the force exceeds the threshold, pressure is relieved.

4. Experiment  To confirm the performance of the developed system, it was attempted 100 times. The computer used had an Intel Core (TM) i7-6700 CPU (3.4 GHz) and 16 GB RAM. The model number of the IPM (Fig. 1(a)) was BM63764S-VA. As the pins plastically deform when force is applied, new IPMs were used. The pin row spacing of all the IPMs is wider than the board hole spacing, and each IPM is unique. Therefore, the experiments with new IPMs confirmed the system’s robustness when managing individual differences.

4.1 Results and Discussion  The experimental inserter achieved a 100% success rate. Figure 15 shows the CPU time taken for each task. It is noted that the recorded times vary. The standard deviation of the CPU time for each task is shown in Table 1. The largest values accrued during the insertion of the first pin row because the image processing capability was inadequate for reliable actions. More specifically, some fixed parameters could not process illumination changes and camera noise. Hence, a stable localization algorithm is required. Table 2 shows the shortest, longest, average, and standard deviation of the CPU times. As the shortest time is 17 s, the experimental inserter demonstrates adequate efficiency. However, the system takes more than 60 s when...
Development of an Intelligent Power Module Inserter

Junya Sato et al.

Fig. 15. CPU time of each task

Table 1. Standard deviation of CPU time for each task

| Task                  | Standard deviation |
|-----------------------|--------------------|
| Grasp IPM             | 0.21               |
| Insert pin row 1      | 10.88              |
| Insert pin row 2      | 2.56               |
| Grope motion          | 2.85               |
| Final push            | 0.34               |

Fig. 16. Position response of the pin tips and holes

Table 2. Shortest, longest, average, and standard deviation of the CPU time (second)

|                | Shortest time | Longest time | Average time | Standard deviation |
|----------------|---------------|--------------|--------------|--------------------|
| Grasp IPM      | 17.20         | 77.48        | 29.25        | 11.27              |
| Insert pin row 1 | 10.88        |              |              |                    |
| Insert pin row 2 | 2.56         |              |              |                    |
| Grope motion   | 2.85          |              |              |                    |
| Final push     | 0.34          |              |              |                    |

Fig. 17. Force response of the six-axis force sensor

the insertion fails at the first attempt. The accuracy of the image processing should be improved. The average time is 29 s. In the future, we aim to achieve faster insertion.

Figure 16 shows the robot’s response to the position of the pin tips in relation to the board holes. This result was measured while the pin row on one side was being inserted. As this insertion requires 3D alignment, the front and side cameras are used. The x coordinates in this figure are based on the image coordinate systems of each camera. The solid lines indicate the positional response of the board holes which are determined by processing the image. The dashed lines represent the positional response of the pin tips. The graphs gradually merge. This result indicates that the alignment by visual feedback contributed to the 100% success rate. Figure 17 shows the force response measured by a six-axis force sensor. Due to the amount of data exceeding limited paper space, only the data of the grope motion and the final push is represented. During the grope motion, as the pin row on the other side is inserted while the already inserted pin row is reformed, the large force being exerted along on the x and z axes becomes apparent. The decrease in force on the z-axis when both pin rows are inserted is also illustrated.

As described in Sect. 3.1, the IPM and circuit board docks are adjacent and are fixed in position as is the robot. Therefore, the developed system does not consider the distribution of variation of the tolerance and placement. The manipulated IPM shows minor variations in its position and attitude. Nonetheless, the gripper (Fig. 4(a)) grasps the IPM accurately. When practicalities are considered, consistently depositing the IPM and circuit board at the same place every time is challenging. Hence, our next task is the development of a flexible system, which will address the approximate positioning of the IPM and circuit board.

4.2 Comparison to Workers To compare the performance between the proposed inserter and human workers, the insertion time was measured. The insertion operators were six students from our laboratory. Factory workers do not require special training for IPM insertion. Hence, the measured data of the laboratory students are essentially same as for the factory workers.

Before the measuring, a researcher firstly explained the process and reasons for the measurement procedure. Next, one circuit board and some IPMs were given to each subject. The participants then practiced inserting until they felt competent. At this time, the researcher explained the necessity of applying force to the second pin row to fit it into the hole row because of the uneven spacing. Also, the researcher explained that the pins are easily deformed and that the subjects should exercise due care. After practicing, insertion times were recorded based on the following procedure.

The circuit board is fixed into the system. It starts grasping a put IPM as a first step. Similar to this, a subject has the circuit board before the insertion starts, and the IPM is put on a desk. When the researcher starts measuring, the subject starts grasping the IPM and inserting. Once both pin rows are inserted and the final push is finished, the researcher stops the timer. This task is repeated 10 times for each subject. As there are limited numbers of new IPMs, only two new IPMs were used for each subject. The first new IPM was used from the first to fifth trials, and the second new IPM was used from the sixth to tenth trials.

Table 3 shows the results. The shortest time among the operators was less than 10 s while the inserter took 17 s (Table 2). Therefore, acceleration of the robotic process is necessary. As the longest time of taken by the workers was less than that taken by the robot it requires an improvement.
in the accuracy of insertion. The average time of the workers was also lower than that of the inserter. Conversely, the consistency of the inserter is better than that of the workers. The standard deviation of 100 trials by the inserter was 11.27. This result is lower than the results of Subject 2 and 6. The inserter’s consistency is therefore stable. Of course, if these subjects get used to inserting, they would also become faster and be more consistent. However, if lengthy work periods are taken into consideration, the insertion speed would decrease and consistency would fail due to fatigue. Rotating workers may solve this problem, however, the proposed inserter is cheaper than the labor cost of the workers. The investigation of the relationship between the performance of the human workers, who keep working for long periods, and related costs is the subject of future research.

5. Conclusions

In this research, the development of an automatic inserter for IPMs is undertaken. As the pin row spacing of the IPM is wider than the circuit board, after the pin row of one side is inserted, the opposite side must be inserted while applying force to the already inserted pin row to reform the spacing. To this end, we developed a parallel link robot with servo motors. The gripper to grasp the IPM is fabricated using a 3D printer. To insert the IPM correctly, visual feedback-based alignment is adopted. Two webcams are placed so that the front and side of the IPM is visually captured, and the positions of the pin tips and board holes are located by image processing. By minimizing the distance for alignment, the insertion procedure is possible. However, visual feedback alone cannot determine when an insertion has succeeded. The absence of force control makes the prevention of damage to the IPM difficult. To remedy these shortcomings, a six-axis force sensor is attached to the motion base of the robot. In the experiments, the insertion was attempted 100 times, and the prototype inserter achieved a 100% success rate within 29 s of the average CPU time.

In the future, image processing improvements to automatically tune the fixed parameters can be achieved. Higher speeds to increase the insertion rate are also required. Further investigations into the automatic insertion of the other parts will be addressed to demonstrate system versatility.

Acknowledgment

This work was supported by JSPS Early-Career Scientists Grant No.JP18K18427 and the Grant-in-Aid for Scientific Research (C) Grant No.JP16K06179.

References

(1) X. Li, R. Li, H. Qiao, C. Ma, and L. Li: “Human-inspired compliant strategy for peg-in-hole assembly using environmental constraint and coarse force information”, in Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.4743-4748 (2017)

(2) H. Park, J.-H. Bae, J.-H. Park, M.-H. Baeg, and J. Park: “Intuitive peg-in-hole assembly strategy with a compliant manipulator”, in Proc. IEEE International Conference on Intelligence and Safety for Robotics, pp.1–5 (2013)

(3) K. Kronander, E. Burdet, and A. Billard: “Task transfer via collaborative manipulation for insertion assembly”, in Proc. Workshop on Human-Robot Interaction for Industrial Manufacturing, Robotics, Science and Systems, pp.1–6 (2014)

(4) T. Tang, H. Lin, Y. Zhao, W. Chen, and M. Tomizuka: “ Autonomous alignment of peg and hole by force/torque measurement for robotic assembly”, in Proc. IEEE International Conference on Automation Science and Engineering, pp.162–167 (2016)

(5) T. Inoue, G.D. Magistris, A. Munawar, T. Yokoya, and R. Tachibana: “Deep reinforcement learning for high precision assembly tasks”, in Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.819–825 (2017)

(6) C.-C. Ho, Y.-M. Chen, and P.-C. Li: “Machine vision based in-process light-emitting diode chip mounting system”, Measurement and Control, Vol.51, No.7–8, pp.293–303 (2018)

(7) S. Huang, N. Bergstrom, Y. Yamakawa, T. Senoo, and M. Ishikawa: “Applying high-speed vision sensing to an industrial robot for high-performance position regulation under uncertainties”, Sensors, Vol.16, No.8, pp.1–15 (2016)

(8) J.C. Tryinoputro, W. Wan, and K. Harada: “Quickly inserting pegs into uncertain holes using multi-view images and deep network trained on synthetic data”, arXiv, Vol.arXiv:1902.09157, No. cs.RO, pp.1–8 (2019)
Development of an Intelligent Power Module Inserter (Junya Sato et al.)

Kazuaki Ito (Senior Member) received the B.S., M.S. and Ph.D. degrees in electrical and computer engineering from Nagoya Institute of Technology, Nagoya, Japan, in 1998, 2000, and 2003 respectively. In 2003, he joined the Department of Electrical and Electronic Engineering, National Institute of Technology, Toyota College, Toyota, Japan, as a Research Associate and he became an Associate Professor in 2009. From 2012 to 2013, he was a Visiting Scholar with the Department of Management and Engineering, University of Padova, Vicenza, Italy. He has been an Associate Professor with the Department of Mechanical Engineering, Gifu University, Gifu, Japan since 2017. His current research interests include applications of motion control theory and soft computing techniques for mechatronic systems and real-world haptics. Dr. Ito is a senior member of the Institute of Electrical Engineers of Japan. He is also a member of IEEE, the Japan Society for Precision Engineering, the Society of Instrument and Control Engineers, and the Society of Signal Processing Applications and Technology of Japan.

Hidehiko Yamamoto (Non-member) received his B.S., M.S., and Ph.D. from the Nagoya Institute of Technology. After 12 years of developing production lines for automotive parts at Toyota Industrial Corporation, he moved to Wakayama University. He is currently a Professor in the Department of Mechanical Engineering at Gifu University. His fields of interest are production systems, intelligent systems, knowledge learning and cyber physical factory. He is the fellow of the Japan Society of Mechanical Engineers.

Motoharu Fujihara (Non-member) joined AISIN AW CO., LTD in 2017, and currently works for the Manufacturing Engineering Department to develop Automated Manufacturing Technology.

Satoshi Kawaguchi (Non-member) joined AISIN AW CO., LTD in 2006, and currently works for the Manufacturing Engineering Department to develop Automated Manufacturing Technology.

Takehiko Suzuki (Non-member) joined AISIN AW CO., LTD in 1997, and currently works for the Electronics Planning Department to develop Natural Language Processing for improvement designing process.

Jin Izawa (Non-member) joined AISIN AW CO., LTD in 2004, and currently works for the Electronics Planning Department to develop robotics control system.