Intuitive Peg-in-Hole Assembly Strategy with a Compliant Manipulator

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***Abstract*— To realize a peg-in-hole assembly with a multi–degree of freedom (DOF) manipulator, the precise position of the hole is required. If the hole is not circular, orientation information is also necessary. A force/torque (F/T) sensor is widely used to sense the position and orientation of the hole. Attaching the F/T sensor on the wrist of a manipulator helps in estimating the position between the peg and hole. However, a person does not need precise information of an object when completing an assembly task. For example, when inserting a plug into an outlet, a person does not need to know the exact information and coordination about the position and orientation of the plug and outlet. A closer look at the process shows that the person tries to place a plug near the outlet and then finds the two holes by rubbing the plug against the outlet without looking. This paper introduces an intuitive assembly strategy inspired by this human behavior. This strategy does not need the precise location of the hole. Instead of an F/T sensor, this strategy adopts hybrid force/position control and passive compliance control for successful peg-in-hole assembly. The feasibility of the proposed strategy was verified through simulation and a hardware experiment.**

***Index Terms*—assembly, peg-in-hole, manipulator, compliance.**

I. Introduction

The peg-in-hole assembly is the most common assembly task for a manipulator. For a manipulator to insert a peg into a hole, information on the hole location is required. There are two common methods to find the hole location: using visual information such as from a camera [1][2] and using a force/torque (F/T) sensor to estimate the hole location by measuring the reaction moments when the peg is tilted into the hole [3][4]. A manipulator can insert the peg into the hole using this information.

The F/T sensor is equipped at the wrist of the robot arm and includes information on the environmental contact forces, inertial forces, and forces due to gravity [5]. The environmental contact forces are the only useful information for estimating the hole position. However, the inertial forces of the end-effector significantly affect the F/T sensor measurements. Thus, using an F/T sensor has the drawback of requiring a precise process, such as for a contact force estimator or force observer. Further, applying this method to polyhedral objects is difficult considering the object rotation.

When a person inserts a plug into an outlet, he or she only needs the approximate location of the outlet rather than the exact position. A person tries to place the plug near the outlet using his or her eyes and then rubs the plug against the outlet until the pegs match the holes. When a human unlocks a door using a key in the dark, the insertion process is similar: the key is placed near the keyhole and rubbed around until the key is inserted.

Thus, the difference between the tasks performed by the human and manipulator is the necessity of knowing the precise hole location. The manipulator inserts the peg into the hole with the calculated hole location, but a human has no need for the exact hole location. Inspired by human behavior, this paper proposes an intuitive assembly strategy (IAS) that does not require precise location of the hole. The point of the IAS is to skip the process of calculating the hole location. The IAS does not use an F/T sensor.

IAS comprises three main parts. The first part is a hybrid control system that pushes the peg towards the hole, similar to pushing a plug toward an outlet. Simultaneously, the manipulator rubs the peg around the hole, similar to rubbing the plug around an outlet

The second part is a compliance control strategy. Without exact hole location information, using precision control to insert the peg is almost impossible. To insert the peg in the hole without information on the hole location, IAS uses compliance control. Compliance control helps the manipulator easily insert the peg into the hole by making the peg soft when it is located near the hole.

The last part is an exploration strategy. IAS needs a specific pattern like the human rubbing motion. To generate an exploration pattern, two strategies were designed: a spiral trajectory where the peg moves to follow and a rotating trajectory to equalize the orientation of the peg and hole. These patterns allow the manipulator to explore the hole using the peg, similar to human behavior.

To verify the feasibility of IAS, a simulation and hardware experiment were performed. The peg was set to be rectangular so that orientation could be considered, and it was attached to the end of the manipulator.

II. Assembly Strategies

A. Hybrid control system

The hybrid control system consists of two parts. The first part is the force control. In the environment, the hole is located in the positive x-direction of the peg (Fig. 1). A uniform force is applied to push the peg towards the hole. If the position and orientation of the peg and hole are almost the same, the peg should be inserted into the hole by the force.

The second part is the position control. To follow the trajectory generated by the exploration pattern, the peg needs to be controlled by the position controller. This controller also contains an orientation controller to rotate the peg and equalize the rotation angles of the peg and hole.

The proposed hybrid control system is as follows:

$$\tau = J_{\mathrm{v}}^{\mathrm{T}} \begin{bmatrix} F_{\mathrm{d}} \\ k_y e_y \\ k_z e_z \end{bmatrix} + J_{\mathrm{w}}^{\mathrm{T}} \delta\Phi + G \quad (1)$$

where τ is the input torque to the manipulator, J_v is the velocity Jacobian, F_d is the desired force generated by the peg towards the hole, k_y and k_z are the position error gains, J_w is the angular Jacobian, $\delta\Phi$ is the orientation error [6], and G is the gravity vector.

B. Compliance control strategy

In the absence of exact information on the hole position, completing the peg-in-hole task with precision control is almost impossible. To insert the peg in the hole without hole location information, IAS uses the compliance control strategy.

In Figure 1, the peg heads towards the hole in the positive x-direction. In this situation, Peshkin [7] and Mason [8] suggested making the peg soft in the x-direction and hard in the y- and z-directions to help put the peg in the hole. In other words, the peg is controlled in the y- and z-directions by the precision control and in the x-direction by the compliance control. In contrast, the compliance control strategy of IAS makes the peg soft in the y- and z-directions and the rotation direction about the x-axis. This compliance control strategy allows the peg to be inserted when the peg is located near the hole.

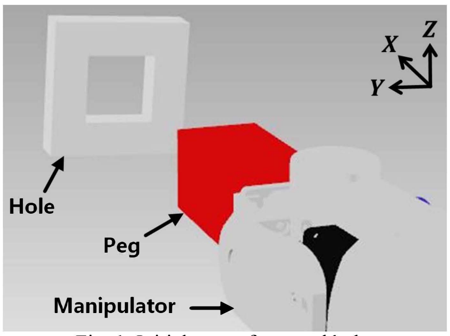


Fig. 1. Initial state of peg and hole.

C. Exploration strategy

To generate the exploration pattern, IAS suggests a trajectory for the position and orientation, as shown in Fig. 2. The translation of the exploration pattern makes the peg move following the spiral trajectory. The rotation of the exploration strategy makes the peg rotate following the bidirectional trajectory. Consequently, the peg attached on the end of the manipulator moves and rotates simultaneously, following each trajectory, until the peg is inserted into the hole.

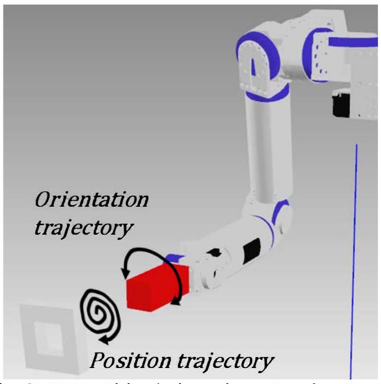
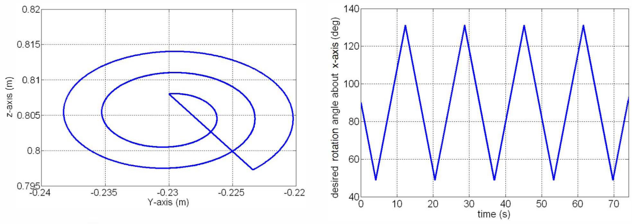


Fig. 2. Peg position/orientation control strategy.

Figure 3 shows the designed exploration pattern about the position and orientation trajectory. The peg moves, following the spiral trajectory, in a circle around the approximate hole location (Fig. 3(a)). The peg is rotated ±40° by the orientation trajectory (Fig. 3(b)).



(a) Position trajectory (b) Orientation trajectory

Fig. 3. Exploration patterns.

III. Simulation

To verify the feasibility of the developed IAS, a simulation was performed using commercial software from Roboticslab [9]. The peg and hole were shaped as squares with sides of 39 and 40 mm, respectively. The manipulator had eight degrees of freedom (DOF), the hole was placed in the positive x-direction from the peg, and the peg was attached to the end of the manipulator.

IAS assumes that the exact hole location is unknown. In a simulation environment, however, the peg and hole location are public information because the simulation environment is created by the user. To satisfy the assumption for the situation, the hole position and orientation were set to have noise.

A. Simulation result

The simulation result is shown in Fig. 4. The peg started from 0.2 m on the x-axis and was moved towards the positive x-direction by the force control. At 0.36 m on the x-axis, the peg contacted the vicinity of the hole. The peg hovered around the hole, following the position and orientation trajectory, until the shapes of the peg and hole matched. When the position of the peg was close to the hole, the peg was inserted into the hole by the compliance control.

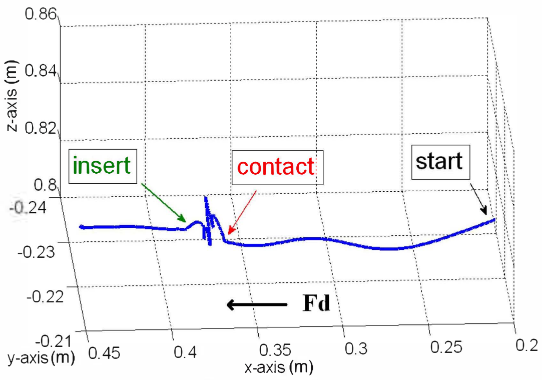
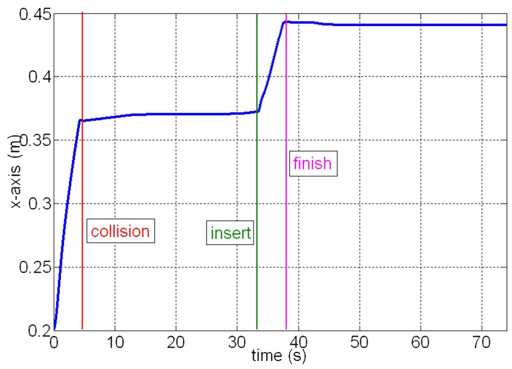


Fig. 4. Path of peg.

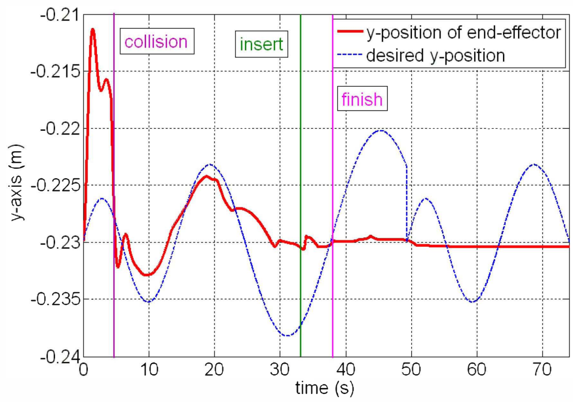
B. Result analysis

Fig. 5 shows four graphs about the x-, y-, and z-positions and the rotation angle about the x-axis of the peg. Fig. 5(a) shows the position of the peg on the x-axis. The peg moved in the positive x-direction for 5 s. Then, the peg stopped for 28 s owing to disagreement. After that, the peg moved towards the positive x-direction until the peg started to be inserted into the hole.

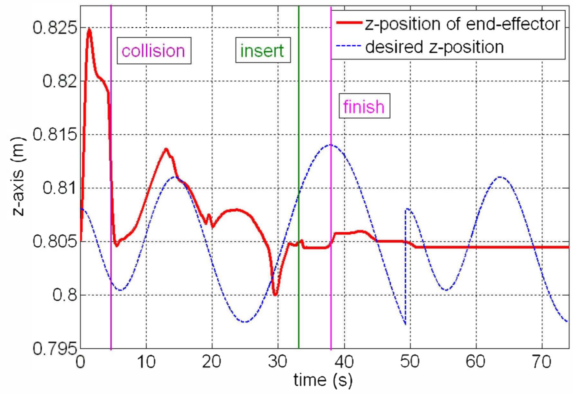
In Figures 5(b) and (c), the red line shows the y- and z-positions of the peg. Between 0 and 5 s, the peg hardly followed the trajectory and was affected by the force control. After contact, the peg rubbed against the hole, following the desired trajectory. After 33 s, the peg started to be inserted into the hole, and the y- and z-positions became saturated. The fluctuation after 38 s was caused by clearance between the peg and hole. Fig. 5(c) shows the rotation angle about the x-axis. The peg rotated -25° to +5°. This is because the peg was tilted by the hole at +5°. After the peg started to be inserted into the hole, the rotation angle became saturated.



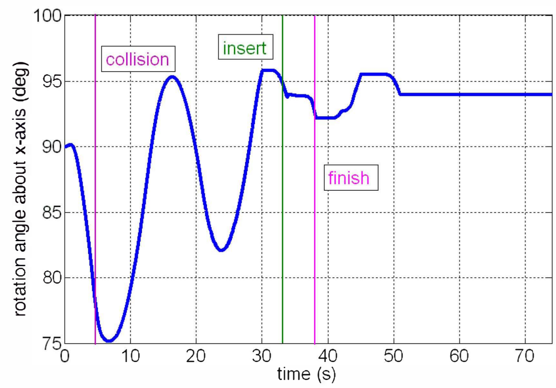
(a) x-position



(b) y-position



(c) z-position



(d) rotation angle about x-axis

Fig. 5. Position and orientation of peg.

The simulation was run 30 times. IAS always inserted the peg in the hole within 1 min. The average success time was 32.3 s, and jamming did not occur.

IV. HARDWARE EXPERIMENT

The hardware experiment was conducted using KITECH ARM, which has 8 DOF. The peg and hole were square-shaped with sides of 49.95 and 50 mm, respectively. The other conditions were the same as in the simulation. Fig. 6 shows the hardware experiment result. Like the simulation, the peg moved towards the positive x-direction where the hole was located. The peg contacted near the hole at 0.48 of the x-axis and hovered near the hole.

After 0.48 m of the x-axis, there was fluctuation caused by forward kinematic error. The peg hardly moved in the hole with 0.05 mm clearance.

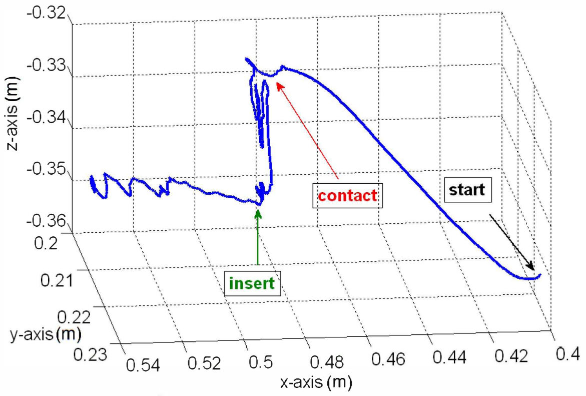
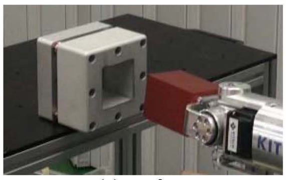


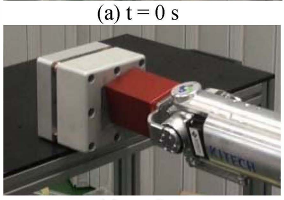
Fig. 6. Path of peg on XYZ space.

Figure 7 shows the experiment process. Fig. 7(a) shows the initial position. Figs. 7(b)–(d) show the peg as it made contact with the hole and rubbed against it. Figs. 7(e) and (f) show the peg being inserted into the hole.

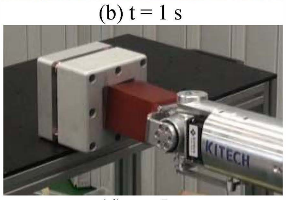


(a) t = 0 s

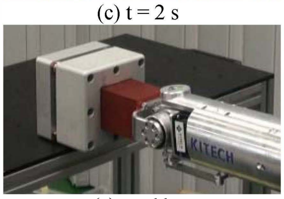
(b) t = 1 s



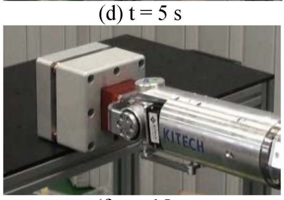
(c) t = 2 s



(d) t = 5 s



(e) t = 11 s



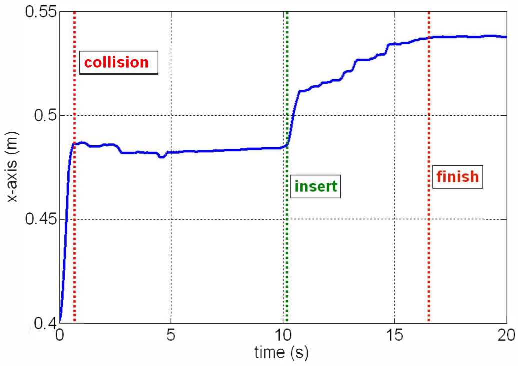
(f) t = 15 s

Fig. 7. Experiment result.

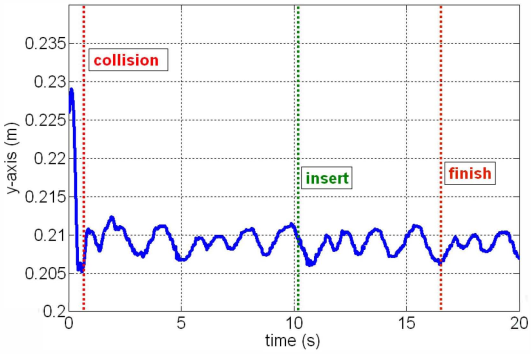
The graphs of Fig. 8 show the experiment results in detail. The four graphs show the x-, y-, and z-positions and the rotation angle about the x-axis. The characteristics of each graph were similar to those of the simulation graphs.

Between 4 and 10 s, the peg hardly rotated, as shown in Fig. 8(d). The peg was tilted by the hole edge, and one side of the peg was inside the hole. In this situation, the peg tried to move following the exploration strategy, and the peg was finally inserted.

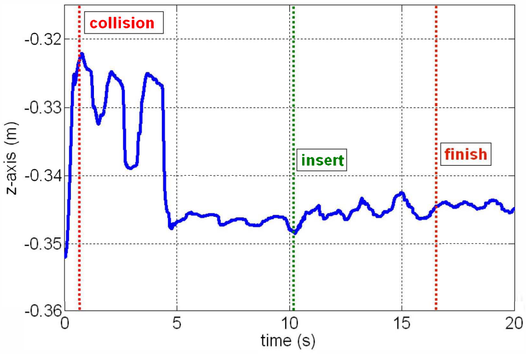
The difference with the simulation result was due to the jamming effect. In thirty experimental trials, jamming occurred about 20% of the time. When the peg jammed within the hole, the peg was unjammed by movement created by the position trajectory. Jamming affected the success time, not the success rate. The average success time was 5.3 s without jamming and 15.4 s when jamming occurred.



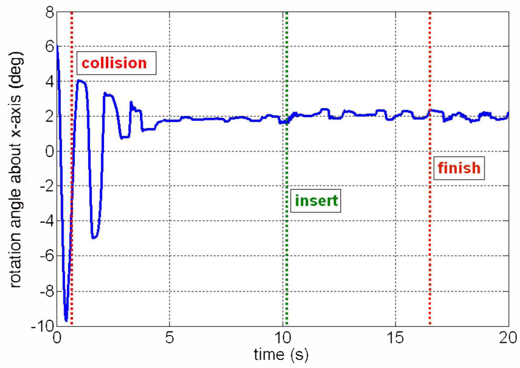
(a) x-position



(b) y-position



(c) z-position



(d) rotation angle about x-axis

Fig. 8. Position and orientation of peg.

V. CONCLUSIONS

The proposed IAS is a powerful peg-in-hole strategy that does not need the exact hole location. This means that the IAS does not need an F/T sensor or to estimate the hole location. It has a 100% success rate when given unlimited time.

One drawback of the IAS is that the elapsed time is unpredictable. Based on the results of the hardware experiment, a tilted peg can consume half of the overall elapsed time.

If the elapsed time caused by a tilted peg was reduced, the success time of the IAS can be decreased. Future work will involve developing a strategy to estimate the hole position and orientation using an active sensing algorithm to reduce the elapsed time caused by a tilted peg.

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