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# Active Peg-in-hole of Chamferless Parts using Force/Moment Sensor

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**Abstract**

This paper discuss the peg-in-hole task of chamferless parts using force/moment sensor. In this paper, when the directional error occurs during the task, it is supposed that there are two cases with small and large errors, and quasi-static analysis has been accomplished for each case. In most other algorithms, however, when there is large directional error during the task, the robot has to return to the initial position and start the task from the beginning, which is considered to be inefficient. This paper proposes the algorithm which enables a robot to continue the task even with large directional error by adjusting the positional and directional error. This algorithm has been implemented for the 5-axis robot and is shown to be effective.

## I. Introduction

In modern industry, robots play major role in various fields in the place of human workers. Especially, robots take significant part in the automation of the manufacturing process, and the parts insertion task in the assembly process is one of such examples. Typically, since robots do the same task repeatedly for a long period of time, they sometimes malfunction due to the cumulative error which occurs during the task. Therefore, to solve such a problem, many analyses and algorithms for the insertion task using robots have been presented.

The insertion task can be accomplished in two different ways, passive and active method. In the passive method, the most common methods are to use RCC(Remote Center Compliance) or to use the parts with chamfer. On the other hand, in the active method, since the robots are capable of correcting the errors based on the feedback data obtained from the sensors, they can be used for the assembly task requiring more accurate action comparing with the passive method. This paper discuss the peg insertion strategy using a force/moment sensor for a chamferless parts.

M. E. Caine[1] presented static analyses of the assembly task for the chamferless parts in 2 and 3 dimensional plane. In his 2-dimensional analysis, he considered two cases with large and small directional errors for the tilted mode and accomplished static analysis for each cases, however, did not propose any algorithm for the insertion task. The significance of his paper is that he classified the tilted mode into two cases with large and small directional errors. In most other similar studies, the case with large directional error has been considered to be erroneous and the robot has to return to the initial position and begins the task from the beginning, which is considered to be very inefficient[3]. However, this paper proposes the algorithm which enables the robot to continue the task even with large directional error by adjusting the positional and directional error as in the case with small directional error. This algorithms has been successfully implemented for the 5-axis robots using force/moment sensor and is shown to be effective.

In the next chapter, the quasi-static analysis is presented for the normal and tilted modes, and the insertion algorithm is proposed in chapter 3. Chapter 4 shows the experimental results and finally chapter 5 concludes the paper.

## II. Insertion Task

When a robot performs an insertion task, there are two possible erroneous situations, which are called normal and tilted mode. In normal mode, the peg is perpendicular to the surface, and there is only positional error. The tilted mode represents the situation the peg is not aligned with the hole direction and there are both positional and directional error.

### II.1 Normal mode

In normal mode, the peg is perpendicular to the surface without directional error and there is only a positional error. Figure 1 shows the moments when the peg end touches the hole opening. In this case, the center

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of the force/moment sensor is assumed to be aligned with the center of the upper face of the peg. As the peg approaches to the hole while touching the hole opening, there exists a force which is perpendicular to the ground and the moment is perpendicular to the line connecting the centers of the peg and the hole. In Figure 1, $\alpha$ represents the angle between the direction of the $x$ component of the moment vector and the line connecting the centers of the peg and the hole and has the positive value of $0 \sim \pi/2$. If we let $l$ be the initial positional error length and $r$ be the radius of the peg, then the distance between the peg center and the contact point would be $r-l$. Since the moment is $M=(r-l)F$ with the force $F$ which is perpendicular to the ground, the magnitude of the moment is increased as the peg approaches the hole. By measuring the moment, the robot finds the direction in which the peg has to be moved and the unit directional vector for the robot movement can be found as follows.

$$mx = \frac{My}{\sqrt{Mx^2+My^2}}, my = \frac{-Mx}{\sqrt{Mx^2+My^2}} \quad (1)$$

Since there always exits clearance between the peg and the hole, the insertion task can be accomplished successfully by adjusting the peg position using the correctional vector found from the measured moments. Even though the above argument is just for the first quadrant, the same strategy can be applied to the other quadrants.

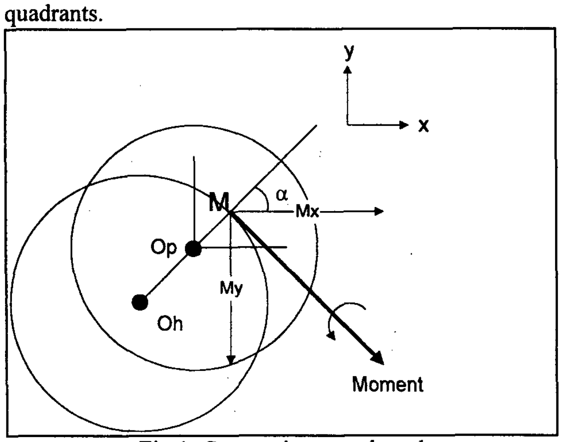

Fig 1. Contact in normal mode

II.2 Tilted mode

The tilted mode represents the status in which the peg is not perpendicular to the hole surface. In this case, there exist both the directional and the positional error. If it is assumed that the peg is tilted to only one direction, there are six possible cases depending on the relative position and the posture of the peg with respect to the hole as shown in Figure 2. If we consider the cases in which the peg is tilted to the opposite direction, there are twelve possible cases. The six cases in Figure 2 can be summarized as follows:

a) The peg is in contact with the surface outside the hole
b) The peg is inside the hole with only one contact at the edge of the hole
c) The peg is in contact with two points
d) The peg is in contact with the hole edge
e) The peg is inside the hole with two contacts
f) The peg is inside the hole with only one contact

When the robot exerts a downward force , each case described in the above is changed to the case (c) or (e) eventually. The case (a) is changed to the case (b),(f) or (e) by adjusting only the position of the peg to decrease the positional error while downward force is exerted. It is clear that the cases (b) and (f) are changed to the case (e) by simply pushing the peg downward. Also, the case (d) is changed to the case (c) by the downward force. In other word, every case with one contact is changed to the case with two contacts. Therefore, in the following static analysis, it is only necessary to consider the cases (c) and (f). We will call (c) the case with small directional error, while (e) the case with large directional error.

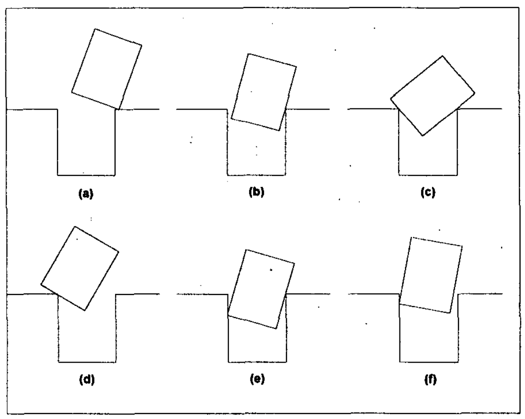

Fig 2. Contact in tilted mode

II.2.1 The Analyses in the Quasi-Static Equilibrium Status

II.2.1.1 The Case with Small Directional Error

Figure 3 shows forces and moments in the static equilibrium for the case with small directional error, and the relationships are as follows.

$$\sum F_y = F\sin\alpha + f_1\cos\theta - \mu f_1\sin\theta - f_2 = 0 \quad (2)$$

$$\sum F_z = F\cos\alpha - f_1\sin\theta - \mu f_1\cos\theta - \mu f_2 = 0 \quad (3)$$

$$\sum M_0 = M + \mu f_2 d + f_2 l$$



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$$-F\frac{d}{2}\cos\alpha - FL\sin\alpha = 0 \quad (4)$$

$$l = \frac{D - d\cos\theta}{\sin\theta} \quad (5)$$

$$f_1 = F\frac{(\cos\alpha - \mu\sin\alpha)}{(1-\mu^2)\sin\theta + 2\mu\cos\theta} \quad (6)$$

$$f_2 = F\frac{\sin\alpha(\sin\theta - \mu\cos\theta) + \cos\alpha(\cos\theta - \mu\sin\alpha)}{(1-\mu^2)\sin\theta + 2\mu\cos\theta} \quad (7)$$

When the peg is inside the hole with two contacts, the forces $f_1$ and $f_2$ are always positive, from which we can find the range of $\alpha$ as in the following.

$$f_1 \geq 0 \quad \alpha \leq \tan^{-1}\frac{1}{\mu} \quad (8)$$

$$f_2 \geq 0 \quad \alpha \geq \tan^{-1}\frac{\mu\sin\theta - \cos\theta}{\mu\cos\theta + \sin\theta} \quad (9)$$

$$\therefore \tan^{-1}\frac{\mu\sin\theta - \cos\theta}{\mu\cos\theta + \sin\theta} \leq \alpha \leq \tan^{-1}\frac{1}{\mu} \quad (10)$$

In order to be the case with a small directional error, the angle $\theta$ between the peg and the hole must satisfy the following inequality.

$$d \leq D\cos\theta \qquad \therefore \theta \geq \cos^{-1}\frac{d}{D} \quad (11)$$

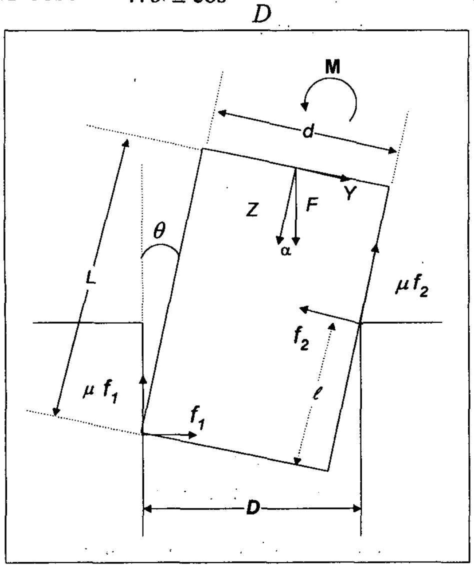


Fig 3. Forces and moments in the case with small directional error

II.2.1.2 The Case with Large Directional Error

Figure 4 shows forces and moments in the static equilibrium for the case with large directional error, and the relationships are as follows.

$$\sum F_y = F\sin\alpha - \mu f_1 - f_2 = 0 \quad (12)$$

$$\sum F_z = F\cos\alpha - \mu f_2 - f_1 = 0 \quad (13)$$

$$\sum M_0 = M - \mu f_1 L - f_1\left(\frac{d}{2} - S\right) - \mu f_2\frac{d}{2} - f_2(L - l) = 0 \quad (14)$$

$$S = d - D\cos\theta \quad (15)$$

$$l = D\sin\theta \quad (16)$$

$$f_1 = F\frac{\cos\alpha + \mu\sin\alpha}{1+\mu^2} \quad (17)$$

$$f_2 = F\frac{\sin\alpha - \mu\cos\alpha}{1+\mu^2} \quad (18)$$

When the peg is inside the hole with two contact, the forces $f_1$ and $f_2$ are always positive, from which we can find the range of $\alpha$ as in the following.

$$f_1 \geq 0 \qquad \tan\alpha \geq -\frac{1}{\mu} \qquad \alpha \geq \tan^{-1}\left(-\frac{1}{\mu}\right) \quad (19)$$

$$f_2 \geq 0 \qquad \tan\alpha \geq \mu \qquad \alpha \geq \tan^{-1}\mu \quad (20)$$

In order to be the case with large directional error, the angle $\theta$ between the peg and the hole must satisfy the following inequality. With the inequality (11), this relation can be used to find out if it is the case with small directional error or large.

$$d \geq D\cos\theta \qquad \therefore \theta \leq \cos^{-1}\frac{d}{D} \quad (21)$$

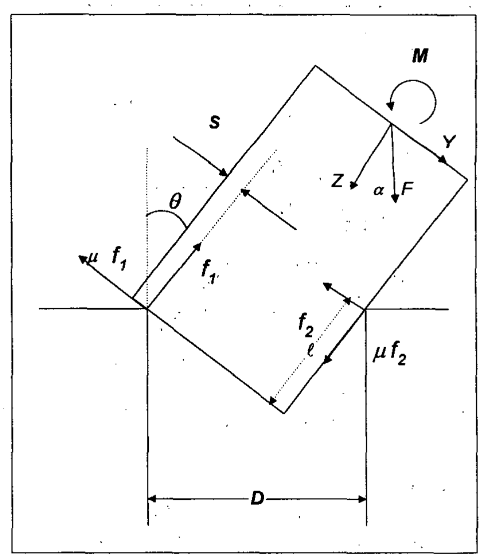


Fig 4. Forces and moments in the case with large directional error



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## III. Insertion Algorithm

In normal mode, since it is necessary for a robot only to keep correcting the positional errors to complete the insertion, there is no need for a particular strategy for the task. Therefore, in this chapter, only the tilted mode is discussed.

Let us consider the six cases in Figure 2. In the case (a), where the peg touches the surface outside the hole, the correction action is performed as if there is only positional error exists. Then, the case is changed to the case that the peg touches inside the hole, such as (b),(f) and (e). In the cases (b) and (f), the peg touches inside the hole, and the peg is pushed downward until the reaction force in the $z$ direction is sensed. Then, this case is changed to the case (e). In the state of (e), if the position and direction error corrections are performed, the state is changed to (f). By pushing the peg downward, the state is changed to (e), again. By repeating this process, the insertion task is completed.

In order to perform the insertion task, there are several things to be decided during the task. First, it has to be determined whether the peg touches the inside of the hole or outside. By comparing the horizontal component of the reaction force with the vertical component, this can be done. If the vertical force is greater than the horizontal force, it is decided that the peg touches the outside, or vice versa.. The next thing to be determined is if it is the case with large or small directional error, (c) and (e) in Figure 2. This can be decided using the following relations.

$S = d - D\cos\theta > 0$ : the case with large directional error

$S = d - D\cos\theta < 0$ : the case with small directional error

During the task, the positional error correction is performed using the equation (1). The directional error is corrected using the direction of the moment sensed from the sensor. However, the direction of the moment changes as the tilted angle of the peg varies. When the tilted angle is small, the direction of the peg to be moved is the same as the direction of the moment sensed. However, for a large tilted angle the peg must be moved in the opposite direction of the sensed. Figure 5 shows the relations between the direction of the moment sensed and the direction to be moved for the six possible cases. As can be seen from the Figure 5, there is a threshold angle to change the direction of the movement relative to the sensed direction. This angle cannot be determined exactly, because the center of the rotation keeps changing as the peg moves. However, if it is assumed that the peg is rotated about the one edge of the bottom, the threshold angle can be determined approximately as follows.

$$\tan\theta_{th} = \frac{\frac{d}{2}}{L} = \frac{d}{2L} \qquad \theta_{th} = \tan^{-1}\frac{d}{2L} \tag{22}$$

In the above equation, $d$ and $L$ represent the radius of the peg and the distance between the bottom of the peg and the center of the sensor, respectively. From the experimental results, this approximately calculated threshold angle proves to be valid.

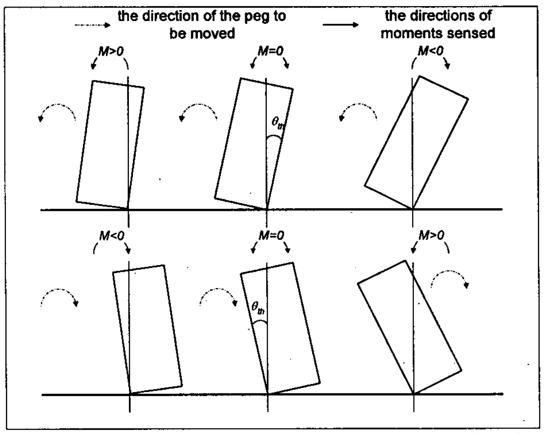


Fig 5. The relations between the peg movement directions and the sensed moment directions

## IV. Experimental Results

The robot used for the experiment is 5-axis ESHED ROBOTECH's SCORBOT EX-IX with force/moment sensor attached between the tool flange and the gripper. The peg to be inserted is of cylindrical shape with 29.5 mm and the hole radius is 30.0mm. The experiment is performed for the two cases with a small and a large directional error.

IV.1 The Case with a Small Directional Error

Figure 6 and 7 show the angle and the force/moment variations during the task, respectively. The initial positional error is 6.366 mm and the initial directional error is 6.69 degrees which is less than the threshold value determined from the relation (21). The horizontal axes of the figures represent time in second. If we look at the position and angle variation in Figure 6, we can see that the peg touches the hole approximately at 1 second. After the contact, only $x$ and $y$ positions are changed, which means the peg is moved while it is in contact with the surface outside the hole. After approximately 3 seconds, the peg begins to move in $z$ direction, and keeps moving until the peg is inserted completely.



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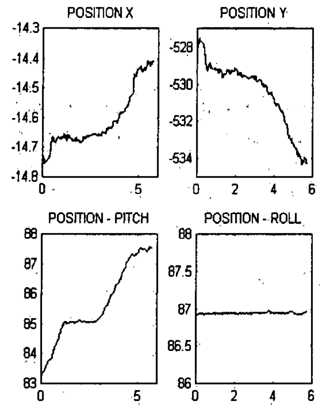


Fig 6. Position and angle variations for the case with small directional error

As can be seen in Figure 7, the $z$ direction force is kept almost constant while the peg is in touch with the surface of the hole. After the hole touches the inside the hole, the $z$ force varies as the peg is inserted. The value of $\theta_{th}$ determined using equation (22) for this experimental setup is 5.4 degrees. As can be seen in the figure, the direction of $x$ moment is changed when pitch angle is approximately 85 degrees.

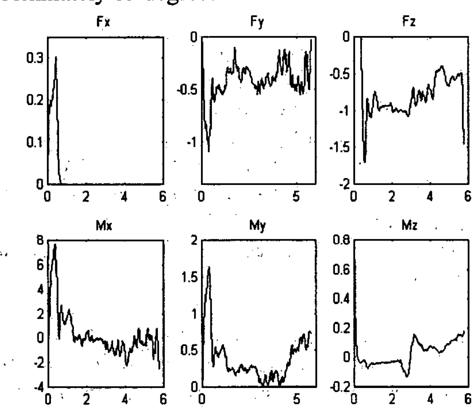


Fig 7. Force and moment variations for the case with small directional error

IV.2 The Case with a Large Directional Error

Figure 8 and 9 show the angle and the force/moment variations during the task, respectively. The initial positional error is 8.145 mm and the initial directional error is 17.96 degrees which is greater than the threshold value determined from the relation (21). The horizontal axes of the figures represent time in second. As in the case with a small directional error, the peg moves in only x and y direction, while it is in touch with the surface outside the hole. At this time, it takes more time, since there is a large directional error to be corrected. After some time passed, the peg begins to move in $z$ direction and keeps moving until it is inserted successfully. Again, as can be seen in the Figure 9, the direction of $x$ moment is changed when pitch angle is approximately 85 degrees.

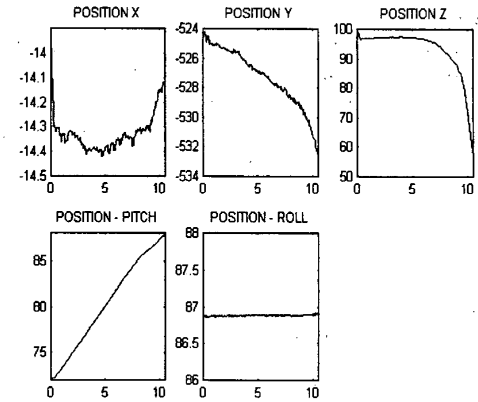


Fig 8. Position and angle variations for the case with small directional error

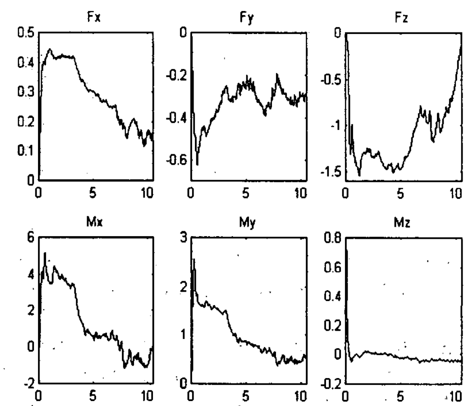


Fig 9. Force and moment variations for the case with small directional error

The task is performed using the pegs with smaller clearances down to 0.1 mm and the algorithms works well with longer period of time.

## V. Conclusions

In this paper, the insertion algorithm for the cylindrical peg using force/moment sensor is discussed. Depending on the positional and the directional error, it is supposed that there are two possible cases, normal and tilted mode. For the tilted mode, two cases with a small



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and a large directional error are considered. For each case, the quasi-static analysis and the insertion algorithm using the sensor are presented. The algorithm is implemented for the robot and shown to be effective. The proposed algorithm differs from the previous results in that it enables a robot to continue the task even with the large directional error by adjusting the positional and directional error.

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