Human-Inspired Compliant Strategy for Peg-in-Hole Assembly Using Environmental Constraint and Coarse Force Information

Xiaoqing Li[1], Rui Li[2], Hong Qiao[2,3,4], Chao Ma[1], and Liang li[5]

***Abstract*— Automated assembly, especially peg-in-hole insertion, is a common task in manufacturing. In particular, the high-precision assembly is achieved by high-precision manipulator and sensing system. However, uncertainty and various parts for assembly are still challenges for robotic assembly, especially for low-precision robot and sensors. It is noteworthy that human can implement assembly tasks although the precision of the arm and hand is not comparable with a common industrial robot, in which process compliance is the key characteristic of their motion. In this paper, we present a human-inspired compliant strategy for peg-in-hole assembly task using the environmental constraint and coarse force information. In the proposed strategy, a constraint region is designed for motion planning and utilized for eliminating the uncertainty of the initial positioning error of the peg. Force sensor is applied to sense the contact force of which the direction is used to adjust the movement of the peg. Therefore, high-precision sensor is not necessarily required. Inspired by human compliant assembly, a from coarse to fine adjustment strategy is executed. The contribution of our strategy is that high precision assembly task can be solved by low precision system. The constraint region and force guided directional adjustment have increased the robustness of the system. The strategy is carried out in simulation for round peg-in-hole assembly task. The experimental results show that the assembly task can be successfully completed and demonstrate the effectiveness of our strategy.**

I. INTRODUCTION

Robotics has made great contribution to industry productivity and to assisting workers on various tasks, such as assembly, palletizing and painting. Robotic assembly is a kind of high-precision manipulation task. However, it is still a challenging problem to achieve high-precision assembly with very narrow clearance ($10^{-5} \sim 10^{-6}$m).

Robotic assembly research has been studied for a long time. At early stage, the main method for robotic assembly is model-based without sensor. A typical work is proposed by Xiao [1]. Considering the control parameters and manufacturing errors, the re-planning strategy has been developed with the motion constraints to guarantee the success of peg-in-hole tasks [2].

However in unstructured environment, the model-based method cannot accomplish the assembly task. As a result, an alternative is applied by multi-sensors. In [3], involvement of many different sensors is realized to improve the robustness, flexibility and performance of common robot assembly. This method is feasible and yields a good performance. There are some other related work in robotic assembly area. Readers are suggested to refer [4] for a complete review of intelligent assembly.

With the assembly tasks becoming more complex, a new approach is applied by learning from human. Up to date, researches about artificial intelligence and neural network have achieved great development. A new method is developed in an assembly task by learning from a human teacher to get the desired direction and compliant axis for an impedance controller [5]. A graphical user interface is designed so that the programmed robot can extract a relational plan by learning from demonstration, feedback and knowledge transfer [6]. It's convenient for user to reset task plan and the geometrical knowledge. A learning-from-demonstration approach is used for motion planning to accomplish assembly task in a structured environment [7]. A new concept human-in-the-loop teaching robot how to solve assembly tasks is proposed to involve interaction with environment [8].

In general, compliant motion plays an important role for successfully assembly when robot interacts with the environment or human. In this aspect, some methods presented to solve this problem show some different advantages. A review of the basic compliant control and solutions in the case of human-robot interaction is presented in [9]. A force-controlled assembly task is achieved by detecting transients in force/torque data [10]. Compliant motion planning and control are designed to overcome position and motion uncertainty during assembly task of mating surface of two parts [11].

To avoid the problem of jamming and collision during the assembly process, it is important to measure the position of robot and workpieces. One way is compliant control. A compliant control approach has been successfully implemented on industrial system [12]. Crossed with biological disciplines, it comes up with a concept of compliance for assembly with biomechanism [13]. The other way is compliant mechanism design. A solution considering compliance for extremely small clearance is proposed using an RCC(remote center compliance) [14].

In this paper, we propose a human-inspired compliant

[1]Xiaoqing Li is with School of Automation and Electrical Engineering, University of Science and Technology Beijing, 100083 Beijing, China xq_li@xs.ustb.edu.cn

[2]Rui Li is with Institute of Automation, Chinese Academy of Sciences, 100190 Beijing, China lirui2013@ia.ac.cn

[2]Hong Qiao is with Institute of Automation, Chinese Academy of Sciences, 100190 Beijing, China hong.qiao@ia.ac.cn

[3]Hong Qiao is with CAS Center for Excellence in Brain Science and Intelligence Technology, 200031 Shanghai, China

[4]Hong Qiao is with University of Chinese Academy of Sciences, 100049 Beijing, China

[1]Chao Ma is with School of Automation and Electrical Engineering, University of Science and Technology Beijing, 100083 Beijing, China cma@ustb.edu.cn

[5]Liang Li is with Beijing Institute of Spacecraft System Engineering, 100094 Beijing, China 501liliang501@sohu.com

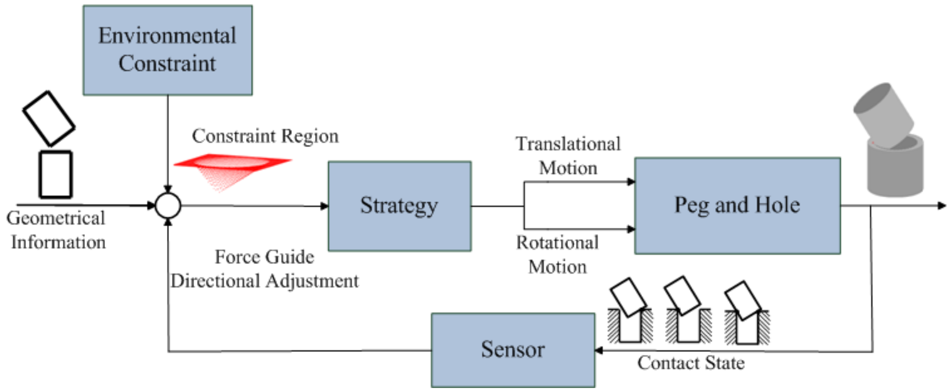

Fig. 1. Framework of peg-in-hole assembly strategy using environmental constraint and coarse force information

strategy that utilizes the environmental constraint and coarse force information for assembly task, as shown in Fig. 1. In peg-in-hole assembly, the position and orientation of the peg and the contact force are measured. The constraint region is used for motion planning. The coarse force information is used to guide a directional adjustment of the peg. After a stable contact, an orientation adjustment is executed by human-inspired compliant operation mechanism that rotates the peg form coarse to fine until aligned with the hole. Finally, the strategy is studied by simulation with the round peg and hole.

In Section II we explain the model used for assembly and analyze the constraint region and contact state. In Section III we address our strategy and introduce a framework of our strategy for assembly. Next, experiment is carried out in simulation and shows the process of assembly in Section IV. Finally, the results are discussed in Section V.

II. Modeling and Analysis of peg-in-hole

To achieve high precision assembly task, one important factor is the state of the peg that has a direct impact on successful assembly. The other is the contact force between the peg and hole. Also a compliant method is applied to adjust the peg when the peg and hole is stably contacted. Our method is developed form these three aspects to analyze the peg-in-hole assembly.

A. Geometrical analysis of peg-in-hole

To analyze the state of the peg and hole in the process of assembly, firstly a coordination of the system based on geometrical information is established, as shown in Fig. 2. The original point O_h of the coordinate is defined as the center of the upper surface of the round hole. The axis O_hZ_h is along the hole axis upward. The axis O_hX_h is fixed on the line form O_h to the base of robot. The axis O_hY_h is perpendicular to O_hZ_h and O_hX_h and satisfies the right-hand rule with them.

Then, in the defined coordination based on the hole, the peg can be described as follows:

$$O_p = (x, y, z, \theta_x, \theta_y, \theta_z) \in C^6 \quad (1)$$

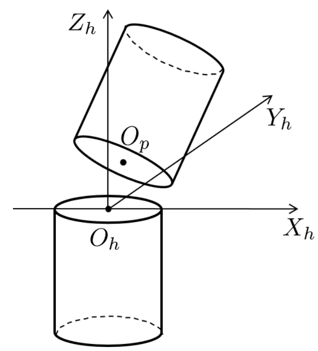

Fig. 2. The coordination of the peg and hole

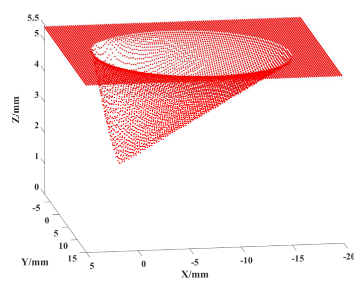

Fig. 3. The constraint region formed by the hole

The O_p is the center of the lower surface of the round peg and clarifies the peg's characteristics. This means that the parameters of O_p are settled, the peg is completely motionless. The first three parameters (x, y, z) describe the position of the peg in the coordination, and the last three parameters $(\theta_x, \theta_y, \theta_z)$ describe the orientation of the peg. Simply, let $x = |O_pO_h|_x$, $y = |O_pO_h|_y$, and $z = |O_pO_h|_z$. If the orientation of the peg is fixed, the motion of the peg can be described as follows:

$$P_{peg} = (x, y, z) \in C^3 \quad (2)$$

As illustrated in Fig. 3, the constraint region like a bowl formed by the edge of the hole is first called as ARIE(attractive region in environment) [15], [16]. The ARIE has been found in many kinds of robotic operations, such as localization, assembly and grasping [17]. The constraint region shows the range of the peg movement.

It has been proven that the lowest point of the constraint region is the stable state for round peg and round hole assembly associating with the fixed orientation [17]. That is to say, wherever the start position of the peg is, the final position is definite if the orientation is fixed. For better understanding, like a bean in a bowl, no matter where the bean is, the bean will finally be stable at the bottom of the bowl under the force of friction and gravity.

It turns out that the constraint region can reduce the uncertainty of the peg. Since if there exit small errors about the start position of the peg, the final state of the peg will be the same, which is the lowest point of the constraint region. Consequently, the operation precision of the round peg and hole assembly can be improved by means of the constraint region formed by the hole. In general, the attractive region in environment has a good advantage in cutting down the uncertainty of the system and improving the operation precision.

B. Contact model of peg and hole

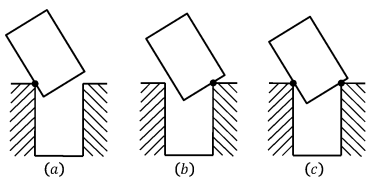

Fig. 4. The Contact model of round peg and hole during the insertion (a)One point contact model; (b)Two points contact model; (c) Three points contact model.

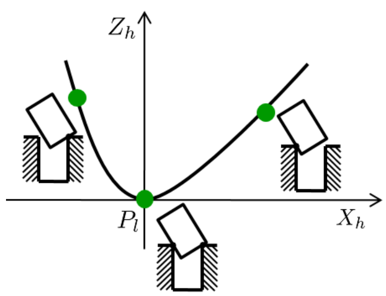

Fig. 5. The relationship between the constraint region and the contact model

When the peg moves in the range of hole, contacts may happen. As shown in Fig. 4, there are three typical contacts models during the insertion of round peg and hole. For one contact, the side line of the peg touches the edge of upper surface of the hole, as shown in Fig. $4(a)$. It seems that in Fig. $4(b)$ there is a one point contact, but there exists another point that is behind of the view. Because of symmetry, the edge of the lower surface of the round peg is crossed with the edge of the upper surface of the round hole and there are two contact points. In Fig. $4(c)$, there are three contact points.

It is worth saying that the constraint region has a close relationship with the contact of the round peg and hole, as shown in Fig. 5. The curve is one edge of the constraint region surface and P_l is defined as the lowest point of the curve. The points above the curve mean no contact. Furthermore, the points on the curve except P_l have two conditions, one point contact or two points contact. There exists and only exists a three points contact at the point of P_l, which is also the lowest point of the constraint region.

C. A direction adjustment by coarse force information

During the inserting process, the state of the peg is always changing. If it is not planned or sensed, the assembly task cannot be accomplished. And damages to robot or workpiece may happen. As a consequence, using sensors to sense the peg state and guide the robotic assembly becomes an effective way.

However, a high accuracy sensor is of high-cost, leading to much higher cost of the system. To solve this problem, an effective strategy has been developed. Using coarse force information and environment constraint, it turns out that high precision assembly task can be achieved.

The radius of the peg and hole, defined as R_p and R_h respectively, have a very small clearance. The $\overrightarrow{i} = (1,0,0)$ and $\overrightarrow{j} = (0,1,0)$ are defined as the positive unit vector of axis O_hX_h and O_hY_h. If any point on the peg $(x^{'}, y^{'})$ satisfies $x^{'2} + y^{'2} = R^2$, then a contact between the peg and the hole happens. And the relationship between contact force and contact position is analyzed as follows:

i) One point contact.

- If the contact point is on the side surface of the peg, like the situation in Fig. $4(a)$, the force is parallel to the vector $\overrightarrow{P_aO_p}$. P_a is the lowest point of the peg lower surface. Thus the unit contact force is that:

$$\overrightarrow{f_u} = \overrightarrow{P_aO_p} / \left|\overrightarrow{P_aO_p}\right| \tag{3}$$

- If the contact point is on the edge of the lower surface of the round peg, the force will be on the line form the contact point P_b to the O_h. Thus the unit contact force is that:

$$\overrightarrow{f_u} = \overrightarrow{P_bO_h} / \left|\overrightarrow{P_bO_h}\right| \tag{4}$$

ii) Two points contact.

- If the two contact points are both on edge of the peg lower surface, like the situation in Fig. $4(b)$, the force is parallel to the $\overrightarrow{n_p}$, which is a unit vector up along the axis of peg. Thus the unit contact force is that:

$$\overrightarrow{f_u} = \overrightarrow{n_p} \tag{5}$$

- If one contact point is on the side surface of the peg and another point P_c is on edge of the peg lower surface, the contact force is the sum of both. Thus the unit force is that:

$$\overrightarrow{f_u} = (\overrightarrow{P_aO_p} + \overrightarrow{P_cO_h}) / \left|\overrightarrow{P_aO_p} + \overrightarrow{P_cO_h}\right| \tag{6}$$

iii) Three points contact. With the orientation fixed, the three points contact means that the peg and the hole system is stable. It has reached the lowest point in the constraint region and the peg can not go down any more. The sum force of the peg is that

$$\overrightarrow{f_{sum}} = 0 \tag{7}$$

In all, for both one point contact and two points contact, the direction adjustment of the position of the peg is guided by coarse force sensor. During the insertion, the force in the horizontal plane helps to slide the peg to achieve a three points contact, while the force in the direction of axis O_hZ_h helps to balance the force downward. So the position adjustment is designed as follows:

$$\delta x = \overrightarrow{f_u} \cdot \overrightarrow{i} = \overrightarrow{f_{ux}} \tag{8}$$

$$\delta y = \overrightarrow{f_u} \cdot \overrightarrow{j} = \overrightarrow{f_{uy}} \tag{9}$$

Based on the unit contact force $\overrightarrow{f_u}$, the δx means the contact force along axis O_hX_h, and the δy means the contact force along axis O_hY_h.

At three points contact, the adjustment of the orientation of the peg is a human-inspired compliant operation. The orientation adjustment is from large to small, which is related to the extent of angles θ_x, θ_y. If the center axis of the peg is far from the axis O_hZ_h, the orientation adjustment is large. If the center axis of the peg almost coincides with the axis O_hZ_h, the orientation adjustment is small. To illustrate this mechanism, a orientation adjustment function is designed as follows:

$$\delta\theta_x = g(\theta_x), \theta_x \in (-\pi/2, \pi/2) \tag{10}$$

$$\delta\theta_y = g(\theta_y), \theta_y \in (-\pi/2, \pi/2) \tag{11}$$

where the function $g(x)$ has a positive correlation with $|x|$ when $x \in (-\pi/2, \pi/2)$.

III. Strategy for Peg-in-Hole assembly

Our strategy is motivated by human manipulation. Let us think a man handles the peg in a hole: 1)First, it is usually that he finds the hole position by eyes and sets the peg an appropriate angle with the hole at the start position. 2)Then he puts down the peg and makes the peg touch the hole. 3)And the next step is to align the peg with the hole, a compliant orientation adjustment is carried out from coarse to fine. All the insertion process he always sees the contact of peg and hole, feels the force and makes small adjustment. In this way, a human can perform high precision assembly although the precision of the arm and hand is not comparable with a common industrial robot. By analyzing the human performance, process compliance is regarded as the key characteristic in their assembly operation.

For the robotic assembly, an integrated strategy using environmental constraint and coarse force information is designed. Depending on constraint region, there is always a lowest point of the region that is the position of three points contact with the orientation of the peg fixed. At the insertion stage, the coarse force sensor is used to sense the contact force of the peg and hole. Only a force guided directional adjustment is needed that can ensure the peg reach the lowest point of the region. When the peg reaches the three points contact, an orientation adjustment is carried out by human-inspired compliant operation.

The framework of our strategy for peg-in-hole assembly is shown in Fig. 1. The strategy seems as a controller for the assembly system. The peg and hole are the controlled objects. And the sensor provides the feedback of the state of the peg and hole. The input of the system is the geometrical information of the peg and hole. The constraint region is formed by the hole. And coarse force sensor will guide a directional adjustment corresponding to different contact states. The output of the strategy is the motion of translation or rotation. The framework can also work with a wide range of other parts assembly.

Algorithm 1 Strategy for round peg-in-hole assembly task

Input: The parameters of the round peg and round hole, the radius R_p and R_h and length L;
The coarse force during insertion f_u;
Output: The constraint region [20] formed by the hole;
The adjustment at different contact state δx, δy, $\delta\theta_x$, $\delta\theta_y$;

Initialize the parameters of the peg and hole, and fix the orientation of the peg $(\theta_x, \theta_y, \theta_z)$;
Design the constraint region $(x, y, z) \in C^3$, in Fig. 3;
With the fixed $(\theta_x, \theta_y, \theta_z)$, let the peg go down with a start position in the constraint region;
if the peg contacts the hole but not stable **then**
  get the unit contact force by sensor $\overrightarrow{f_u}$;
  make directional adjustment by coarse force information: $\delta x = \overrightarrow{f_{ux}}$, $\delta y = \overrightarrow{f_{uy}}$;
end if
if three points contact of peg and hole **then**
  make the orientation adjustment: $\delta\theta_x = -sin(\theta_x)$, $\delta\theta_y = -sin(\theta_y)$
end if
The peg axis is almost aligned with the hole axis and the fore is quite small, smoothly will the peg be assembled in the hole.

IV. Experiment

Assembly of an object from various parts is one of the common industrial task and plays an important role in industry production. Peg-in-hole is an common example of robotic assembly task that has been studied in the [18]-[20]. Different from learning from human demonstration, this human-inspired compliant strategy is to imitate the mechanism of human compliant motion. Generally, the repeatability of industrial robot is ± 0.08 mm. While the clearance of the peg and hole is within 0.05 mm. To solve the above problem, a human-inspired compliant strategy is designed for industrial robot with coarse sensor system to achieve high precision assembly. As shown in Algorithm 1, the strategy is illustrated the main process of the assembly.

The assembly process is carried out in MATLAB. At first stage, a coordination is established to analyze the position

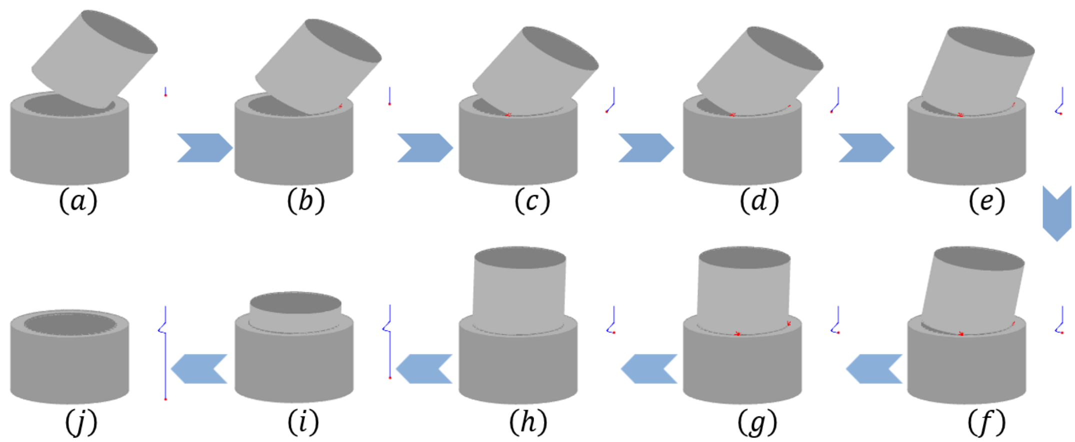

Fig. 6. Results of the states of round peg and hole in assembly experiment. The contact points of the peg and hole are marked (red points). And the solid line (blue) on the right side of each state is the trajectory of the center point of the peg, on which a point (red) represents the current position. There are ten typical states of the assembly and the blue square arrows show the process of assembly.

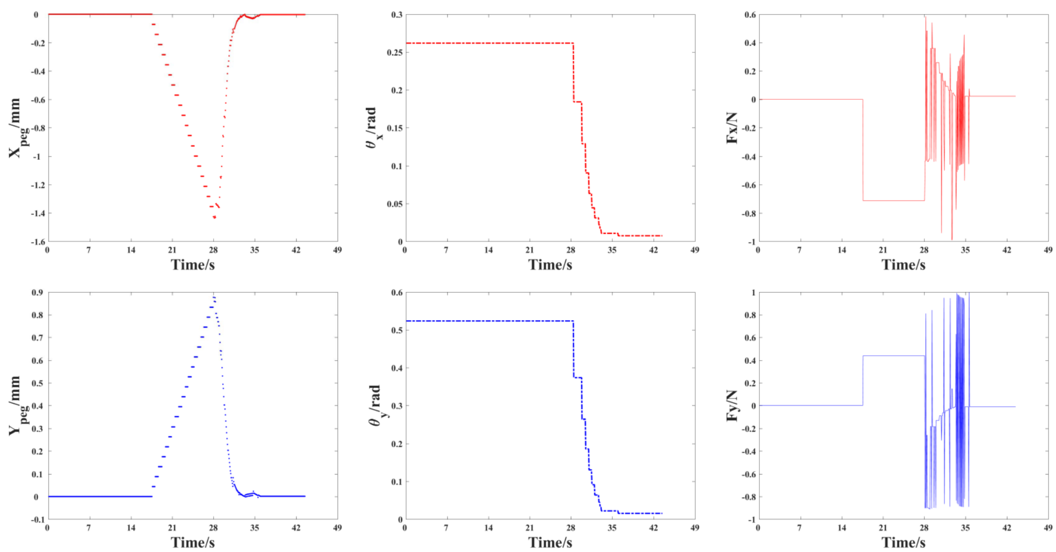

Fig. 7. Results of the assembly task execution with respect to simulation time. The two graphs in the left column show the measured x and y position of the peg. The two graphs in the middle column show the measured orientation θ_x and θ_y of the peg. The two graphs in the right column show the contact force along x-axis and y-axis.

and pose of the peg based on the initial geometric information, as shown in Fig. 2. The radius of the peg is $R_p = 10.00$ mm and the radius of the hole is $R_h = 10.01$ mm. The length of the peg and hole $L = 20.00$ mm. The orientation of the peg is set as $(\pi/12, \pi/6, 0)$. Let the peg go down and it will face the contact with the hole. During the insertion, the position and orientation of the peg can be calculated by each simulation step. Based on the measurement of the peg, the contact points can be calculated so that the force measurement is obtained. By the constraint region as shown in Fig. 3, a solution to push the peg and reach a three points contact can be worked out.

To illustrate the effectiveness of our strategy, a dynamic simulation of round peg and hole assembly is carried out. In our strategy, the coarse force information is used to guide a directional adjustment during the insertion. And an orientation adjustment inspired by human compliant operation is carried out after three points contacr, as described in Section II-C. The function is defined as $g(\theta_x) = -ksin(\theta_x)$ and $g(\theta_y) = -ksin(\theta_y)$, in which the k is a constant. So the orientation adjustment can be calculated by:

$$\delta\theta_x = -ksin(\theta_x), \theta_x \in (-\pi/2, \pi/2) \tag{12}$$

$$\delta\theta_y = -ksin(\theta_y), \theta_y \in (-\pi/2, \pi/2) \tag{13}$$

Fig. 6 shows the process of peg-in-hole assembly. The ten different typical states show the peg and hole position and orientation during the assembly. The solid line (blue) at the right side of each state shows the trajectory of the center point of the peg, with a point (red) showing the current position of the center point of the peg. On the condition of the start orientation $(\pi/12, \pi/6, 0)$, a feasible start position is provided by the constraint region established at the first stage shown as state (a). Next, push the peg down and sense if the peg contacts the hole. The state (b) is a one point contact and the state (c) is a two points contact. It is worth mentioning that the state (d) is a first three points contact. And The states (e), (f) and (g) are also three points contact. The final state (j) shows the final successfully assembly of peg and hole.

The results of the assembly task execution with respect to simulation time are demonstrated in Fig. 7. The position of x and y is recorded in the left column. It is obvious that a max distance form x-axis and y-axis arrives at the same time, which results the state (d) in Fig. 6. The special point is corresponding to a three points contact. The two graphs in the middle column show the orientation of x-axis and y-axis. At first the orientation is set $\theta_x = \pi/12$, $\theta_y = \pi/6$ and $\theta_z = 0$. Because of the shape of round peg and hole, the θ_z can not effect the real pose of the peg. The curve of θ_x illustrates that the orientation adjustment is positive correlative to the measurement of $|\theta_x|$, so is the curve of θ_y. The right column of the Fig. 7 shows the force during the assembly process. The contact force sensed by coarse force sensor is simulated and modeled by Equation $(3) - (7)$. If $f_x \neq 0$ or $f_y \neq 0$, it means that there is a contact between the peg and hole. And depending on the modeled force, it is known that $f_x^2 + f_y^2 = 1$. Therefore, a coarse force is used to guide a directional adjustment. Finally, the peg is successfully assembled by the designed strategy.

The experimental results show that the coarse force sensor guided directional adjustment works well, which add robustness and flexibility of the system. And inspired by human operation, a compliant operation is carried out without jamming and damaging to the assembly parts. The results show the effectiveness and advantages of our designed strategy for high precision assembly.

V. CONCLUSIONS

This paper introduces a new strategy for fine robotic assembly tasks using low precision system. We have presented a framework of the strategy with constraint region and force guided directional adjustment. Round peg and hole is addressed as an illustration for a wide set of assembly process. The proposed strategy can handle a wide range of peg and hole tasks without modifying the framework. The hole is considered as an environmental constraint to the peg and the constraint region is designed for motion planning. Some errors about the start position of the peg can be eliminated by the constraint region. And the coarse force information is used for directional adjustment no matter how much the force size is. This approach adds the robustness of the system. And the orientation adjustment is inspired the process of human assembly form coarse to fine that conducts a compliant motion. Finally, our proposed strategy is carried out on round peg and hole assembly simulation and found to be successful.

REFERENCES

[1] J. Xiao and R. A. Voltz, Design and motion constraints of part-mating planning in the presence of uncertainties, In Proc. of 1988 IEEE International Conference on Robotics and Automation, pp. 1260-1268, 1988.

[2] J. Xiao and R. A. Volz, On replanning for assembly tasks using robots in the presence of uncertainties, Proceedings, In Proc. of 1989 International Conference on Robotics and Automation, pp. 638-645, 1989.

[3] S. Jorg, J. Langwald, J. Stelter, G. Hirzinger and C. Natale, Flexible robot-assembly using a multi-sensory approach, In Proc. of 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings, pp. 3687-3694, 2000.

[4] W. S. Newman, M. Branicky, Y. H. Pao, et al. Intelligent strategies for compliant robotic assembly,In Proc. of 11th Yale Workshop on Adaptive and Learning Systems, pp. 139-146, 2001.

[5] M. Suomalainen and V. Kyrki, Learning compliant assembly motions from demonstration, In Proc. of 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 871-876, 2016.

[6] Y. Mollard, T. Munzer, A. Baisero, M. Toussaint and M. Lopes Robot programming from demonstration, feedback and transfer, In Proc. of 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1825-1831, 2015.

[7] C. Paxton, F. Jonathan, M. Kobilarov, and G. D. Hager, Do what I want, not what I did: Imitation of skills by planning sequences of actions, In Proc. of 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3778-3785, 2016.

[8] L. Peternel, T. Petric, and J. Babic, Human-in-the-loop approach for teaching robot assembly tasks using impedance control interface, In Proc. of 2015 IEEE International Conference on Robotics and Automation, pp. 1497-1502, 2015.

[9] A. Calanca, R. Muradore, and P. Fiorini, A Review of Algorithms for Compliant Control of Stiff and Fixed-Compliance Robots, IEEE/ASME Transactions on Mechatronics, vol. 21, no. 2, pp. 613-624, 2016.

[10] A. Stolt, M. Linderoth, A. Robertsson, and R. Johansson, Detection of contact force transients in robotic assembly, In Proc. of 2015 IEEE International Conference on Robotics and Automation, pp. 962-968, 2015.

[11] A. Saric, J. Xiao, and J. Shi, Robotic surface assembly via contact state transitions, In Proc. of 2013 IEEE International Conference on Automation Science and Engineering, pp. 954-959,2013.

[12] F. Suarez-Ruiz and Q.-C. Pham, A framework for fine robotic assembly, In Proc. of 2016 IEEE International Conference on Robotics and Automation, pp.421-426, 2016.

[13] R. Li, W. Wu, and H. Qiao, The compliance of robotic hand-from functionality to mechanism, Assembly Automation, vol. 35, no. 3, pp. 281C286, 2015.

[14] H. Park, P. K. Kim, J.H. Bae, et al. Dual arm peg-in-hole assembly with a programmed compliant system, In Proc. of 2014 11th International Conference on Ubiquitous Robots and Ambient Intelligence, pp. 431-433, 2014.

[15] H. Qiao, Attractive regions formed by the environment in configuration space: The possibility of achieving high precision sensorless manipulation in production, International Journal of Production Research, vol. 40, no. 4, pp. 975C1002, 2002.

[16] Hong Qiao, Application of generalized attractive region in orienting 3D polyhedral part, In Proc. of 2003 IEEE International Conference on Robotics and Automation, pp. 2248-2254, 2003

[17] H. Qiao, M. Wang, J. Su, S. Jia, and R. Li, The Concept of "Attractive Region in Environment" and its Application in High-Precision Tasks With Low-Precision Systems, IEEE/ASME Transactions on Mechatronics, vol. 20, no. 5, pp. 2311C2327, 2015.

[18] F. Dietrich, D. Buchholz, F. Wobbe, et al. On contact models for assembly tasks: Experimental investigation beyond the peg-in-hole problem on the example of force-torque maps, In Proc. of 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2313-2318, 2010.

[19] Seung-kook Yun, Compliant manipulation for peg-in-hole: Is passive compliance a key to learn contact motion?, 2008 IEEE International Conference on Robotics and Automation, pp. 1647-1652, 2008.

[20] Hyeonjun Park, Ji-Hun Bae, Jae-Han Park, Moon-Hong Baeg, and Jaeheung Park, Intuitive peg-in-hole assembly strategy with a compliant manipulator, In Proc. of 2013 44th International Symposium on Robotics, 2013.