Robotic Soft Servo for Industrial High Precision Assembly

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***Abstract*—Industrial robots can be made compliant to the environment when the control loop gains are reduced, creating a so-called "soft servo" capability. This allows industrial robots to be used for assemblies with limited contact requirements. In this paper, we propose an assembly method using soft servo to perform certain assembly tasks where part location errors typically require the use of force control or Remote Center of Compliance (RCC) methods. A typical industrial application, valve body assembly, was used to validate the developed method. This assembly was chosen because it is simple, yet requires compliance in all directions. Lab experiments were performed and the assembly operations were consistently successful enough to show that the developed soft servo strategy can perform certain assembly tasks with small part location errors. Therefore, the soft servo strategy may open a new door for low cost industrial assembly.**

Experiments with force control were also performed to compare the performance between soft servo and force control. We found that the force control method is much more sensitive to environmental contact, that the contact forces can be controlled directly and that greater part location errors can be tolerated. Conversely, assembly with soft servo may either fail to assemble the parts or generate bigger contact forces than allowed. Thus, applications of soft servo are more limited while force control can be successfully used in most all applications. Further investigation is needed to determine the practical industrial use of soft servo for particular types of precision assembly.

***Keywords*— Industrial Robot, Soft servo, High precision assembly, force control**

I. INTRODUCTION

Assembly tasks using industrial robots have increased both in number and complexity over the years. Tight tolerance assembly that is also high precision assembly is difficult even for manual assembly. Figure 1 demonstrates an example of tight tolerance assembly, where an accumulator is inserted into a hole in the valve body of an automatic transmission system.

The valve body is the control center of an automatic transmission. It contains a maze of channels and passages that direct hydraulic fluid to the accumulators and valves that then activate the appropriate clutch pack or band servo to smoothly shift to the appropriate gear for each driving situation. The radius of the accumulator is about 24.96 mm while the radius of the hole in the valve body is 25.00 mm with a tolerance about 40 μm. With such a small tolerance, it is almost impossible to assemble it using traditional assembly methods because traditional industrial robots are so stiff that even small position or orientation errors will cause the tight tolerance assembly to fail. Figure 2 is the illustration of the tight tolerance assembly process.

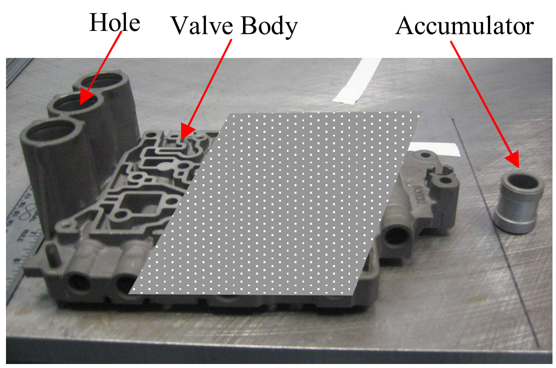

Figure 1. The accumulator and valve body in an automotive transmission. The accumulator is inserted into the hole on the valve body. The radius of the accumulator is 24.96 mm and the inside radius of the hole on the valve body is 25.00 mm with the tolerance about 40 μm. Part of the valve body is blocked.

Because of the fixture errors, the accumulator can not be aligned with the holes on the valve body exactly. Therefore, the accumulator can be stuck at the surface of the valve body due to the positioning errors or in the middle of the valve body due to the orientation errors due to the stiffness of the industrial robots in position control mode. Both cases will cause the assembly to fail. Therefore, more advanced methodologies have to be developed to perform such a tight tolerance assembly.

Several methods have been developed to perform precision assemblies to reduce the design efforts and cost of fixtures that are typically required by such highly accurate robotic assembly applications. The passive compliance device or Remote Center Compliance (RCC) is an example that allows an assembly robot to compensate for positioning errors due to machine inaccuracy, vibration or tolerance, thereby lowering contact forces and avoiding part and tool damage.

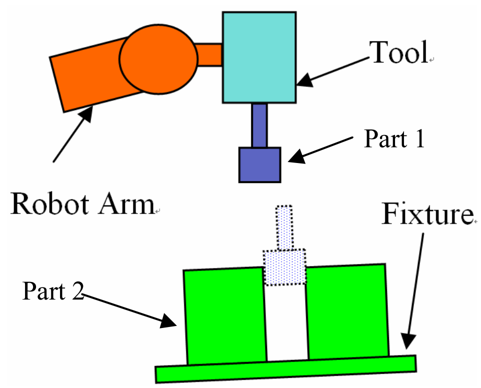

Figure 2. The tight tolerance assembly in a semi-structured environment.

There are many research works [1, 2, 3] done using the passive compliance device for assembly or other tasks. However, specific passive compliance devices have to be designed and manufactured for parts with different geometries, which makes robotic assembly with passive compliance devices more difficult. Also, these devices are expensive to design and manufacture. To overcome the shortcomings of the passive compliance devices, robotic assembly using force control [4, 5, 6] was then developed. A force/torque sensor is used to measure the contact force/torque and the force/torque signals are used to control the motion of the assembly tool. Since the force/torque control is sensitive to contact with the environment, the tool position/orientation can be accurately controlled. This makes the force controlled assembly a good solution for robotic assembly. There are many successful stories about robotic force controlled assembly, such as the forward clutch, torque converter and valve body assemblies, in industrial implementations [7, 8, 9, 10]. The position and orientation errors due to the part fixture or location errors can be easily compensated using the force control strategy. Therefore, the force control method can greatly reduce the requirements of the part fixtures. Moreover, it can be used for high precision or tight tolerance assemblies. However, the force control method requires extra devices, such as the force/torque sensors and control software package etc, which can make the robot control system more complicated and more expensive. Therefore, a simpler compliant robot control methodology was developed to perform high precision industrial assembly that does not require extra equipment or cost yet can be successfully utilized in many cases.

Position control of industrial robots is very accurate when done with high controller gains. However, contact forces increase rapidly when the robot tooling makes a contact with the environment, making industrial robots difficult to use when limited contact force is needed in high precision assemblies. By reducing the robot control loop gains, the servos can make the robot compliant to the environment, creating a so-called “soft servo” capability. In this paper, we propose an assembly method using soft servo to perform high precision assembly tasks where part location errors typically require the use of Force Control or RCC methods. The valve body assembly was used to validate the developed method. Robotic assemblies using both soft servo and force control were performed to compare their performances.

II. SOFT SERVO AND FORCE CONTROL

A. *High Precision Assembly Process*

A high precision robotic assembly requires a robot to perform assemblies in which the assembly tolerance is better than the robots repeatability. Figure 3 shows a typical method used for high precision assemblies. A searching method is used to find the exact location of the workpiece. After the part is engaged with the workpiece, an insertion force is applied to insert the part into the workpiece. During insertion, the tool orientation is changed according to the orientation of the workpiece to avoid sticking. Therefore, any developed assembly method needs to be able to locate the workpiece accurately and adjust the tool orientation accordingly.

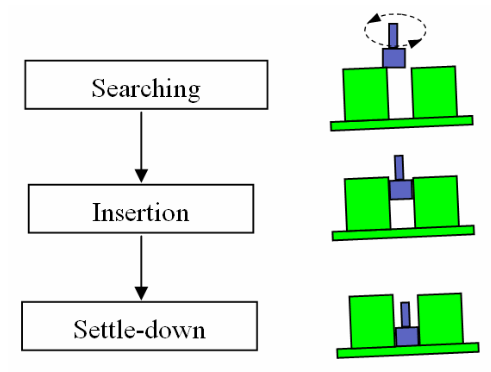

Figure 3. The assembly process for high precision assemblies.

B. *Soft Servo Control System*

Consider a rigid manipulator of n links, the dynamic equation of motion in the joint space is:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + B(q,\dot{q}) + G(q) = \tau \qquad (1)$$

Where,

$\tau \in R^n$ vector of applied joint torques,

$q \in R^n$ vector of joint positions,

$M \in R^n$ symmetric positive definite (SPD) manipulator inertia matrix,

$C \in R^n$ vector of Coriolis and centrifugal torques,

$B \in R^n$ vector of torques due to friction acting on the manipulator joints,

$G \in R^n$ vector of gravitational torques.

When there is an external force applied to the robot end-effector, the dynamic equation (1) becomes,

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + B(q,\dot{q}) + G(q) + \tau_e = \tau \quad (2)$$

Where,

$\tau_e \in R^n$ vector of forces/torques exerted on the environment by the manipulator end-effector expressed in the joint space.

For model based control, the model parameters are estimated. Suppose the estimated corresponding parameters are $\hat{M}(q)$, $\hat{C}(q,\dot{q})$, $\hat{B}(q,\dot{q})$ and $\hat{G}(q)$ respectively, a typical feed forward PD (Proportional plus Derivative) controller can be expressed as:

$$\tau = \hat{M}(q)\ddot{q}_d + \hat{C}(q,\dot{q})\dot{q}_d + \hat{B}(q,\dot{q}) + \hat{G}(q) + K_p e_q + K_v \dot{e}_q \quad (3)$$

Where,

$e_p, \dot{e}_p \in R^n$ vectors of position and velocity errors in the joint space.

Comparing equations (2) and (3), we have

$$\tau_e = K_p e_q + K_v \dot{e}_q + \Delta\tau \quad (4)$$

Where

$\Delta\tau \in R^n$ vector of forces/torques errors generated by the model estimation error.

Assuming $\Delta\tau$ is small, the position and velocity errors will balance the external forces/torques exerted on the robot end-effector. Therefore, by decreasing the position control loop gains, the robot position errors could be increased to make the robot compliant to the environment. Since the gains for each joint are tuned individually, this is called joint soft servo. One of the advantages of joint soft servo is that the orientation of the tool can be adjusted due to the compliance of each joint. Therefore, the tool position and orientation can be continuously changed based on the contact with the environment.

The overall control system flow with soft servo is shown in Figure 4.

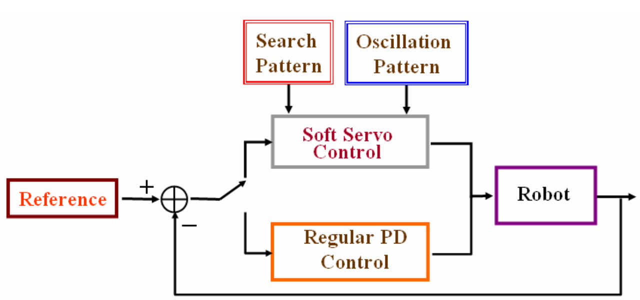

Figure 4. The controller for the robotics system with soft servo.

There is a switch to select the regular high gain position control and soft servo control. In the normal position control loop, the regular high gain position control is used. For soft servo control, the search pattern and oscillation patterns are implemented in order to perform high precision assemblies.

Since the robotic high precision assembly requires a robot to perform assemblies in which the assembly tolerance is better than the robot repeatability, a search pattern has to be implemented in order to compensate for the part positioning errors. A spiral search pattern is used in the X and Y searching directions.

$$x = R\sin\alpha\sin\beta$$
$$y = R\sin\alpha\cos\beta \quad (5)$$

The search pattern is shown in Figure 5.

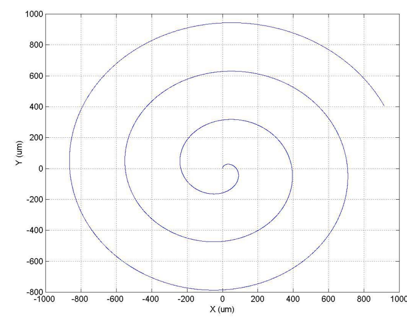

Figure 5. A spiral search pattern to find the exact position for tight tolerance assembly. The units are μm.

For the Z direction, which is the insertion direction, a certain contact force has to be maintained in the insertion assembly process. To achieve this, a constant error along the Z axis is maintained.

$$F = K_{pz}\Delta z \quad (6)$$

Where K_{pz} is the proportional gain along the Z axis and Δz is the set error along the Z axis. These two values should be tuned such that the contact force can be maintained in a certain range.

Since the inserted part may become stuck during the assembly, an oscillation is added to the Z direction to keep the part from sticking.

$$\Delta z_s = d_z \sin w_s t \quad (7)$$

Where Δz_s is the positioning oscillation along the Z-axis; d_z and w_s are the oscillation amplitude and frequency respectively.

C. *Force Control*

The force controlled assembly method is more typically used to perform high precision assembly in industrial applications [7, 8, 9, 10]. In this paper, the force control was developed and implemented in the robot tool frame. The measured force/torque is directly used to change the tool velocity as shown in equation (8).

$$\dot{X} = KF \quad \text{i.e.,}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} k_x & 0 & 0 & 0 & 0 & 0 \\ 0 & k_y & 0 & 0 & 0 & 0 \\ 0 & 0 & k_z & 0 & 0 & 0 \\ 0 & 0 & 0 & k_\alpha & 0 & 0 \\ 0 & 0 & 0 & 0 & k_\beta & 0 \\ 0 & 0 & 0 & 0 & 0 & k_\gamma \end{bmatrix} \cdot \begin{bmatrix} F_x \\ F_y \\ F_z \\ \tau_\alpha \\ \tau_\beta \\ \tau_\gamma \end{bmatrix} \quad (8)$$

Where $\dot{X}$ is the tool velocity; K is the damping matrix and F is the contact force transferred into the tool frame.

Since the force control in the tool frame is decoupled using the damping matrix, the tool position and orientation are directly controlled by the force/torque sensed in the tool frame. The force control loop is shown in Figure 6.

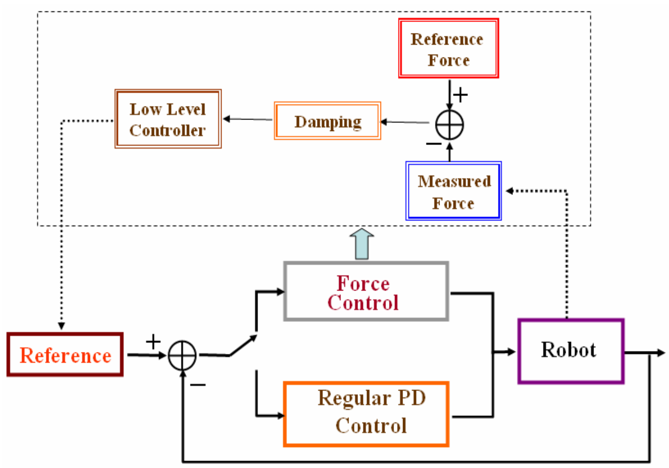

Figure 6. The force control system for the robotics system.

The force/torque measured in the sensor frame is transferred into the tool frame and used to control the motion of the tool by modifying the tool path reference. The search pattern shown in Figure 5 is also used to search the location of the workpiece.

III. Experimental Results

To demonstrate high precision assembly using soft servo, several experiments were performed. The assembly process using force control was also implemented to compare the assembly performance between soft servo and force control.

The valve body assembly, was implemented using an ABB IRB140 robot, which is mounted horizontally on a stand. The software for soft servo and force control was developed on ABB IRC5 controller. An ATI Delta force/torque sensor for force control was mounted on the robot end-effector and a suction tool used to pick up the accumulator was mounted under the force/torque sensor. The experimental system is shown in Figure 7.

The valve body was placed in a vise and, to demonstrate a generic assembly process, the assembly was performed along the horizontal direction. For the search process using the spiral pattern, the search radius was set to 1.5 mm and the number of turns to 4. For soft servo, the oscillation amplitude was set to 1 mm and the frequency to 3Hz. The settle-down point was set to be 20mm since there is no feedback available. For force control, the search force was set to be 20 N. For the insertion process, the spring force constant was set to 50N/mm and the settle-down force set to 50 N.

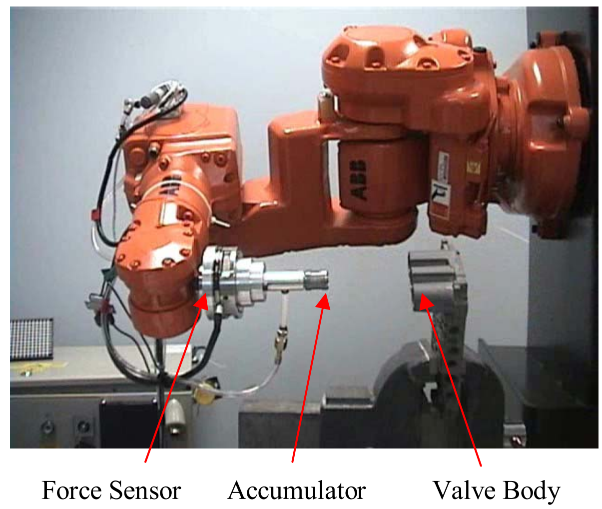

Figure 7. A high precision robotic assembly system. The suction tool picks up the accumulator and inserts it into the hole in the valve body. The robot controller is not shown in the figure.

A reference configuration was taught by inserting the accumulator into the valve body manually while the force control is active. The position and orientation are recorded as the reference position and orientation in the robot base frame. Therefore, there are no position and orientation errors if the reference position and orientation are used. However, since there are always fixture errors in a production line, errors were intentionally added to the X and Y axes as disturbance. To compare the performance between the soft servo and force control without bias, the errors are added along both positive and negative directions along the X and Y axes as shown in Table 1. For the assembly with different errors, the insertion time for both soft servo and force control is recorded in Table 1.

The data in Table 1 shows that the insertion time using force control is quite close to that using soft servo. Therefore, soft servo can be used to perform high precision assembly with cycle time comparable to that using force control. For larger errors (Both the X and Y axes have offsets), the insertion time is longer. This is because the searching time with big errors is longer. For soft servo, this is more obvious. And illustrates that soft servo control is not as sensitive as the force control.

TABLE I. THE POSITION OFFSET AND INSERTION TIME FOR BOTH SOFT SERVO (SS) AND FORCE CONTROL (FC)

Position offsetX	Position offset Y	Insertion time (SS)	Insertion time (FC)
1	0	3.72	3.17
1	0	3.75	3.17
-1	0	3.51	3.15
-1	0	3.53	3.17
0	1	3.80	3.21
0	1	3.82	3.11
0	-1	3.70	3.21
0	-1	3.64	3.20
1	1	4.1	3.20
1	-1	4.72	4.20
-1	-1	5.17	4.67
-1	1	6.30	4.53

Figure 8 shows the valve body assembly process. The accumulator is inserted into the valve body. Figure 9 shows there are offsets along both the X and Y directions in the tool frame before the searching method starts.

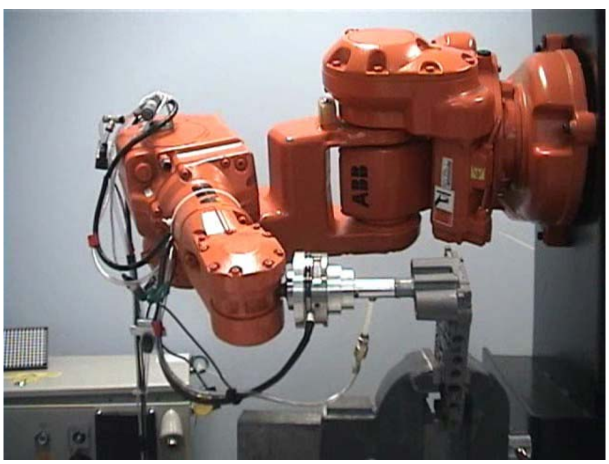

Figure 8. The valve body assembly process. The accumulator is inserted in to the valve body.

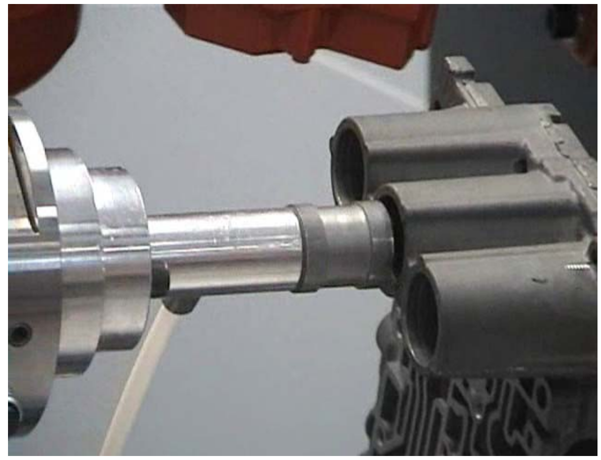

Figure 9. The valve body assembly process. There are offsets along both the X and Y axes.

The contact force signals for both the soft servo and force control were recorded and are shown in Figures 10 and 11 respectively.

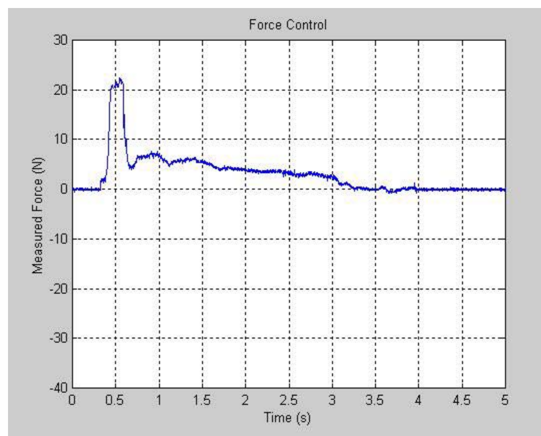

Figure 10. The recorded force signal for force controlled assembly.

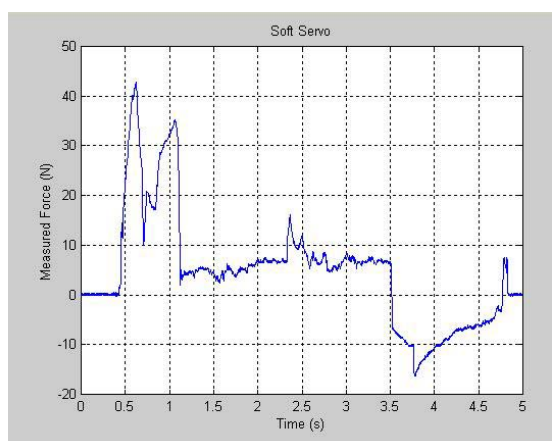

Figure 11. The recorded force signal for soft servo based assembly.

The recorded force signals in Figures 10 and 11 show that the contact force for both methods are reasonably close. For force control, the reference force is set to 20 N and the real force signals is quite close the reference force. Since there is no direct force control using soft servo, the contact force is indirectly controlled by the position offset. The recorded maximum force is about 40 N, which is reasonable for the valve body insertion assembly. Thus, soft servo techniques can be used for high precision assembly with reasonable performance compared with the force control method. However, the contact force signals are much more smooth using force control than that using soft servo. Also the retract force using force control is almost 0 while there is large retract force when using soft servo. This is because soft servo is still based on a position control loop and lower control gains still generate big contact force. The searching time is also much longer using soft servo than when using force control and searching using soft servo is not as smooth as that using force control.

Although soft servo can be used for high precision assemblies, there are some limitations. The parameters, such as controller gain and maintained contact force during assembly, have to be carefully tuned, otherwise the parts or the robotic system could be damaged if there was a jam during the insertion process. The main reason is that soft servo is not sensitive to the contact force since it is based on the position errors and not force measurement. Also, the assembly process using soft servo is not as smooth as that using force control and there can be large contact forces generated during assembly. The soft servo method is also not as stable as the force controlled method. While, it can be used to perform assemblies with small errors, if there are large offsets, it will likely fail and generate large contact forces. Because of these limitations, careful consideration of the intended system is needed before implementing soft servo in an industrial application even though the laboratory implementation looks promising.

Although there are some significant shortcomings for soft servo assembly methods with compliance in all directions, its performance can be quite close to that using force control, especially for small initial positioning errors and when using small robots. For large disturbances, a vision system could be used to compensate the workpiece location errors, but the added cost and complexity might be similar to just using force control.

IV. Conclusion

In this paper, we propose an assembly method using soft servo to perform assembly tasks where part location errors typically require the use of force control or Remote Center of Compliance (RCC) methods and the assembly process requires compliance in all directions. The proportional and derivative controller gains are reduced to make the robot compliant when performing the assembly tasks. A search algorithm is developed to find the location of a feature, such as a hole in a part. The tool is kept in contact with the part while search motion is performed. An oscillation motion is added along the contact direction whenever the contact friction is severe to prevent binding. Once the tool is engaged with the part, a measured relative mating position (e.g. insertion distance) is used to determine the completion of the assembly. A valve body assembly was used to validate the developed method. Experiments were consistently successful when the relative part location errors were within 1 mm, showing that the developed soft servo strategy can perform assembly tasks with small part location errors. Experiments with force control were also implemented to compare the performance between soft servo and force control. We found that force control methods are much more sensitive to environmental contact and the contact forces can be controlled directly. Conversely, we can not directly control the contact force when soft servo is used because it is passive to the contact. Therefore soft servo requires careful programming and tuning in order to reduce the contact forces, otherwise, damage could be caused to the products as well as the robotic system. Also, for bigger part location errors soft servo either fails to assemble the parts or generates bigger contact forces than force controlled assembly. Thus, applications of soft servo are more limited while force control can be successfully used in most all applications. Further investigation is needed to determine the practical industrial use of soft servo for particular types of precision assembly.

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