A ROBOT COMPLIANT WRIST SYSTEM FOR AUTOMATED ASSEMBLY

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ABSTRACT

A compliant wrist combining passive compliance and a displacement sensor has been developed for a robot manipulator to be used in assembly operations. The wrist provides the necessary flexibility to accommodate transitions as the robot makes contact with the workpiece, to correct positioning error, and to avoid high impact forces in automatic assembly. Sensing from the device makes it possible to actively control the contact forces or to compensate the positioning error during motion and contact. In this paper, the design features of two prototypes of the device are described. Using the device, a hybrid position force control scheme incorporating the passive compliance is presented. Application of the system in automated assembly is discussed. Two basic primitives in the assembly process, edge tracking and insertion operation with the compliant wrist are investigated. A fuzzy controller is presented to assign velocity instead of evaluating exact force zones in insertion. The experimental results show that the system provides a feasible and economical solution to the provision of necessary compliance in automated assembly and manufacturing.

1. INTRODUCTION

In manufacturing, especially in automated assembly, compliance is necessary to avoid high impact forces, correct the positioning error of robots or special tools, and to allow the relaxation of part tolerances. The compliance may be provided by passive compliance, such as the Remote Center of Compliance (RCC) [3] or in many of its other versions [10][12][16], or provided by active force control methods [8][9][11][12]. However, there are fundamental problems for both techniques when they are implemented in industry. Passive compliance may degrade the positioning capability of robot. Active compliance may present an instability problem in a stiff environment. Therefore, although various investigations to this research issue have been reported on recently [5][6][7], a simple, economical, and reliable method is still sought.

In this paper, we propose to use a passive compliance mechanism with a six degrees-of-freedom (DOF) compliance which is also capable of measuring the six DOF deflections within the device, that is, between the end-effector and robot wrist. Passive compliance can correct the position error automatically and accommodate the transition between the position and force control modes. The sensing from the device can be used for feedback control such that the entire system is controllable. Such a device, with both passive compliance and sensor, was developed in our laboratory. The passive compliance is constrained with rubber elements. The device is instrumented by providing a simple six joint serial linkage with potentiometer sensors at its joints. In the paper, two prototypes of the device are presented.

The sensing from the device is used in two ways. In position control, the sensed information is utilized to compensate deflection of the wrist, due to the load or external forces, in such a way as to increase the apparent stiffness of the manipulator wrist system. In force control, the wrist is used as a force sensor by which means the manipulator is driven in the same direction as the sensed force allowing the desired contact force to be maintained. Ultimately, these two control modes are executed concurrently and a hybrid position force control scheme is presented in the paper.

Application of such a system to automated assembly is possible. Based on the features of assembled parts, assembly operations may be represented by a small number of primitives, such as sliding, insertion, and screwing. The sliding action could occur in a plane or multiple planes, for which edge tracking function is essential. Edge tracking is also a basic primitive for many manufacturing operations, such as two-flat-surface grinding. The experiments of edge tracking and insertion using the robot compliant wrist system is described in the paper.

For insertion operation, we used the passive compliance in the system to correct any positioning error of assembly. We do not try to remotely or precisely locate the center of compliance. Rapid assembly operations are dynamic processes and the actual location of the compliant center varies with the inertial properties of parts and environmental characteristics. To apply heuristic decision rules to control the insertion, we used fuzzy control algorithms to assign velocity in and around each axis based on the corresponding deflection measured in the device. The experimental results showed that, compared to the principle of the exact force zone [16], fewer steps are taken to full insertion and jamming is effectively avoided.

2. TWO PROTOTYPES OF THE COMPLIANT WRIST DEVICE

There are two plates, upper plate and lower plate, in the compliant wrist device. The lower plate is attached to the robot and the upper one is connected with the end-effector. The sensing mechanism installed between these two plates is capable of measuring six DOF relative motion of the upper plate with respect to the lower one. The sensing mechanism is formed by a serial linkage with six transducers at its six joints. The joint angular error is measured and then the position error in
sandwiched rubber in such a way that it yields the required stiffness. An example of the block structure is shown in Figure 5. It consists of two portions: the upper one with three rubber elements in an equilateral triangle and the lower one with eight elements horizontally in four sides of the cube connected to the lower part. The upper compliance is mainly attributed to the axial stiffness, and the lower one is for lateral and torsional stiffnesses.

3. HYBRID POSITION FORCE CONTROL

To control the robot, which is equipped with the compliant wrist, the hybrid position force controller must be designed with consideration of passive compliance in the system. The generalized surface on which the robot works can be defined in a constraint space having six degrees of freedom, with position constraints along the normal to this surface and force constraints along the tangents. In what follows, based on these two constraints, the hybrid position force control scheme is described.

We first consider the position control case when the robot moves in free space. The position error due to the passive compliance in the wrist device can be compensated by driving the robot in the opposite direction of the measured deflection in such a way that the overall stiffness is increased. Using the joint rate coarted representation, the desired joint motion to correct the position error is

$$\Delta \theta_{\text{des}} = -J^{-1}_{\text{w}} \Delta X_{\text{w}}$$  \hspace{1cm} (1)

where $J_w$ the manipulator Jacobian matrix, $\Delta X_{\text{w}}$ is the generalized position error vector, and $\Delta \theta_{\text{des}}$ is the corresponding joint motion. For a proportional control, the desired joint motion $\theta_{\text{des}}$ is

$$\theta_{\text{des}} = \theta_{\text{req}} + \Delta \theta_{\text{des}} = \theta_{\text{req}} - J_w K_p \Delta X_{\text{w}}$$ \hspace{1cm} (2)

where $K_p$ is the gain matrix, and $\theta_{\text{req}}$ is the desired joint angle supplied by a trajectory generator function.

For the second prototype the rubber blocks are made up from sheets which may be changed to achieve any desired compliance for different operations. Each block is assembled with several pieces of
For the directions that force is controlled, the force error is tracked by driving the manipulator in the same direction as the measured force such that the desired stiffness is obtained. The desired stiffness $K_d$ is related to the exerted force $F_e$ from the wrist device and the corresponding robot motion $\Delta X_e$ by

$$ F_e = K_d \Delta X_e $$

(3)

On the other hand, the exerted force $F_e$ is evaluated by the physical stiffness of the device $K_e$ and the device deflection $\Delta X_w$:

$$ F_e = K_e \Delta X_w $$

(4)

Substituting yields

$$ \Delta X_e = K_r \Delta X_w $$

(5)

where $K_r$ is the dimensionless ratio of the stiffnesses

$$ K_r = K_e / K_e $$

(6)

Thus, the desired joint angles $\theta_{des}$ are

$$ \theta_{des} = \theta_{curr} + \theta_{act} = \theta_{curr} + J_{r1}^T K_r \Delta X_w $$

(7)

where $\theta_{curr}$ are the current joint angles. Similarity may be found if the position control algorithm is compared with force control scheme. Note that the desired joint angles $\theta_{des}$ is based on the specified joint angles $\theta_{ref}$ in position control (2), while based on the current joint angles $\theta_{curr}$ in force control (7).

The system, however, normally involves position and force control simultaneously. We at first partition the measured deflection $\Delta X_w$ into two parts: $\Delta X_w$ corresponding to the force controlled component, and $\Delta X_e$ in the remaining directions corresponding to position control. For the given desired residual force $F_e$, the corresponding residual deflection of the wrist device $\Delta X_e$ can be evaluated by

$$ \Delta X_e = K_e^{-1} F_e $$

(8)

where $K_e^{-1}$ is the physical stiffness of the device. Considering the gain matrix, the desired differential motions of the end-effector corresponding to position and force control are

$$ \Delta X_p = K_p \Delta X_e $$

(9)

$$ \Delta X_f = K_f (\Delta X_e - \Delta X_p) $$

(10)

Therefore, considering only force control, the desired joint motion of the end-effector tracks the force error represented by $\Delta X_F$, based on the current motion.

$$ \theta_{j} = (\theta_{j-1} + J_{r1}^T \Delta X_F) $$

(11)

Concurrently, when the position control is also considered, the end-effector motion must be modulated by the deflection $\Delta X_e$, thus the final motion is

$$ \theta_{j} = (\theta_{j-1} + J_{r1}^T \Delta X_p + J_{r1}^T \Delta X_e) $$

(12)

Control experiments of the compliant wrist were performed on a PUMA 560, and executed on a MicroVAX II using the RCI primitives of RCL [4], which allows the software to directly command robot joint angles. The software package allowed various parameters to be set, and also allows trajectory and wrist displacement data to be logged to a file for subsequent analysis.

4. EDGE TRACKING

When robots are used as components of automated assembly systems, the compliance of robots is needed to correct positioning errors, to relax parts tolerance, and to absorb impact forces between parts. The robot compliant wrist system addressed above provides an ideal tool for automated assembly in the sense of adaptability of the compliance and of the feasibility of passive and active method. The instrumented passive compliant wrist also provides an economical solution to the assembly problem.

Based on the features of assembled parts, assembly operations can be represented by a small number of primitives, such as sliding, insertion, and screwing. The sliding action could occur in a plane or multiple planes, for which edge tracking is essential. Edge tracking is also a basic primitive for many manufacturing operations, such as two-flat-surface grinding. In the following sections, we will discuss experiments of edge tracking and insertion using the robot compliant wrist system, and envision the possibility of applying the technique to automated assembly.

The edge to be tracked is formed by two surfaces. One of them is assumed as a flat surface and these two surfaces form an arbitrary angle $\alpha$ as shown in Figure 6. Tracking is accomplished by moving along the edge while maintaining contact in the other two directions. For the edge shown in Figure 6, the contact forces in the X and Z directions are controlled and other directions are position controlled. The end-effector follows the Y axis at a specified velocity. A special tool to facilitate contact with both surfaces of the edge is fabricated as shown in Figure 7. The geometry of the tool determines the possible maximum and minimum angles of the edge $\alpha$ that can be tracked. The tool is attached to the upper plate of the wrist device.

The edge tracking process can be simply divided into three phases: approaching, searching, and tracking as shown in Figure 8.
Approaching Phase: The robot approaches the edge at a specified velocity \( v_s \). The controller is set as full position control in all directions. Upon making contact with one side of the edge, the contact force is detected. By the sensed force, motion in this direction is ended, and the controller is switched to force control in this direction and position control in all other directions.

Searching Phase: When the approaching phase is ended, one side of edge is in contact with the tool at its one side. The robot then moves in the direction perpendicular to the approaching motion at a specified searching velocity \( v_r \). When this side of the tool is also contacted with the edge, searching phase is finished, and force control is assigned in the searching direction.

Tracking Phase: When the previous two phases are finished, both surfaces of the edge are contacted with the tool. Tracking is then being executed at a desired tracking velocity \( v_t \) along the third axis perpendicular to the directions of approaching and searching motions. In this phase, force is controlled in the normal directions of two contact surfaces, and position is controlled in the other directions.

Experiment of the edge tracking was investigated using the control scheme presented above. It was determined, from the experiment, that the desired contact force must be carefully assigned in each contact direction since the physical stiffness of the compliant wrist device is different, and as a result, the deflection in and around each axis is different if an identical contact force is specified. Thus, the contact force must be selected according to the task demand and the physical stiffness in the corresponding direction. On the other hand, when a high contact force is specified for the surface which is not smooth, tracking is likely to stick due to friction. In this case, a relative large tracking velocity, and relative small searching velocity and approaching velocity are suggested. The detail analysis and experimental results can be found in [14].

5. INSERTION OPERATION

The insertion operation is another paradigm to utilize the robot compliant wrist system in assembly. It has been known that the passive compliance provides an adaptable output which permits self-correction in order to accommodate dimensional uncertainties of hole and shaft. Force sensing makes it possible to actively control the contact force and thereby avoid a jamming. In experiments, the parts shown in Figure 10 were fabricated with chamfered edges, and tolerance is 0.025mm. The hole location can be specified manually or by a camera, and the path towards the hole is generated by the robot trajectory generator. The shaft held by the robot is brought above the hole and the positioning error is such that the shaft is within the chamfer of the hole.

A two dimensional model for the experimental system can be illustrated in Figure 9. The similar model was proposed in the paper [16], but the angular stiffness is considered in our case. Instead of evaluating the measured force, checking the exact force zone, and assigning a constant step size to reduce the contact force, as suggested in [16], we used a fuzzy controller to specify the velocity for a certain measured force. The experimental results showed that, compared to the force zone approach, the fuzzy control approach yields fewer steps to full insertion and jamming is effectively avoided. In what follows, we will discuss the fuzzy controller.

The basic idea of the controller is to assign the velocity in and around each axis for the given deflection in corresponding direction in a heuristic way in which a human operator might perform the insertion. The process of the controller is to assign the measured deflection to fuzzy variables, such as "deflection big" (DB), and evaluate the decision rules using the compositional rules of inference, and thereby determine the output, i.e., velocity as a fuzzy variable. The form of decision rule and fuzzy variables used in decision depends on the specific control problem. We used the deflection of the compliant wrist \( D \) and rate of the deflection \( DE \) as an input. In the paper, we only list the deflection as an input for simplicity. The sensed deflections value are quantized into a number of points corresponding to the elements of a universe of discourse, and the values are then assigned as grades of membership in several fuzzy subsets as shown in Table 1. Then the output of the controller, i.e., velocity in and around each axis, can also be defined in Table 2.
The relationship between the input, i.e., measured deflections, or the output, i.e., velocities, and grade of membership can be defined according to operator experiences and task requirements. From several tests, we defined the empirical membership functions for all elements of input and output. As an example, the membership function for the deflection in the Z direction is shown in Figure 11, and that for the others is not listed for simplicity. The decision rules are implemented as a set of fuzzy conditional statements. For insertion operation, it is presented as follows, and that for pulling out process is slightly different and can be found in [14].

The rational of the controller can be explained as follows. We assume that approaching and insertion are along Z axis, i.e., the axis of hole is parallel to the Z direction. When the deflection in the Z direction (Z_D) is small, the phase is considered as that robot moves towards the hole. No motion in any direction is assigned corresponding to any slight deflection of the device in order to resist random disturbance when the robot moves in free space. When the Z_D is getting large, the shaft is expected to have made contact with the hole, the motion in the X, Y and around X, Y, Z axes is being controlled with a small gain so that the shaft motion is modified by the deflection, and the initial location error is corrected. As the Z_D is increased again, we may expect that jamming occurs or is likely to occur. Correction for rotation around the X and Y is especially required. Thus a large gain of rotation around the X and Y is set. In the meantime, since rotation around the Z direction is helpful to avoid jamming, a relatively larger gain for rotation around the Z direction is specified. For insertion of the square parts, a small gain for rotation around the Z axis is selected to avoid an angular error in this case.

For a particular set of input, i.e., the measured deflection, evaluating the fuzzy rules yields a fuzzy set of grades of membership for control actions. In order to take a deterministic action one of these values must be chosen. In this application, the control value with the largest grade of membership was selected. The rules are evaluated at regular intervals in the same way as a conventional control system.

6. SUMMARY

The robot compliant wrist system with passive compliance and active control software has been developed. Two prototypes of the device were designed. Hybrid position force control with the wrist device is presented. Application of the system in assembly process is discussed with experiments of edge tracking and insertion. A simple fuzzy controller was implemented in insertion for velocity assignment instead of checking exact force zones. The results show the system is feasible for
assembly application and provides an economical solution for compliance
control functions significant in assembly.

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