Experiments of Force Control Algorithms for Compliant Robot Motion

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Abstract: The main objective of this paper is to analyze the performance of various force control algorithms in improving and adjusting the compliance of industrial robots in contact with their environment. Some of fundamental force control algorithms such as sensorless control, impedance control and hybrid position/force control are theoretically analyzed and simulated for various situations of an environment, and then a series of experiments using them were performed. In this paper, a control scheme to use position control in implementing the impedance control was investigated in order to nullify the effect of joint friction. The new reference trajectory is generated using contact force feedback and original desired trajectory. And an inner position control loop is designed to provide accurate position tracking for the new reference trajectory and good disturbance rejection. Experiments to insert a peg in a hole (so-called the peg-in-a-hole task) were performed with HILS (hardware-in-the-loop simulation) system based on the results of the analyses and simulations on the characteristics of each control algorithm. The experiments showed that various force control methods improved the performance of robots in close contact with the environment by adjusting their compliance with respect to an arbitrary set of coordinates.

Keywords: Force Control, Impedance Control, Hybrid Position/Force Control, Peg-in-a-Hole

1. Introduction

The control methodology of robot manipulator is divided into position control and force control corresponding to applications of robot manipulator. The works such as welding, painting is sufficient to get a good performance using only the position control algorithm. And many researchers and engineers have developed the position control algorithms.

However, in many industrial applications as, for example, automatic assembly, deburring and grinding operations, the end-effector of a robot manipulator has to maintain contact with the environment. In this case, the small position error can lead to extremely large contact force.

So, the force control of robot manipulator has been an attractive area of research for many years and many approaches to force control have been proposed [1] - [9].

For example, the impedance control algorithm proposed by Hogan aims at controlling position and force by adjusting the mechanical impedance of the end-effector to external forces generated by contact with the environment [5]. In hybrid position/force control proposed by Raibert et al, the position control and force control can be separately considered [7].

In this paper, the main objective is to analyze the performance of various force control algorithms, which is used in order to produce compliant robot motion. In general, the impedance control and hybrid position/force control algorithms are theoretically very effective techniques for robot force control. However, achieving the expected impedance is difficult in practice, due to uncertainties on the robot dynamics model and disturbances such as joint friction. In hybrid position/force control, it may cause some unstable response when selection matrix is switched.

Also experiments to insert a peg in a hole are performed with HILS system based on the results of the analyses and simulations on the characteristics of each control algorithm.

This paper is supported by Hyundai Heavy Industries Co., Ltd.

2. Robot Model and Force control algorithms

2.1. Robot model

In contact situation with environment, the robot manipulator dynamics can be described by

$$\tau = M(\theta)\ddot{\theta} + V(\theta,\dot{\theta})\dot{\theta} + G(\theta) + J(\theta)^T F_e \quad (1)$$

where τ is the $n \times 1$ vector of the joint torque supplied by the actuators; $M(\theta)$ is the $n \times n$ symmetric, positive definite inertia matrix; $V(\theta,\dot{\theta})$ and $G(\theta)$ represent torques due to centrifugal and gravity respectively; $J(\theta)$ is the configuration-dependent Jacobian matrix; and F_e denotes the force exerted by the end-effector on the environment and measured by a force sensor.

2.2. Implicit force control

Implicit force control is the sensorless control. It is to control the predefinition of position for a desired force, which is determined to obtain a particular stiffness of the end-effector without force sensor. Generally, the force of an end-effector generated by contact with the environment can be represented by spring force with six degrees of freedom in response to a virtual displacement δX.

$$F_e = K_{px}\delta X \quad (2)$$

Diagonal elements of the matrix K_{px} are stiffness constants representing linear and torsional stiffness.

From the definition of the manipulator Jacobian,

$$\delta X = J(\theta)\,\delta\theta \quad (3)$$

At steady-state, the contact force with environment can be transformed as follows.

$$\tau = J^T F_e \tag{4}$$

Combining the above equations yields

$$\tau = J^T K_{px} J \delta\theta = K_q(\theta)\delta\theta \tag{5}$$

where $K_q(\theta)$ is called a joint stiffness matrix.
In general, most industrial robots are using an individual joint-based PD control scheme with gravity compensation in order to control the position of the manipulator.

$$\tau = K_p \left(\theta_d - \theta\right) + K_v \left(\dot{\theta}_d - \dot{\theta}\right) + G\left(\theta\right) \tag{6}$$

Salisbury suggests the control method as follows [4].

$$\tau = J^T K_{px} J \left(\theta_d - \theta\right) + K_v \left(\dot{\theta}_d - \dot{\theta}\right) + G\left(\theta\right) \tag{7}$$

Therefore, we can achieve the stiffness of the manipulator through adjustment of the matrix K_{px} values.
In case of implicit force control algorithm, there is no force feedback and it is a steady-state analysis. So it does not describe the transient force response, that is, the transient force resulting from interacting with their environment.

2.3. Impedance control

The impedance control algorithm aims at controlling position and force by adjusting the mechanical impedance of the end-effector to external forces generated by contact with the environment.
The desired impedance model is represented by a desired dynamic behavior between the contact force and the motion of the manipulator.

$$M_d \left(\ddot{X}_d - \ddot{X}\right) + B_d \left(\dot{X}_d - \dot{X}\right) + K_d \left(X_d - X\right) = F_e \tag{8}$$

where M_d , B_d and K_d represent the desired inertia, damping and stiffness parameter matrices. X_d is the desired end-effector trajectory.
If there is no contact with their environment, the end-effector position follows asymptotically the desired trajectory. In contact situation, the manipulator behaves as a mass-spring-damper system with desired impedance parameters. Changing the impedance parameters may then regulate dynamic interaction between the manipulator and its environment.
From manipulator Jacobian relationship,

$$\ddot{\theta} = J^{-1}\left(\ddot{X} - \dot{J}\dot{\theta}\right) \tag{9}$$

When Jacobian inverse is exists, from equations (1), (8) and (9), we can obtain a control law that realizes the desired impedance model.

$$\begin{aligned}\tau = \quad & M(\theta)J^{-1}[\ddot{X}_d + M_d^{-1}(B_d(\dot{X}_d - \dot{X}) + K_d(X_d - X)) \\ & -\dot{J}\dot{\theta}] + V(\theta,\dot{\theta}) + G(\theta) + J^T F_e\end{aligned} \tag{10}$$

However, achieving the expected impedance is difficult in practice, due to uncertainties on the robot dynamics model and disturbances such as joint friction. Generally, friction parameters are difficult to identify, especially for the dynamics models, and may be affected by different environment factors. So, it is not easy that the friction compensation control method is applied to force control. In this paper, a control scheme to use position control in implementing the impedance control is investigated in order to nullify the effect of joint friction [9].
The new reference trajectory is generated using contact force feedback and original desired trajectory.

$$M_d(\ddot{X}_d - \ddot{X}_r) + B_d(\dot{X}_d - \dot{X}_r) + K_d(X_d - X_r) = F_e \tag{11}$$

where X_r , $\dot{X}_r$ and $\ddot{X}_r$ are new reference trajectory, which must be followed by the end-effector.
And an inner position control loop is designed to provide accurate position tracking for the new reference trajectory and good disturbance rejection.

$$\begin{aligned}\tau = \quad & M(\theta)J^{-1}[K_p(X_r - X) + K_d(\dot{X}_r - \dot{X}) - \dot{J}\dot{\theta}] \\ & +V(\theta,\dot{\theta}) + G(\theta) + J^T F_e\end{aligned} \tag{12}$$

where K_p and K_d are proportional, derivative gains respectively.

2.4. Hybrid position/force control

Hybrid position/force control can be used for tracking position and force trajectories simultaneously. In constrained direction by environment, the contact force must be controlled. In the other direction, the position of the end-effector must be controlled.
In hybrid position/force control, the selection matrix is used in order to select the subspace that must be force controlled and the directions that must be position controlled.
The selection matrix S is a diagonal matrix with a 1 entry corresponding to directions that are to be position controlled. And $I - S$ is complement of S. So, each degree of freedom is uniquely determined as being either position-controlled subspace or force-controlled subspace.
Generally, hybrid position/force control algorithm is applied the PD-type computed torque control law in each subspace.

$$\tau = M(\theta)J^{-1}(a - \dot{J}\dot{\theta}) + V(\theta,\dot{\theta}) + G(\theta) + J^T F_e \tag{13}$$

where $a = \begin{bmatrix} a_T & a_N \end{bmatrix}^T$ is an $n \times 1$ vector used to represent the new position and force control input. The subscript T and N denote the tangent and normal direction on constraint respectively.
In position-controlled subspace, a_T is given as

$$a_T = \ddot{X}_d + K_{pp}(X_d - X) + K_{dp}(\dot{X}_d - \dot{X}) \qquad (14)$$

In force-controlled subspace, a_N is as follows.

$$a_N = \ddot{F}_d + K_{pf}(F_d - F) + K_{df}(\dot{F}_d - \dot{F}) \qquad (15)$$

where X_d, F_d are the desired position and force trajectory respectively. And K_{pp}, K_{dp}, K_{pf} and K_{df} are proportional, derivative gains for the position and force controller respectively.

In experiments, it may cause some unstable response due to excessive torque when selection matrix is switched. The excessive torque causes that the end-effector collide the environment with very large contact force. Therefore, it is necessary to interpolate its values when the selection matrix is switched. Also, it is difficult to apply the derivative value of force signal to control law directly because the signal information obtained using force sensor is very noisy.

So, we choose the hybrid impedance control algorithm, which the derivative information of force signal is not necessary, instead of hybrid position/force control. In hybrid impedance control, impedance control with inner position control loop is chosen as the force controller and PD-type computed torque controller is chosen as the position controller.

3. Experiments

3.1. Experimental Set-up

HILS system consists of four links and is controlled using dSPACE products. In this paper, because the robot manipulator is constrained to planar motion, the base link is fixed and second, third and fourth links are used to peg-in-a-hole task experiments.

In order to measure the contact force with their environment, the force/torque sensor JR3 IFS-67M25A25-I40 is mounted at end-effector of HILS system.

The specifications of the force sensor are as follows.

Table 1. The force/torque sensor specification.

sensor	$F_x, F_y(N)$	$F_z(N)$	$M_x - M_z(Nm)$
IFS-67M25A25-I40	100	200	7

The sensor transfers the measured force/torque information to PCI board of the PC after the signal is transformed the digital information. However, because the HILS system equipped with the dSPACE controller must accept the analog information, DAC device is used to convert the signal.

3.2. Peg-in-a-hole experiments

The specifications of the peg and hole are as follows.

The motion of robot manipulator is constrained to Y-Z plane. The movement direction of peg is Y-axis, which is the position controlled, and the vertical direction of peg is Z-axis, which is the force controlled.

Table 2. Peg and Hole diameters.

Rod diameter(mm)	Hole diameter(mm)	Clearance(mm)
30	40	10
30	31	1
30	30.5	0.5
30	30.01	0.01

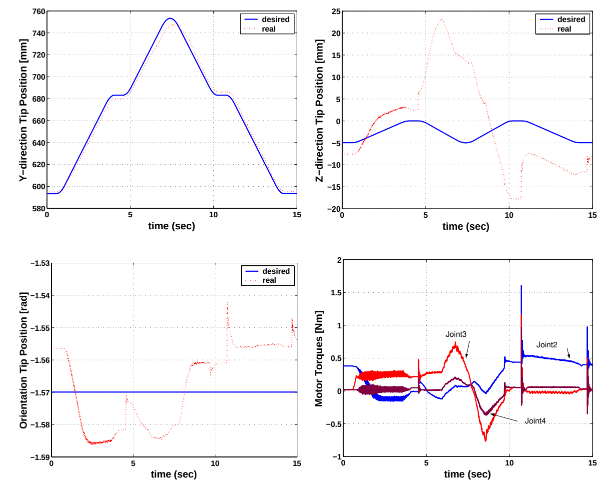

Fig. 1. Implicit control for peg-in-a-hole

3.2.1 Implicit control

In order to control the compliance of robot motion with respect to Z-direction, the experiments are performed with K_{px}, which is reduced in respect of Z-direction.

Because it does not describe the transient force response, that is, the transient force resulting from interacting with their environment, the performance of position control is degenerated. In result, the performance of force control is also degenerated and can lead to extremely large contact force. Moreover, it is impossible to apply to accurate force control due to uncertainties on the robot dynamics model and disturbances such as joint friction.

Figure 1 shows the results of experiment using implicit control.

3.2.2 Impedance control

In case of impedance control, because it is a dynamic-model based control algorithm, the results of experiment show a good performance not only in steady-state response but also in transient response.

The position control is performed with respect to Y-direction and the force control is done with respect to Z-direction same as implicit control

If there is no contact with their environment, the end-effector position follows asymptotically the desired trajectory. In contact situation, the manipulator behaves as a mass-spring-damper system with the reduced desired impedance parameters.

Figure 2 shows the experiment results using impedance control.

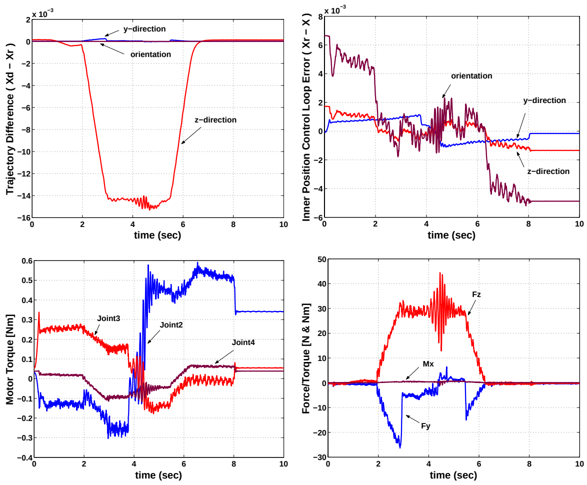

Fig. 2. Impedance control for peg-in-a-hole

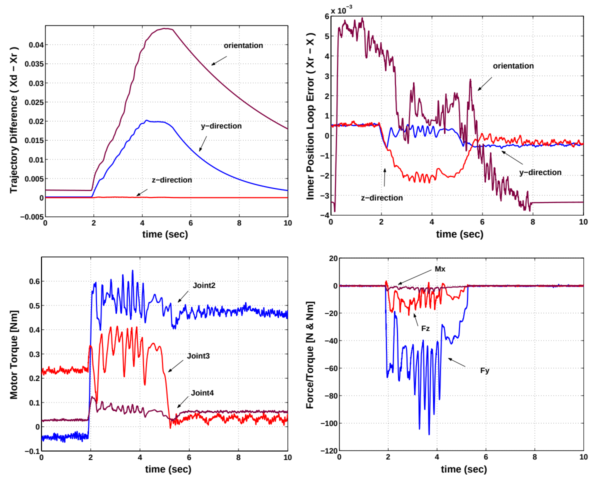

Fig. 4. Impedance control for contact stability

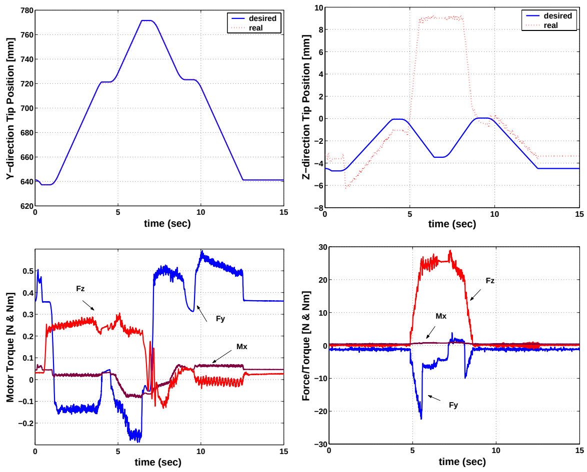

Fig. 3. Hybrid Impedance control for peg-in-a-hole

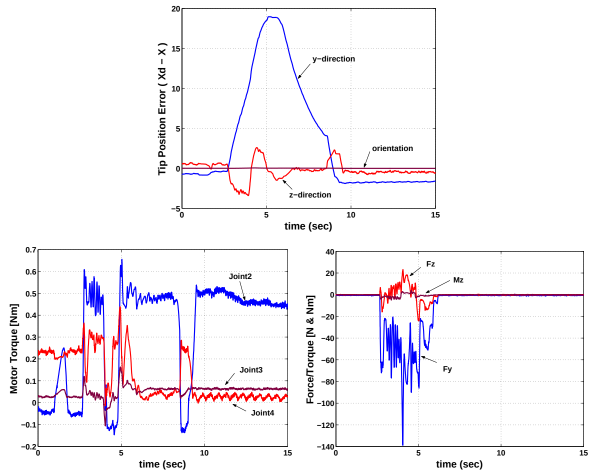

Fig. 5. Hybrid Impedance control for contact stability

In absence of contact, the new reference trajectory is same as the original desired trajectory. But, in presence of contact, that is deviated in comparison with original desired trajectory. That is, the contact with hole is made after about 2 sec. The new reference trajectory is generated higher than original trajectory about 1.4cm and the end-effector is tracking the new trajectory.

3.2.3 Hybrid impedance control

The robot manipulator moves in free space until the end of peg contact with hole. In this case, the position control is performed in all direction. When the contact is made, the position control is applied to Y-direction and the force control is done to Z-direction same as impedance control.

So, we divide the selection matrix transition section into 5 steps corresponding to the position of the end-effector as below figure.

The results of experiment are similar to that of experiments using impedance control.

Figure 3 shows the experiment results using hybrid impedance control.

3.3. Contact Stability experiments

This experiment are performed in order to confirm the contact stability and compliance with respect to orientation direction using the end-effector of plate shape In this experiment, the position control is performed with respect to Z-direction and the force control is done with respect to Y-direction, orientation-direction.

At initial state, the plate has a little tilt angle and the contact with environment is made. So, the end-effector moves in order to parallel with the environment.

Figure 4, 5 show the results using impedance control and hybrid impedance control respectively.

4. Result

Some of fundamental force control algorithms such as sensorless control (implicit control), impedance control and hybrid position/force control are theoretically analyzed and simulated for various situations of an environment, and then a series of experiments using them were performed. Experiments to insert a peg in a hole (so-called the peg-in-a-hole task) are performed with HILS (hardware-in-the-loop simulation) system based on the results of the analyses and simulations on the characteristics of each control algorithm. The experiments showed that various force control methods improved the performance of robots in close contact with the environment by adjusting their compliance with respect to an arbitrary set of coordinates.

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