A New Approach for the Formulation of the Admittance and Hybrid Position/Force Control Schemes for Industrial Manipulators

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Abstract – This paper briefly discusses two of the well-known position/force control schemes used for industrial manipulators: Admittance Control and Hybrid Position/Force Control. In order to eliminate the instability problem that may occur in the customary versions of these schemes for large position errors, a modification is proposed, which is based on determining the joint-space position errors using inverse kinematic solutions rather than using the inverse Jacobian matrix. The feasibility of this modification relies on the fact that almost all of the industrial manipulators have easily obtainable inverse kinematic solutions. The simulation results showing the performance of the modified control schemes are also presented as applied on a Puma 560 manipulator.

I. INTRODUCTION

As the tasks of the robot manipulators become more complex and as the interaction of the manipulators with their environments increases, not only the positions of the manipulators but also the forces exerted by them to their environments are required to be controlled. Two of the prominent schemes encountered in the related literature that may be used to control the position and the applied forces and/or moments are the Hybrid Position/Force Control and the Admittance Control [10]. However, in both schemes, the position error is formed by comparing the reference input (desired position) and the measured data (actual position) with each other in the Cartesian space. Then, using the inverse of the Jacobian matrix, this error is transformed into the joint space as a linear approximation. The approximate error evaluated thus in the joint space is then fed into the control unit to drive the joint actuators. This method can be used to control the manipulator successfully if the error calculated in the Cartesian space is small. As this error increases, the system behavior deteriorates and it may even become unstable. On the other hand, for many manipulators used in practice, the inverse kinematic solutions can be obtained quite easily [8], [9]. For such a manipulator, the exact position error can be evaluated directly in the joint space by first finding the joint space equivalents of the desired and actual positions separately through the inverse kinematics and then comparing them.

In this paper, the necessary modifications are proposed to be incorporated into the customary Hybrid Position/Force Control and the Admittance Control schemes so that the position error is evaluated directly in the joint space as described above. Simulation results for certain tasks are also presented to demonstrate the performance achieved with these modifications.

II. DEFINITION OF THE PROBLEM

While a manipulator performs a desired motion, restricting one or more of its motion freedoms along certain directions by applying forces in those directions may cause instability [13]. In order to cope with this problem, unlike the simple modification introduced in the MSc thesis of Dede [1], many of the researchers in this area have so far concentrated generally on making the conventional position/force control schemes more sophisticated by introducing adaptive or learning features [11, 12]. While forming such sophisticated controls, the method of the comparison of the position errors of the customary position/force control schemes are kept unmodified. The possible instability due to the customary control schemes is discussed in the thesis of Dede [1]. The instability problem for the customary position/force control schemes arises when there are increases in the errors calculated for the position-controlled subsystem in the Hybrid Control scheme and for the position-controlled inner control loop in the Admittance Control scheme. This is basically due to the previously mentioned fact that the position errors in the joint space are obtained approximately by the linear transformation of the actual position errors in the Cartesian space through the inverse Jacobian matrix.

III. CUSTOMARY POSITION/FORCE CONTROL SCHEMES

III.A. Admittance Control

Admittance control specifies a force setpoint and the setpoint is tracked by a force compensator. In contrast with a pure position control which rejects disturbance forces in order to track a given reference motion trajectory, the force compensator attempts to comply with the environmental interaction and reacts quickly to contact forces by rapidly modifying the reference motion trajectory [2]. The mechanical admittance is defined as

$$\dot{X}(t) = AF(t) \qquad (1)$$

This equation can be written in the *s* domain as

$$X(s) = K(s)F(s) \qquad (2)$$

where

$$K(s) = \frac{1}{s}A \qquad (3)$$

In equations (1), (2) and (3), X and $\dot{X}$ are the position and velocity vectors of the end-effector, A is the admittance matrix, and Figure 1 shows the structure of a customary admittance control scheme.

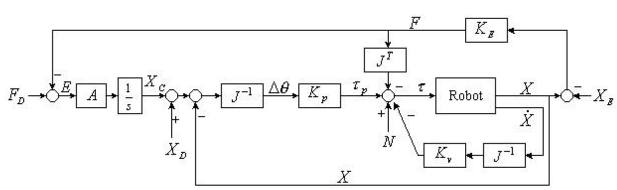

Fig. 1. Customary Admittance Control.

In Figure 1 and in the following Figures 2, 3 and 4, "N", represents the feed-forward torque input to counteract the centrifugal, Coriolis and gravitational forces [7]. The other feed-forward torque input "$J^T K_E (X - X_E)$" is generated to counteract the effect of the environmental interaction forces [7]. Here, "K_E" is the combined stiffness matrix of the environment and the force sensors. In this work, however, environment is modeled as rigid and therefore "K_E"is associated only with the force sensors.

In Figure 1, the admittance matrix A relates the force error vector E ($E = F_D - F$) to the required modification in the end-effector velocity vector. This leads to the following additive modification on the reference trajectory:

$$X_c = \int A(F_D - F)dt \qquad (4)$$

Effective and precise admittance control can be achieved by choosing a suitable A matrix for the known stiffness of the environment. However, if the working environment changes significantly, A matrix should be recalculated in order to adapt the new environment. Changing the admittance value properly due to the changing environment may be realized with adaptive control laws. In general, though, it can be said that the value of the A matrix should decrease as the stiffness of the environment increases causing larger amount of forces to be exerted with the same amount of motion toward the surface.

Although equations (1)-(4) imply that *A* is constant, it is also possible, and in fact expedient, to extend the concept of admittance to involve a variable matrix such as

$$A(s) = k_d s^2 + k_p s + k_i \qquad (5)$$

which then results in the following PID force compensator:

$$K(s) = \frac{1}{s} \cdot A(s) = k_d s + k_p + \frac{k_i}{s} \qquad (6)$$

III.B. Hybrid Position/Force Control

Combining position and force information into one control scheme for moving the end-effector in nondeterministic environments has been introduced as hybrid position/force control [5]. The advantage of hybrid position/force control with respect to others is that the position and force information are processed independently by separate controllers to take advantage of well-known control techniques for each of them. The outcomes of these controllers are then combined only at the final stage when both have been converted to joint torques [3]. Figure 2 shows the application of the hybrid position/force control scheme as a block diagram.

In Figure 2, $S = diag(s_j)\ \ (j = 1 \ldots n)$ is called the compliance selection matrix, n represents the degree of freedom. The matrix S determines the subspaces in which force or position are to be controlled, and s_j is selected as either 1 or 0. When $s_j = 0$, force control must be used in the *j*th direction of the Cartesian space; otherwise, position control must be used in that direction. Depending on the required task, S matrix can be constant, or it can change in time according to the varying gradient of the task surface and the path followed on it [4].

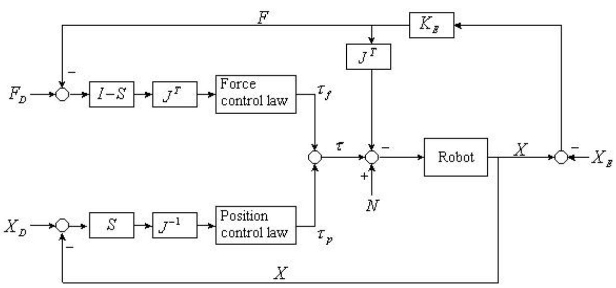

Fig. 2. Customary Hybrid Position/Force Control.

For each task configuration, a generalized surface can be defined with position constraints along the normals to this surface and force constraints along the tangents, which means, the end-effector can not move along the normals into the surface and can not cause reaction forces to arise along the tangents of the surface. These two types of constraints partition the freedom directions of possible end-effector motions into two orthogonal sets along which either position or force control must be used [5]. Utilizing this partitioning, S matrix is formed appropriately in accordance with the required task.

In this control scheme, the command torque is

$$\tau = \tau_p + \tau_f \qquad (7)$$

τ_p and τ_f are the command torques acting in the position and force subspaces, respectively. In this way, position control and force control are decoupled. In general, it happens that PD action is satisfactory for position control, and PI action is satisfactory for force control [10].

IV. MODIFIED POSITION/FORCE CONTROL FORMULATIONS

As pointed out above, for position control, PD action is preferred in both of the Hybrid and Admittance control schemes. However, in the customary versions of these schemes, as seen in Figures 1 and 2, the Cartesian-space position error ($X_{ref} - X$) is assumed to be small and therefore it is transformed into the joint space approximately as

$$(\theta_{ref} - \theta) \approx J^{-1}(X_{ref} - X) \qquad (8)$$

It turns out that this approximation often leads to unsatisfactory behaviors if the position error becomes large. As a proposal of remedy, the Hybrid and Admittance control schemes are modified here as described below. This modification is based on calculating the joint-space position error exactly as follows:

$$(\theta_{ref} - \theta) = IK(X_{ref}) - IK(X) \qquad (9)$$

Here, “ IK ” symbolizes Inverse Kinematics and this modification is of course feasible for those manipulators for which “ IK ” solutions are easy to obtain. Fortunately though, almost all of the industrial manipulators are of this kind [8], [9].

IV.A. Modified Admittance Control

Inner position loop of the Admittance Control scheme is modified to make the necessary comparisons in the joint space and not in the Cartesian space as it was for the customary version. Figure 3 shows the modified version of the Admittance Control scheme.

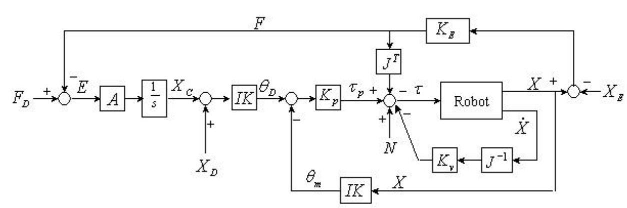

Fig. 3. Modified Admittance Control.

Position feedback of the end-effector is changed to joint position feedback by inverse kinematics “ IK ” in the modified scheme. The inverse kinematics solutions can be achieved easily by using the methodology introduced in [8]. Besides, in a real time application, position feedbacks are received directly from the joint transducers. Therefore, it is sufficient to employ inverse kinematics only for the reference position $X_{ref} = X_C + X_D$ defined in the Cartesian space.

IV.B. Modified Hybrid Control

Hybrid control scheme is also modified to make the necessary comparisons in the joint space and not in the Cartesian space as shown in Figure 4. Again, " IK " in the figure represents Inverse Kinematics.

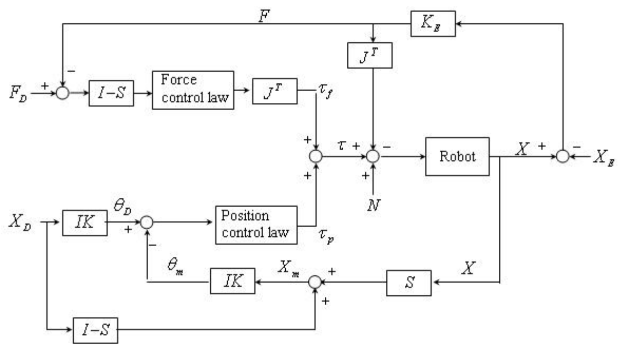

Fig. 4. Modified Hybrid Position/Force Control.

This modified version of the Hybrid Control does not use the selection matrix, " S " after the comparison is made in the Cartesian Space for the position control subspace. The selection matrix is used to take the measured positions along the directions to be position controlled as they are and modify the measured position along the direction to be force controlled to the desired position along that direction. This makes the position error along the direction to be force controlled equal to zero, which means that the controller working in the position control subspace will not try to monitor the position along the force control direction.

After these modifications on the measured position, " X ", the modified measured position, " X_m ", is transformed to the Joint Space to calculate the modified measured joint angles, " θ_m ", using the inverse kinematics equations. Desired position vector is also transformed to the Joint Space using the inverse kinematics equations. As a result of this, the comparison is made in the Joint Space and the outcome is fed into the position controller.

V. SIMULATION RESULTS

The PUMA 560 6R manipulator, for which the system parameters are described in Bascuhadar's thesis [6], is used for numerical simulations. Point type of contact and the force sensor are considered to be at the end point of the end-effector for this study. All the simulations are carried out in Matlab© Simulink environment. The forward kinematics and system dynamics are modeled using the Simmechanics module of Matlab©.

For sake of simplicity, no surface or joint friction is modeled for the simulations presented in this paper. The contact is assumed to occur in such a way that only one degree of freedom is constrained by a flat surface normal to $\vec{u}_1^0$ (X) axis as illustrated in Figure 5.

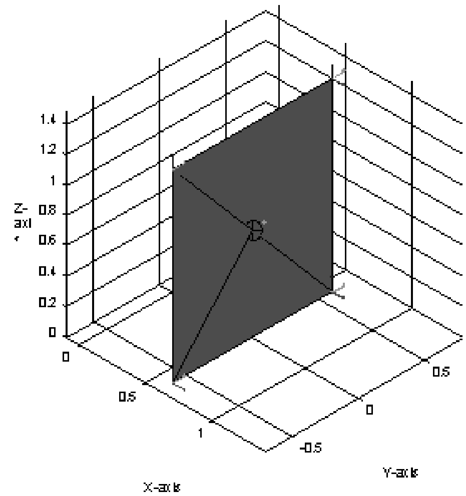

Fig. 5. The task plane considered in the simulation examples

The task to be accomplished for this simulation study is drawing a circle on a flat and rigid surface. The diameter of the circle to be drawn for the Hybrid Control is 0.3 meters and for the Admittance Control is 0.2 meters. This is an arbitrary selection for the diameters with the only restriction that the circles remain within the workspace of the manipulator. The link and joint parameters of the Puma 560 used in this work are given in Table 1.

TABLE I. Link and Joint Parameters of PUMA 560 Manipulator

Joints	α_k (deg.)	s_k (mm.)	a_k (mm.)	θ_k (deg.)
1	-90°	0	0	θ_1
2	0	81.5	300	θ_2
3	90°	0	0	θ_3
4	-90°	304.5	0	θ_4
5	90°	0	0	θ_5
6	0	0	0	θ_6

The manipulator is required to apply a 15 N pressing force while drawing the circles. Figures 6 and 7 show the end-effector position in $\vec{u}_2^0$ (*Y*) and $\vec{u}_3^0$ (*Z*) axes while it tries to follow the required circular trajectories with the modified Admittance and Hybrid controls, respectively.

Different parameters are tried for the force-controlled outer loop of the Admittance Control and the force-controlled sub-space of the Hybrid Control. A suitable set of parameters lead to the force plots shown in Figures 8 and 9. The corresponding parameters are presented in the legends of these plots. PID control is used for the force-controlled outer loop of the Admittance Control to form the A matrix as in equation (5). On the other hand, as mentioned before, PI control is preferred for the force-controlled sub-space of the Hybrid Control.

As for the mobility directions, PD parameters for the position-controlled inner loop of the Admittance Control and the position-controlled sub-space of the Hybrid Control are selected using the method explained in the thesis of Dede [1], which is also briefly outlined here: Since the nonlinear feed-forward compensation term "N" cancels out the Coriolis, centrifugal and gravitational forces, the reduced equation of motion ($M\ddot{\theta} = \tau^* + \tau'$) resembles to that of a double-integrator plant with control and disturbance inputs τ^* and τ'. Utilizing this fact, the control input is generated with a PD action as

$$\tau^* = K_p(\theta_r - \theta) + K_d(\dot{\theta}_r - \dot{\theta}) \quad (10)$$

and the parameters K_p and K_v are determined as follows:

$$K_v = 2\zeta\omega_n M' \quad (11)$$

$$K_p = \omega_n^2 M' \quad (12)$$

Here, for sake of simplicity, M' is taken as the diagonal portion of the mass matrix *M*. The damping ratio ζ is selected as 0.8 and the natural frequency ω_n is selected as 50 rad/s, which happens to be a reasonable value determined after few trials. The position control performance of the manipulator in tracking the required circular paths are shown in Figures 6 and 7 using the Admittance and the Hybrid control schemes.

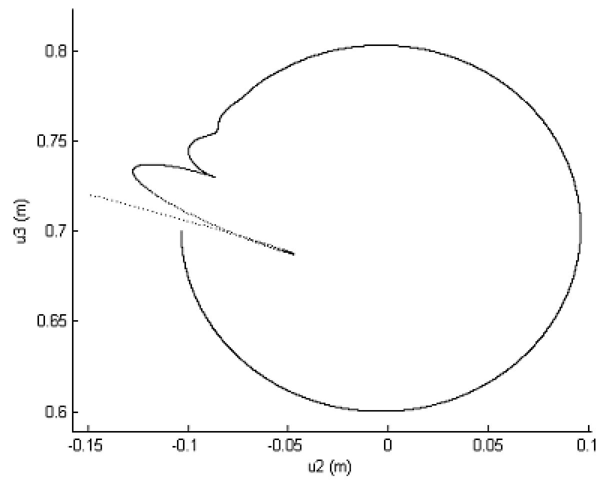

Fig. 6. Circle drawn on the task plane by the manipulator using Admittance Control.

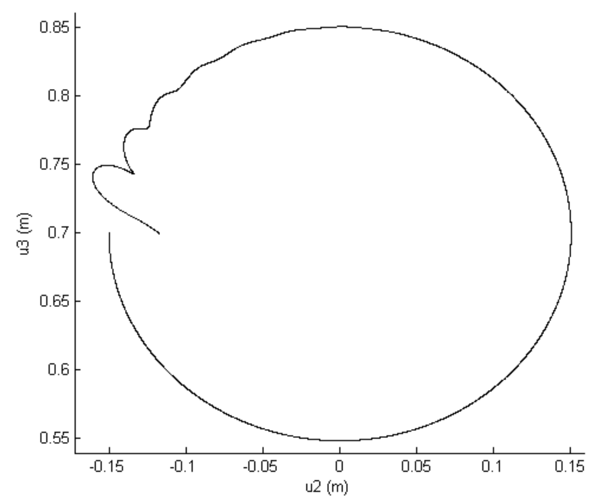

Fig. 7. Circle drawn on the task plane by the manipulator using Hybrid Control.

As it can be observed from Figures 6 and 7, there are overshoots and oscillations at the beginning of the operation in both control schemes. This is due to the disorientation of the end-effector from the desired one at the beginning and trying to catch up with the desired orientation as the operation continues. The initial overshoots and oscillations can be eliminated to a large extent by starting the operation at the correct orientation or by giving the manipulator some time to correct its orientation before starting the task. Another fact to be pointed out is that the operation does not necessarily start at contact with the surface and it takes varying amount of time for each control scheme to drive the end-effector into contact. Moreover, for the Hybrid Control application, it is required to switch to a pure position controller until the contact is established.

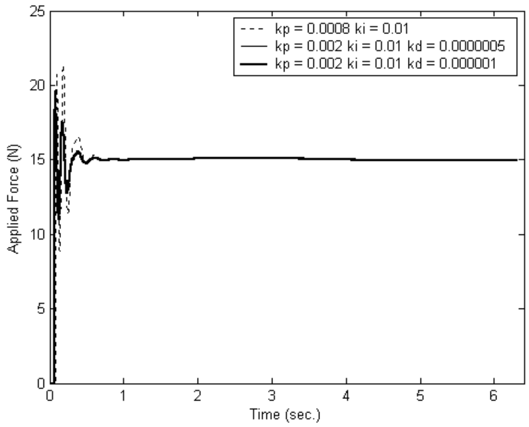

Fig. 8. Force applied by the end-effector to the task plane with the modified Admittance control scheme.

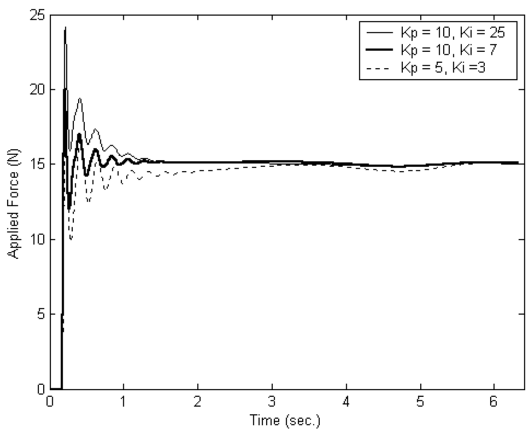

Fig. 9. Force applied by the end-effector to the task plane with the modified Hybrid control scheme.

VI. CONCLUSIONS

In the modified position/force control schemes introduced in this paper, the position errors in the joint space are determined exactly by using the inverse kinematic solution instead of determining them approximately by means of the inverse Jacobian matrix as in the customary schemes. Thus, with the modified schemes, it becomes possible to eliminate the instability problem that may occur in the customary schemes when the initial errors are large or when the end-effector is distracted largely from its desired course by a heavy disturbance.

The overshoots and oscillations that are observed in the simulations during the transient phase of both control schemes may be reduced, even if the starting orientation of the end-effector is not as desired, by using more elaborately determined control gains that contain scheduling with error and/or time. Such an improvement can be studied as an extension of this work.

Other items that may be considered in an extended study include surfaces other than planar ones, edge and surface contacts in addition to point contacts, and contacts with friction involving stick/slip motions.

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