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Design of Force / Position Controller and Position / Position Controller for Two Cooperating Robot Arms

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Abstract

This paper presents force/position control and position/position control schemes for two cooperating robot manipulators. The control mode for this system is a type of the leader/follower. The dynamics of the object are incorporated into the dynamics of leader arm, which yields a reduced order model of the dual-arm system dynamics. To control the system, a computed torque scheme is used to coordinate the leader arm. For the follower arm, the dynamics are expressed as a force dynamic equations, and a direct force control scheme to regulate interacting forces between two arms is devised. When two arms treat low stiffness materials, as an alternate approach, a computed torque scheme to control the leader arm and a position control scheme to control the follower arm are also devised. A numerical simulation is shown.

1. Introduction

Many tasks arise in assembly, repair and inspection that require multiple robot manipulators to perform in a coordinated manner. A multitude of challenging research issues arise from multi-arm coordinated control[1-5]. One of the fundamental problems that control designers face

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is the fact that a dual-arm robotic system manipulating a common load is described by a closed kinematic chain, resulting in system dynamic constraints and a reduction in the degrees of freedom[6]. Ahmad and Luo described a technique for coordinated motion control of multi-arm manipulators based on a master/slaver control structure for welding applications[7]. In this paper, a redundant manipulator with seven degrees of freedom(equivalent to two non-redundant arms) is required to weld on specific trajectory along a table. Constraints on singular conditions and motion limits are incorporated into a performance measure to be optimized. Seraji[9] develops an adaptive position/force control approach to the dual-arm problem. By employing an adaptive PID structure, knowledge of the mathematical model of the system is not required. The coupling effects between the manipulators are modelled as disturbances in the position and force equations which are then compensated for in the adaptation rule. In[11], Ro and Youcef-Toumi present a leader/follower control approach, but with a reference model structure. The leader manipulator is directed according to a prescribed reference model system while the follower arm follows via interacting force feedback. Robustness issues of the control scheme in the presence of actuator nonlinearities and model uncertainties as well as bounded disturbances are presented in[12]. In[15], M.A. Unseren and A.J. Koivo devised decoupled control architecture with reduced order model of dynamic equation.

In this paper, the reduced order model presented in[16] is further reduced by incorporating the object dynamics directly into the arm dynamics. To control the two-arm system, a force/position control structure is composed. To regulate the interacting force between two arms, the follower arm dynamics are expressed as a force dynamic equations and which is regulated by direct proportional/derivative force feedback. Also, when two arms treat low stiffness materials, as an alternate approach, to regulate the interacting force, a position/position control scheme is devised. In this scheme, in stead of using force feedback, a position feedback is used. By appropriate gain assignments, the interacting force is regulated such that a good motion coordination is achieved with dynamic decoupling, and a numerical simulation is shown to validate the result.

2. Two-arm Dynamics

The dynamic equations for the coordination of a two-arm system are derived[16] in which the object dynamics are treated independently. In this paper, the dynamics of the object are incorporated into that of the leader arm and considered as a portion of the robot arm dynamics. Therefore, the $3n \times 1$ size of two-arm dynamic systems are reduced to a $2n \times 1$ size of dynamic systems. In this paper, for convenience, the leader arm is called arm b and the follower arm is called arm a. The equations of motion for two robot arms coordinating an object can be expressed as the following :

$$H_a(q_a)\ddot{q}_a + C_a(q_a, \dot{q}_a) = \tau_a + J_a^T(q_a) F_a \tag{1}$$

$$H_b(q_b)\ddot{q}_b + C_b(q_b, \dot{q}_b) = \tau_b + J_b^T(q_b) F_b \tag{2}$$

where $q_a(q_b)$ is the $n \times 1$ joint angle vector for arm a(arm b) ; $\tau_a(\tau_b)$ is the $n \times 1$ joint torque vector for arm a(arm b) ; $H_a(H_b)$ is the $n \times n$ inertia matrix associated with arm a(arm b) ; C_a (C_b) is the nonlinear force vector of size $n \times 1$ including the gravity term ; and $J_a(J_b)$ is the $n \times n$ Jacobian matrix of arm a(arm b). $F_a(F_b)$ is an $n \times 1$ vector representing the forces and the moments at the point of interaction between arm a(arm b) and the object. Similar expressions for the dynamics of two – arm systems have been used in[15] and by others. The equations of motion for the object can be expressed as the following :

$$M_o \ddot{x}_o + Q_o(x_o, x_o) = -L_a^T F_a - L_b^T F_b \tag{3}$$

where

$$M_o = \begin{bmatrix} m_o I & 0 \\ 0 & K \end{bmatrix}, \quad Q_o = \begin{bmatrix} -m_o g \\ \vec{\omega} \times (K\, \vec{\omega}) \end{bmatrix}$$

where M_o is an inertia matrix of an object ; Q_o is an nonlinear force vector ; x_o is an $n \times 1$ vector representing the position and the orientation of the object center in the inertial space, and m_o is the mass matrix associated with the object. The $n \times n$ matrix $L_a(L_b)$ represents the transformation matrix associated with a finite length between the center of the object and the interaction point of arm $a(b)$. The object is assumed to be rigidly grasped by arm b and there is no force sensor on arm b such that

$$\dot{x}_o = L_b^{-1} \dot{x}_b \tag{4}$$

where $\dot{x}_b = [v_b^T,\ \omega_b^T]^T$ v_b and ω_b represent translational and angular velocities at the interaction point of arm b with the object. The Jacobian matrix J_b relates the joint velocities of robot arm to its endpoint velocities as $\dot{x}_b = J_b \dot{q}_b$. By substituting this into eq.(4), the velocities of the mass center position of the object is expressed in terms of the joint coordinates of robot arm b as the following :

$$\dot{x}_o = L_b^{-1} J_b \dot{q}_b \tag{5}$$

The acceleration of the mass center of the object, $\ddot{x}_o$, can be expressed in joint coordinates of arm b by differentiating eq.(5) with respect to time as follows :

$$\ddot{x}_o = L_b^{-1} J_b \ \ddot{q}_b + L_b^{-1} J_b q_b + L_b^{-1} J_b \ddot{q}_b \tag{6}$$

The object dynamics are expressed in the joint space with Eq.(6) as

$$M_o G\ (\ddot{q}_b,\ \ddot{q}_b) + Q_{0b}(q_b,\ q_b) = -L_a^T F_a - L_b^T F_b \tag{7}$$

where

$$G(\dot{q}_b,\ \ddot{q}_b) = L_b^{-T} J_b \dot{q}_b + \dot{J}_b q_b + L_b^{-T} J_b \ddot{q}_b,$$

$$Q_{ob} = \begin{bmatrix} -m_o g \\ \Omega(K L_b^{-1} J_b q_b)_l \end{bmatrix}$$

and Q_{ob} represents Q_o in the joint coordinates of arm b. l means that the matrix(·) Contains only the lower three rows of the matrix of (·). In eq.(7), the external force term, F_b is expressed as the following :

$$F_b = -L_b^{-T} M_o G - L_b^{-T} Q_o - L_b^{-T} L_a^T F_a \tag{8}$$

The dynamics of the object are incorporated into the dynamics of arm b by substituting Eq.(8) into Eq.(2).

$$H_b^* \ddot{q}_b = \tau_b + C_{ob} - \ \gamma F_a \tag{9}$$

where $H_b^* = H_b + H_b^T L_b^{-T} M_o L_b^{-1} J_b$, $\gamma = J_b^T L_b^{-T} L_a^T$, and

$$C_{ob} = -J_b^T L_b^T Q_{ob} - C_b - J_b^T L_b^{-T} M_o (L_b^{-1} J_b + L_b^{-T} \dot{J}_b)\ \dot{q}_b$$

and H_b^* represents the inertia matrix of arm b dynamics incorporating that of the object ; C_{ob} represents the nonlinear force vector of arm b dynamics incorporating that of the object ; γ represents the Jacobian matrix reflecting the interacting force F_a in the joint space of arm a to arm b.

3. Design of A Force/Position and A Position/Position Controller

In this chapter, a force/position control scheme and a position/position control schem are devised for motion coordination of two cooperating robot arms.

3.1 A Position Control of Leader Arm via Computed Torque Method

The open－loop dynamic equations of arm b show that the dynamics of arm b are forced by the interacting force, F_a. A form of computed torque method is proposed to achieve position control of arm b. The controller τ_b is composed as

$$\tau_b = \hat{H}_b^*(\ddot{q}_{db} - K_{ab}\dot{E} - K_{pb}E) - \hat{C}_{ab} \tag{10}$$

where $E = q_b - q_{db}(t)$; $q_{db}(t)$ is the desired joint angle vector ; $\hat{H}_b^*$ is an estimate of the inertia matrix of arm b ; $\hat{C}_{ob}$ is a feedforward estimate of the nonlinear force vector of arm b dynamics and the object dynamics ; K_{db} and K_{pb} are $(n \times n)$ derivative and proportional gain matrix, respectively. Applying the control τ_b to Eq(9) yields the resulting equations of motion as

$$\ddot{q}_b = H_b^{*-1} \{ \hat{H}_b^*(\ddot{q}_{db} - K_{ab}\dot{E} - K_{pb}E) - \hat{C}_{ob} + C_{ob} - \gamma F_a \} \tag{11}$$

Suppose that all the states and parameters of arm b are perfectly known such that $\hat{H}_b^* = H_b^*$ and $C_{ob} = \hat{C}_{ob}$ are satisfied, then arranging Eq.(11) yields the following error dynamics

$$\ddot{E} + K_{db}\dot{E} + K_{pb}E = -H_b^{*-1} \gamma F_a \tag{12}$$

where F_a represents the interacting force vector between arm a and arm b. In the error dynamic equation(12), the interacting forcing term $-H_b^{*-1} \gamma F_a$ disturbs the error dynamics. Therefore, by regulating the interacting forces, a desirable motion coordination is achieved. In order to regulate the interacting forces, the dynamics of arm a are expressed in terms of force dynamic equations, and then the regulation of the interacting force can be achieved by controlling the force dynamics.

3.2 A Force Regulator for Follower Arm via A Computed Torque Method

In order to express the arm a dynamics in terms of force, the dynamics expressed in the joint space must be expressed in the task space beforehand. The joint space can be mapped to the task space by the Jacobian matrix as

$$\dot{q}_a = j_a^{-1}\dot{x}_a, \ \ddot{q}_a = \dot{J}_a^{-1}\dot{x}_a + J_a^{-1}\ddot{x}_a \tag{13}$$

where it is assumed that the Jacobian matrix is not singular such that there always exists an inverse Jacobian matrix. Substituting Eq.(13) into Eq.(1) and arranging it yield the following dynamic equations,

$$\ddot{x}_a = J_a H_a^{-1}(\tau_a + J_a^T F_a - C_a) - J_a \dot{J}_a^{-1} \dot{x}_{a*} \tag{14}$$

Eq.(14) represents the dynamics of arm a interacting with arm b where the acceleration and the velocity of the arm a are expressed in the task space. The interacting force can be expressed by the position differences of the end points between arm a and b in the task space as

$$F_a = K_{pp}(x_a - x_b) \tag{15}$$

where K_{pp} is an $n \times n$ diagonal stiffness gain matrix of sensor and gripper. Also, in Eq.(14), the velocity and acceleration of arm a in task space can be expressed by the first and the second derivative of force vector, respectively as

$$x_a = x_b + K_{pp}^{-1} F_a,\ \dot{x}_a = \dot{x}_b + K_{pp}^{-1} \dot{F}_a,\ \ddot{x}_a = \ddot{x}_b + K_{pp}^{-1} \ddot{F}_a \tag{16}$$

By substituting the above equations into Eq.(14) and arranging the equations, the force dynamic equations for arm a are expressed as

$$\ddot{F}_a = K_{pp} J_a H_a^{-1}(\tau_a + J_a^T F_a - C_a) - K_{pp} J_a \dot{J}^{-1} K_{pp}^{-1} \dot{F}_a - K_{pp}(\ddot{x}_b + J_a \dot{J}_a^{-1} \dot{x}_b) \tag{17}$$

In the open-loop force dynamics in Eq.(17), there is a coupling term including the second derivative of x_b, which can be expressed in the joint space by the Jacobian relation as $\dot{x}_b = J_b \dot{q}_b$ and $\ddot{x}_b = \dot{J}_b \dot{q}_b + J_b \ddot{q}_b$. In this way, the second derivative term $\ddot{x}_b$ can be expressed by the second derivative of the joint angles of arm b. With the assumption of $H_b^* = \hat{H}_b^*$ and $C_{ob} = \hat{C}_{ob}$, the second derivative of the joint angles in Eq.(15) is expressed the first order states by the following relation $\ddot{q}_b = \ddot{q}_{ab} - K_{db}\dot{E} - K_{pb}E + D_b(t) - \gamma F_a$. In the force dynamic equations of arm a, the interacting force F_a in the closed-loop dynamics of arm b can be regulated by a direct force control scheme. In order to control arm a, a computed torque control scheme with a feedforward compensator is composed as

$$\begin{aligned}\tau_a = -(\hat{J}_a \hat{H}_a^{-1})^{-1} K_{pp}^{-1}\ \{ (K_{pf} F_a + K_{df} \dot{F}_a) - J_a \dot{J}_a^{-1} K_{pp}^{-1} \dot{F}_a \\ - K_{pp}(\dot{J}_b + J_a \dot{J}_a^{-1} J_b)\dot{q}_b + K_{pp} J_b\ \gamma\ F_a\ \} - J_a^T F_a + \hat{C}_a\end{aligned} \tag{18}$$

where K_{pf} and K_{df} are $n \times n$ proportional and derivative gain matrix, respectively ; $\hat{C}_a$ is a feedforward compensating term of the nonlinear force vector of arm a dynamics ; Applying the control in Eq.(18) to Eq.(17) and arranging it with the assumption of $\hat{J}_a \hat{H}_a^{-1} = J_a H_a^{-1}$ and $\hat{C}_a = C_a$, then the closed-loop force dynamic equations of arm a which regulate the interacting force F_a are obtained as

$$\ddot{F}_a + K_{da}\dot{F}_a + K_{pa}F_a = -K_{pp}J_b(\ddot{q}_{db} - K_{db}\dot{E} - K_{pb}E) \quad (19)$$

So far, in this paper, the dynamics of the object are incorporated into those of the leader arm such that the dynamics of the two－arm system are expressed in a simplified equation. Therefore, the scheme becomes computationally feasible. Also, the dynamics of the follower arm are expressed in force dynamic equations which are appropriate for a direct force control. To regulate the interacting forces between two arms, a force control based on a computed torque method is used. This force control scheme is based on the information of the force and its derivative. The control scheme damps out the chattering which usually occurs when only a force feedback control is used. In control of the two－arm system, the gains for Eq.(12) and Eq.(19) can be designed appropriately such that the interacting forces are regulated. In this way, the interacting forces are eventually regulated to zero in error dynamics. Therefore, arm b dynamics become independent of arm a dynamics such that a good motion coordination is achieved with dynamic decoupling.

3.3 A Position Controller for the Follower Arm

In eq.(19), the dynamic equations of arm a are expressed in task space with interacting force. In case where there is no rigid grasping at the interaction point, e.g. a follower arm with an elastic gripper, a position sensor can substitute a force sensor such that the interacting force, F_a can be expressed by the task space variables as in eq.(14). In this kind of system, an alternate approach to force regulation is to use a position control scheme to control arm a. In control of arm a, a proportional and derivative position feedback controller with feedforward estimate is composed as

$$\tau_a = (\hat{J}_a \hat{H}_a^{-1})^{-1} P^* + \hat{C}_a \quad (20)$$

where

$$P^* = -K_{fp}K_{pp}(x_a - x_b) - K_{fd}K_{pp}(\dot{x}_a - \dot{x}_b)$$

where, as in Eq.(20), the feedback force, F_a and the derivative of it are expressed by the multiplication of force sensor gain matrix to the position difference and the velocity difference between the end point of arm b and arm a, respectively. Applying the proposed control to eq.(17) and arranging it with the assumption of $\hat{J}_a \hat{H}_a^{-1} = J_a H_a^{-1}$ and $\hat{C}_a = C_a$ yields

$$\ddot{x}_a = -(K_{fp} - J_a H_a^{-1} J_a^T) K_{pp}(x_a - x_b) - K_{fb}K_{pp}(\dot{x}_a - \dot{x}_b) - J_a J_a^{-1} \dot{x}_a \quad (21)$$

Eq.(21) can be rearranged as

$$\dot{x}_a + K_D \dot{x}_a + K_p x_a = K_p x_b + K_{fd} K_{pp} \dot{x}_b \tag{22}$$

where

$$K_p = (K_{fp} - J_a H_a^{-1} J_a^T) K_{pp}, \; K_D = (K_{fd} + J_a J_a^{-1} K_{pp}^{-1}) K_{pp}$$

and where K_{fp} and K_{fd} are design parameter such that they can be designed to make K_D and K_p positive diagonal matrices. Eq.(22) describes the closed-loop dynamic equation of arm *a* where the position control scheme is applied for controlling arm *a*. In control of the two-arm system, the gains for Eq.(19) and Eq.(22) can be selected properly such that the arm *a* is controlled to follow arm *b* such that the interacting force is regulated, which eventually yield zero interacting force in error dynamics. Therefore, arm *b* dynamics become independent of arm *a* dynamics such that good motion coordination is achieved with dynamic decoupling. For the proposed force-position control scheme, a numerical example is made with dual 3 degree-of-freedom planar arms.

4. Numerical Example

In these numerical examples, the motion coordination by the force-position control scheme is simulated. Dual 3 degree-of-freedom planar arms are used with a point mass at the center of each arm as shown in Fig.1.

The dimensions of the dual arms are also shown in Table 1. In the simulation of force-position control scheme, the initial and the final position of the center of the object in cartesian coordinates are given as : X_i=1.346m, Y_i=0, and X_f=1.8m, Y_f=0. For the desired dynamics of arm *b*, a joint space scheme is applied with cubic polynomials. Based on a computed torque scheme, the position control is applied to coordinate arm *b* along the desired dynamics, and the force control scheme is ap-

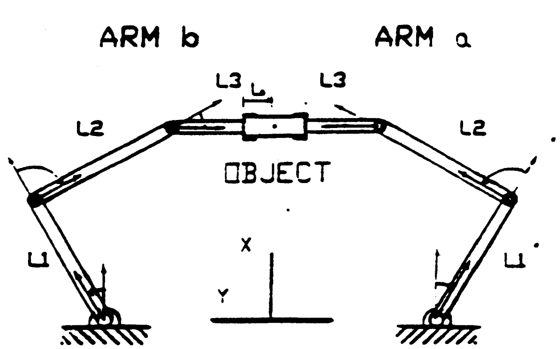

Fig. 1 Dual-arm System.

Table 1 Dimensions of dual-arm system.

Arm. Obj.	Len. of arm	mass	Moment of Ine.
L_1	1 *m*	2 *kg*	0.2 *kg-m*^{2}
L_2	1 *m*	2 *kg*	0.2 *kg-m*^{2}
L_3	0.5 *m*	1 *kg*	0.1 *kg-m*^{2}
L_4	0.134 *m*	0.5 *kg*	0.04 *kg-m*^{2}

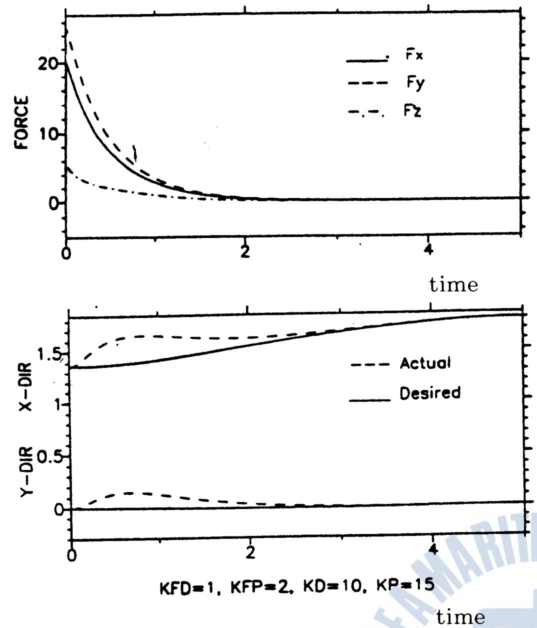

Fig. 2 Force/Position control with overdamped gains.

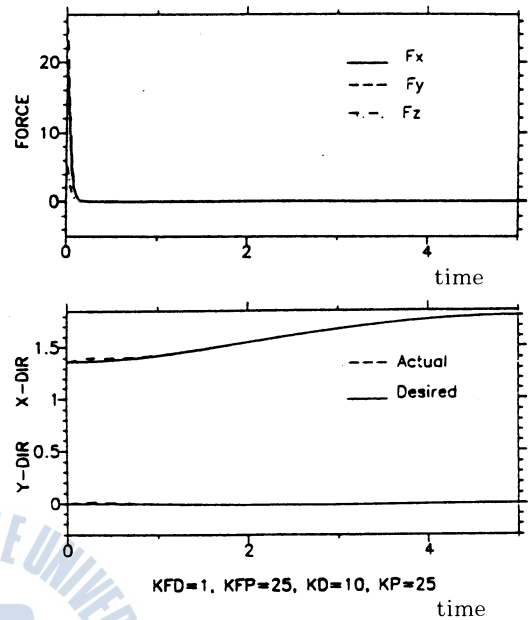

Fig. 3 Force/Position control with critical damped gains.

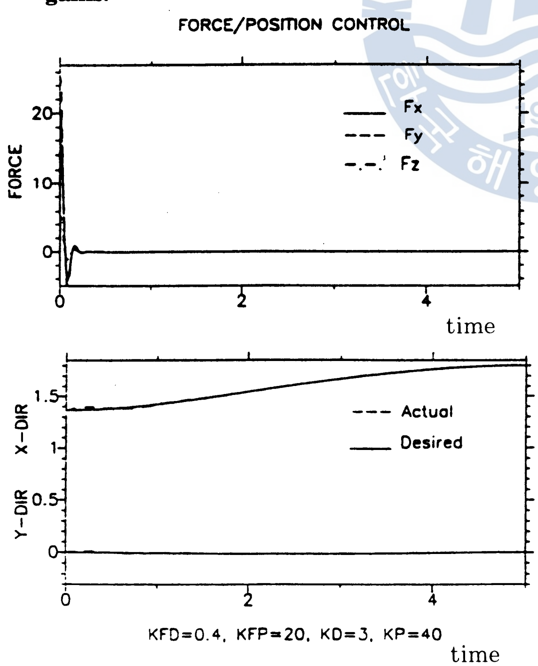

Fig. 4 Force/Position control with underdamped gains.

plied to regulate the interacting forces.

For the force/position control, arm b is coordinated along the X-axis with initial force excitations of 10 (N) for F_x and F_y (no torque excitation). Fig.2 shows that the actual system dynamics of arm b are following the desired dynamics by the computed torque scheme while the interactive force F_a is regulated by the force control. In Fig.2 gains are set such that the closed-loop system shows overdamped characteristics. In Fig.2, the initially excited positions are not regulated fast enough such that the coupled dynamics of arm b are affected for a while. Therefore, the motion coordination of arm b is not desirable over the transient period. In Fig.3, with near-critical gains, the initially excited interactive force converges to zero fast enough such that the dynamics of both arms are decoupled. As a result, a good motion coordination is achieved. in Fig.4, with underdamped gains, the coupled dynamics of the arm ***b*** are affected by the transient dynamics of arm ***a*** such that the motion coordination of the arm ***b*** is not desirable. By a good regulation of the interactive force with appropriate selection of feedback gains, the dynamics of both arms are decoupled such that a good motion coordination is achieved.

According to the above numerical simulation results, it is shown that the proposed control schemes exhibit a good motion coordination of the two-arm system. Also, with appropriate control gains, the decoupling of the dynamics between arm ***a*** and arm ***b*** is achieved.

Conclusion

In this paper, the dynamics of the object are incorporated into the dynamics of leader arm such that the order of the two-arm system dynamics are reduced. To control the two-arm system, two different control schemes, a force/position control and a position/position control scheme are devised. By assigning appropriate gains to the proposed control schemes, the interacting force between two arms is regulated to zero over the motion coordination such that the dynamics are decoupled. As a result, a good motion coordination is achieved. As an extension of this paper, a study of the stability and performance robustness is on-going.

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