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Adaptive Control of Dual-Arm Robots

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Abstract: The paper describes three strategies for adaptive control of cooperative dual-arm robots. In the position-position control strategy, the adaptive controllers ensure that the end-effector positions of both arms track desired trajectories in Cartesian space despite unknown time-varying interaction forces exerted through the load. In the position-hybrid control strategy, the adaptive controller of one arm controls end-effector motions in the free directions and applied forces in the constraint directions; while the adaptive controller of the other arm ensures that the end-effector tracks desired position trajectories. In the hybrid-hybrid control strategy, the adaptive controllers ensure that both end-effectors track reference position trajectories while simultaneously applying desired forces on the load. In all three control strategies, the cross-coupling effects between the arms are treated as "disturbances" which are rejected by the adaptive controllers while following desired commands in a common frame of reference. The adaptive controllers do not require the complex mathematical model of the arm dynamics or any knowledge of the arm dynamic parameters or the load parameters such as mass and stiffness. The controllers have simple structures and are computationally fast for on-line implementation with high sampling rates.

1. Introduction

During the past decade, robot manipulators have been utilized in industry for performing simple tasks, and it is foreseen that in the near future anthropomorphic robots will replace human operators in carrying out various complex tasks both in industry and in hazardous environments. Nevertheless, present-day robots can be considered at best as "handicapped" operators due to their single-arm structure. It is evident that multiplicity of robot arms yields greater dexterity and increased efficiency and provides the capability of handling larger loads. Dual-arm robots will therefore have capabilities which may match those of ambidextrous human operators in dexterity and efficiency.

The research on dual-arm robots is at its early stages at the present time, and a few approaches are currently available. Nakano et al. [1] propose a method for control of dual-arm robots in a master/slave manner. Ishida [2] considers parallel and rotational transfer of loads using dual-arm robots. Fujii and Kurono [3] suggest a technique for dual-arm control based on the method of virtual reference. Alford and Belyeu [4] describe a method for coordinated control of two arms. Zheng and Luh [5,6] obtain constrained relations and control laws for two coordinated arms. Tarn et al. [7] employ the exact linearization technique for dual-arm control. Hayati [8] proposes a method for controlling dual-arm robots based on partitioning the load between the arms. Koivo [9] suggests an adaptive control technique for dual-arm robots using the self-tuning approach. Lim and Chyung [10] describe a positional control scheme for two cooperating robot arms.

The control architecture considered in this paper is based on the tri-level hierarchical control of dual-arm robots as shown in Figure 1. In this tri-level control architecture, the high level plans the task to be performed and decomposes the task into appropriate subtasks for the right and left arms. In the intermediate level, each subtask is transformed into a sequence of synchronous desired trajectories of end-effectors motions and applied forces. The low level is concerned with the execution of the desired trajectories and employs feedback from the current status of the arms. In this tri-level hierarchy, the low level "achieves" the desired motion and operates in "millisecond" time-scale, the intermediate level "determines" the motion desired for the subtask in "second" time-scale, and the high level "plans" the subtask sequences in "minute" time-scale.

The present paper describes three control strategies for low-level adaptive control of cooperative dual-arm robots using recent results on adaptive control of single-arm robots [11-13]. In each control strategy, a suitable task-related coordinate frame of reference is chosen for both arms and the desired motions and applied forces for each arm are expressed in this common reference frame. Then each arm will move as though it were carrying out the commanded motion by itself in the reference frame. The adaptive controllers ensure that the controlled variables track the desired reference commands and reject the unwanted disturbances caused by interaction forces and torques exerted through the load.

The paper is structured as follows. In Section 2, the position-position control strategy is discussed. In Section 3, the position-hybrid control strategy is developed. The hybrid-hybrid control strategy is addressed in Section 4. Section 5 discusses the results of the paper and draws some conclusions.

2. Position-Position Control Strategy

In this section, we shall investigate the first control strategy for dual-arm manipulators in which both arms are in pure position control, as shown in Figure 2. In other words, the positions and orientations of both end-effectors are required to track desired trajectories in a common frame of reference. In this situation, uncontrolled forces and torques will be exerted on the common load held by the end-effectors. In this section, we investigate the performance of the position control systems in the face of the interaction forces and torques exerted through the load.

2.1 Position Controller for Right/Left Arm

The dynamic model of each manipulator arm can be represented by a differential equation in Cartesian space as [14]

$$M(X)\ddot{X} + N(X,\dot{X}) + G(X) + H(\dot{X}) \pm f = F \qquad (1)$$

where the above terms are defined as:

$X, \dot{X}, \ddot{X}$ = nx1 vectors of end-effector position, velocity and acceleration in a fixed task-related Cartesian frame of reference

F = nx1 vector of "virtual" Cartesian forces applied to the end-effector as the control input

$M(X)$ = nxn symmetric positive-definite Cartesian mass matrix

$N(X,\dot{X})$ = nx1 Cartesian Coriolis and centrifugal force vector

$G(X)$ = nx1 Cartesian gravity loading vector

$H(\dot{X})$ = nx1 Cartesian friction force vector

f = nx1 vector of forces and torques exerted by the end-effector on the load

The force/torque vector f both imparts motion to and applies force/torque on the load and acts as the coupling element between the two arms. In the following analysis, the force/torque vector f will be considered as a "disturbance input" to the position control system. The function of the control system is to ensure that the end-effector position vector X tracks the nx1 vector of desired trajectory X_d despite the disturbance force f. For each manipulator arm, let us apply the linear adaptive position control law [12]

$$F(t) = d(t) + [K_p(t)\, E(t) + K_v(t)\dot{E}(t)] + [C(t)\, X_d(t) + B(t)\, \dot{X}_d(t) + A(t)\, \ddot{X}_d(t)] \qquad (2)$$

as shown in Figure 3, where $E(t) = X_d(t) - X(t)$ is the nx1 position tracking-error vector. In the control law (2), the nx1 vector $d(t)$ is an auxiliary signal to be synthesized by the adaptation scheme, while $[K_pE + K_v\dot{E}]$ and $[CX_d + B\dot{X}_d + A\ddot{X}_d]$ are the contributions due to the feedback and feedforward controllers respectively. Following the method described in Reference [12], the required auxiliary signal and controller gains are updated according to the following adaptation laws:

$$d(t) = d(0) + \delta_1 \int_0^t r(t)dt + \delta_2 r(t) \tag{3}$$

$$K_p(t) = K_p(0) + \alpha_1 \int_0^t r(t) E'(t)dt + \alpha_2 r(t) E'(t) \tag{4}$$

$$K_v(t) = K_v(0) + \beta_1 \int_0^t r(t) \dot{E}'(t)dt + \beta_2 r(t) \dot{E}'(t) \tag{5}$$

$$C(t) = C(0) + \nu_1 \int_0^t r(t) X_d'(t)^{dt} + \nu_2 r(t) X_d'(t) \tag{6}$$

$$B(t) = B(0) + \gamma_1 \int_0^t r(t) \dot{X}_d'(t)^{dt} + \gamma_2 r(t) \dot{X}_d'(t) \tag{7}$$

$$A(t) = A(0) + \lambda_1 \int_0^t r(t) \ddot{X}_d'(t)^{dt} + \lambda_2 r(t) \ddot{X}_d'(t) \tag{8}$$

where

$$r(t) = W_p E(t) + W_v \dot{E}(t) \tag{9}$$

is an nx1 vector, $\{\delta_1, \alpha_1, \beta_1, \nu_1, \gamma_1, \lambda_1\}$ are positive scalars, $\{\delta_2, \alpha_2, \beta_2, \nu_2, \gamma_2, \lambda_2\}$ are positive or zero scalars, and the prime denotes transposition. In equation (9), W_p and W_v are nxn constant weighting matrices chosen by the designer to reflect the relative significance of the position and velocity errors E and $\dot{E}$. It must be noted that since we cannot physically apply the Cartesian control force F to the end-effector, we instead compute the nx1 equivalent joint torque vector T to effectively cause this force. Thus, for each manipulator arm, the control law in joint space is given by

$$T(t) = J'(\theta) F(t) = J'(\theta) \{ d(t) + K_p(t)E(t) + K_v(t)\dot{E}(t) + C(t)X_d(t) + B(t)\dot{X}_d(t) + A(t)\ddot{X}_d(t)\} \tag{10}$$

where θ is the nx1 vector of joint angular positions and $J(\theta)$ is the nxn Jacobian matrix of the manipulator arm.

Because of the simplicity of the adaptation laws (3) - (8), the robot control algorithm can be implemented using high sampling rates (typically 1 KHz). In each sampling period (~ 1msec), the controller gains can change significantly; whereas the terms M, N, G, H, and f in the robot model (1) cannot change noticeably. As a result, in deriving equations (3) - (8), it was assumed that these terms are unknown and "slowly time-varying" relative to the adaptation laws. It is seen that the inclusion of the disturbance force f in the robot model (1) does not affect the controller adaptation laws since the change in f over one sampling period is relatively small.

The above argument suggests that when both manipulator arms are controlled using the two independent adaptive position controllers, we expect the end-effectors to track the desired position trajectories despite the interaction forces and torques exerted through the load. It must be noted that since the force on the load is not a controlled variable in this scheme, this strategy can lead to undesirable load forces when the position trajectories are not planned in coordination or are not tracked closely.

3. Position-Hybrid Control Strategy

In this section, the position-hybrid control strategy for dual-arm manipulators will be studied in which the left arm is in pure position control and the right arm is in hybrid position/force control, as shown in Figure 4. In other words, for the left arm, the end-effector position is required to track a desired trajectory in a frame of reference. For the right arm, in the same reference frame, the contact force between the end-effector and the load must be controlled in the directions constrained by the load, while the end-effector position is to be controlled simultaneously in the free directions. This control strategy can be applied when one robot arm is confined to operate only in position control mode whereas the other arm can be controlled in hybrid control mode.

3.1 Position Controller for Left Arm

For the left arm, the interaction forces and torques exerted through the load are considered as "disturbances," and the adaptive position control system can ensure tracking of the desired position trajectories despite such disturbances, as outlined in Section 2. The adaptive position control law for the left arm shown in Figure 3 is given by [12]

$$T_\ell(t) = J_\ell'(\theta_\ell)\ [\bar{d}(t) + \bar{K}_p(t)E(t) + \bar{K}_v(t)\dot{E}(t) + \bar{C}(t)X_{\ell d}(t) + \bar{B}(t)\dot{X}_{\ell d}(t) + \bar{A}(t)\ddot{X}_{\ell d}(t)] \qquad (11)$$

where T_ℓ is the nx1 joint torque vector, θ_ℓ is the nx1 joint angle vector, $J_\ell(\theta_\ell)$ is the nxn Jacobian matrix, $X_{\ell d}(t)$ is the nx1 vector of desired Cartesian position trajectory, $E(t) = X_{\ell d}(t) - X(t)$ is the nx1 position tracking-error vector and the terms in equation (11) are adapted as follows:

$$\bar{d}(t) = \bar{d}(0) + \delta_1 \int_0^t r(t)dt + \delta_2 r(t) \qquad (12)$$

$$\bar{K}_p(t) = \bar{K}_p(0) + \alpha_1 \int_0^t r(t)E'(t)dt + \alpha_2 r(t)E'(t) \qquad (13)$$

$$\bar{K}_v(t) = \bar{K}_v(0) + \beta_1 \int_0^t r(t)\dot{E}'(t)dt + \beta_2 r(t)\dot{E}'(t) \qquad (14)$$

$$\bar{C}(t) = \bar{C}(0) + \nu_1 \int_0^t r(t)\ X_{\ell d}'(t)dt + \nu_2 r(t)\ X_{\ell d}'(t) \qquad (15)$$

$$\bar{B}(t) = \bar{B}(0) + \gamma_1 \int_0^t r(t)\ \dot{X}_{\ell d}'(t)dt + \gamma_2 r(t)\ \dot{X}_{\ell d}'(t) \qquad (16)$$

$$\bar{A}(t) = \bar{A}(0) + \lambda_1 \int_0^t r(t)\ \ddot{X}_{\ell d}'(t)dt + \lambda_2 r(t)\ \ddot{X}_{\ell d}'(t) \qquad (17)$$

where

$$r(t) = W_p E(t) + W_v\ \dot{E}(t) \qquad (18)$$

and the symbols are defined in Section 2.

3.2 Hybrid Controller for Right Arm

We shall now discuss the hybrid position/force controller for the right arm. Consider a task-related "constraint frame" (coordinate system) which is defined by the particular contact situation occurring between the right end-effector and the load. In this frame, the n degrees-of-freedom (or directions) in the Cartesian space {X} can be partitioned into two orthogonal sets; the m constraint directions in subspace {Z} and the ℓ free directions in subspace {Y}, with $n = m + \ell$. In the m constraint directions, the end-effector makes contact with the load and the contact force needs to be controlled. In the ℓ free directions, the end-effector is free to move and the end-effector position is to be controlled. In the hybrid control architecture [16,17], two separate controllers are employed for simultaneous force and position control. The "force controller" achieves tracking of desired force setpoints in the constraint directions; while the "position controller" accomplishes tracking of desired position trajectories in the free directions.

The dynamic model of the right arm in the constraint directions can be written as [13]

$$A(X,\dot{X})\ \ddot{P}(t) + B(X,\dot{X})\ \dot{P}(t) + P(t) + C_p(Y) \pm f_z = F_z(t) \qquad (19)$$

where F_z is the mx1 "virtual" Cartesian force vector applied to the end-effector in the constraint directions, Z is the mx1 vector of end-effector position, the mxm matrices A and B are highly complex nonlinear functions of the end-effector position X, C_p is the cross-coupling from the position loop in the force loop and f_z is the component of the force exerted on the end-effector by the load in the constraint directions. The term f_z represents the cross-coupling that exists between the arms through the load and is considered as a "disturbance" to the hybrid controller.

In a recent paper [13], an adaptive force control scheme is developed within the hybrid control architecture. For the right arm, the linear adaptive force control law in the constraint directions is given by [13]

$$F_z(t) = F_r(t) + d(t) + K_p(t)\, E(t) + K_I(t) \int_0^t E(t)dt - K_v(t)\dot{Z}(t) \quad (20)$$

as shown in Figure 5, where $F_r(t)$ is the desired contact force on the load used as a feedforward term, $d(t)$ is an auxiliary signal, $E(t) = F_r(t) - P(t)$ is the deviation of the actual force $P(t)$ from the desired value, and $\{K_p(t),\ K_I(t),\ K_v(t)\}$ are adaptive gains of the PID controller. The terms in the force control law (20) are adapted as follows:

$$d(t) = d(0) + \delta_1 \int_0^t q(t)dt + \delta_2 q(t) \quad (21)$$

$$K_I(t) = K_I(0) + \alpha_1 \int_0^t q(t)\, E^{*\prime}(t)dt + \alpha_2 q(t)\, E^{*\prime}(t) \quad (22)$$

$$K_p(t) = K_p(0) + \beta_1 \int_0^t q(t)\, E'(t)dt + \beta_2 q(t)\, E'(t) \quad (23)$$

$$K_v(t) = K_v(0) - \gamma_1 \int_0^t q(t)\, \dot{Z}'(t)dt - \gamma_2 q(t)\, \dot{Z}'(t) \quad (24)$$

where

$$q(t) = W_I\, E^*(t) + W_p E(t) - W_v \dot{Z}(t) \quad (25)$$

In equations (21)-(25), $E^*(t) = \int_0^t E(t)dt$ is the integral error vector, $\{\delta_1,\ \alpha_1,\ \beta_1,\ \gamma_1\}$ are positive scalars, $\{\delta_2,\ \alpha_2,\ \beta_2,\ \gamma_2\}$ are positive or zero scalars, and $\{W_I,\ W_p,\ W_v\}$ are constant weighting matrices chosen by the designer to reflect the relative significance of E^*, E and $\dot{Z}$.

The dynamic model of the right arm in the free directions can be written as [13]

$$A_o(X,\dot{X})\, \ddot{Y}(t) + B_o(X,\dot{X})\, \dot{Y}(t) + C_o(X,\dot{X})Y(t) + C_f(P) \pm f_y = F_y(t) \quad (26)$$

where f_y is the component of the end-effector force in the free directions, C_f is the cross-coupling from the force loop, A_o, B_o, C_o are complex nonlinear matrices, Y is the end-effector position vector and F_y is the "virtual" end-effector control force. For the right arm, the linear adaptive position control law in the free directions is given by

$$F_y(t) = \tilde{d}(t) + \tilde{K}_p(t)\, E_p(t) + \tilde{K}_v(t)\, \dot{E}_p(t) + \tilde{C}(t)\, R(t) + \tilde{B}(t)\, \dot{R}(t) + \tilde{A}(t)\, \ddot{R}(t) \quad (27)$$

as in Section 2, where R is the desired position trajectory, $E_p = R - Y$ is the position tracking-error, and F_y is the "virtual" Cartesian force in the free directions. Thus, in order to implement the force and position controllers (20) and (27) in the hybrid control architecture, the joint space control law for the right arm is given by

$$T_r(t) = J_r'(\theta_r) \begin{pmatrix} F_z(t) \\ F_y(t) \end{pmatrix} \quad (28)$$

as shown in Figure 6, where θ_r is the joint angle vector, T_r is the joint torque vector, and J_r is the Jacobian matrix of the right arm with appropriate reordering of columns of J_r if necessary.

The hybrid controller adaptation laws (3)-(8) and (21)-(24) are extremely simple, and therefore the control algorithm can be implemented using high sampling rates ($\simeq$ 1 KHz); yielding improved performance particularly in force control applications. Since in each sampling period ($\simeq$ 1 msec) the terms in the robot models (19) and (26) cannot change noticeably, it is reasonable to assume that these terms are "slowly time-varying" compared to the adaptation scheme. Thus the inclusion of the disturbance forces f_z and f_y in the robot models (19) and (26) does not affect the controller performance.

We conclude that using the position-hybrid control strategy, the left end-effector will track the desired position trajectory despite the interaction forces through the load. The right end-effector will exert the desired force on the load in certain directions while simultaneously tracking the desired position trajectory in the orthogonal directions. It must be noted that in this control strategy, slight fluctuations may be observed on the load force due to very small vibrations of the left arm under position control.

4. Hybrid-Hybrid Control Strategy

In this section, the hybrid-hybrid control strategy for dual-arm manipulators will be studied in which both arms are in hybrid position/force control, as shown in Figure 7. In other words, in a common frame of reference, for both arms, the forces exerted by the end-effectors on the load in the constraint directions (Z) must be controlled, while simultaneously the end-effectors are required to track desired position trajectories in the free directions (Y). Any unwanted forces and torques on the load generated by the relative position and orientation of the end-effectors will act as "disturbances," and the adaptive hybrid controllers ensure that the desired position/force trajectories are tracked despite such disturbances.

4.1 Hybrid Controller for Right/Left Arm

Following Section 3, for each manipulator arm the hybrid position/force control law in the joint space can be written as

$$T(t) = J'(\theta)\begin{pmatrix} F_z(t) \\ F_y(t) \end{pmatrix} \qquad (29)$$

where $J(\theta)$ is the Jacobian matrix (with appropriate column reordering if necessary), and $F_z(t)$ and $F_y(t)$ are the "virtual" Cartesian forces applied to the end-effector in the constraint directions (Z) and free directions (Y), respectively. As shown in Figure 5, the force control law is given by

$$F_z(t) = P_r(t) + d(t) + K_I(t)\int_0^t E_z(t)dt + K_p(t)E_z(t) - K_v(t)\dot{Z}(t) \qquad (30)$$

where $P_r(t)$ is the desired force setpoint, $E_z(t) = P_r(t) - P_z(t)$ is the force tracking-error and the adaptation laws are:

$$d(t) = d(0) + \delta_1\int_0^t q(t)dt + \delta_2 q(t)$$

$$K_I(t) = K_I(0) + \alpha_1\int_0^t q(t)\,E_z^{*\prime}(t)dt + \alpha_2 q(t)\,E_z^{*\prime}(t)$$

$$K_p(t) = K_p(0) + \beta_1\int_0^t q(t)\,E_z'(t)dt + \beta_2 q(t)\,E_z'(t)$$

$$K_v(t) = K_v(0) - \gamma_1\int_0^t q(t)\,\dot{Z}'(t)dt - \gamma_2 q(t)\,\dot{Z}'(t)$$

where

$$q(t) = W_I E_z^*(t) + W_p E_z(t) - W_v\dot{Z}(t)$$

and $E_z^*(t) = \int_0^t E_z(t)dt$ and $\{W_I, W_p, W_v\}$ are desired weighting matrices.

The position control law is expressed as

$$F_y(t) = \bar{d}(t) + \bar{K}_p(t)E_y(t) + \bar{K}_v(t)\dot{E}_y(t) + \bar{C}(t)R(t) + \bar{B}(t)\dot{R}(t) + \bar{A}(t)\ddot{R}(t) \qquad (31)$$

where $R(t)$ is the desired position trajectory, $E_y(t) = R(t) - Y(t)$ is the position tracking-error and the adaptation laws are:

$$\bar{d}(t) = \bar{d}(0) + \bar{\delta}_1\int_0^t r(t)dt + \bar{\delta}_2 r(t)$$

$$\overline{K}_p(t) = \overline{K}_p(0) + \overline{\nu}_1 \int_0^t r(t)\, E_y'(t)dt + \overline{\nu}_2 r(t) E_y'(t)$$

$$\overline{K}_v(t) = \overline{K}_v(0) + \overline{\eta}_1 \int_0^t r(t)\, \dot{E}_y'(t)dt + \overline{\eta}_2 r(t) \dot{E}_y'(t)$$

$$\overline{C}(t) = \overline{C}(0) + \overline{\mu}_1 \int_0^t r(t)\, R'(t)dt + \overline{\mu}_2 r(t) R'(t)$$

$$\overline{B}(t) = \overline{B}(0) + \overline{\gamma}_1 \int_0^t r(t)\, \dot{R}'(t)dt + \overline{\gamma}_2 r(t) \dot{R}'(t)$$

$$\overline{A}(t) = \overline{A}(0) + \overline{\lambda}_1 \int_0^t r(t)\, \ddot{R}'(t)dt + \overline{\lambda}_2 r(t) \ddot{R}'(t)$$

where

$$r(t) = \overline{W}_p E_y(t) + \overline{W}_v \dot{E}_y(t)$$

and $(\overline{W}_p, \overline{W}_v)$ are desired weighting matrices.

The above controller adaptation laws are extremely simple, and therefore, the hybrid control algorithm can be implemented using high sampling rates ($\approx$ 1 KHz), yielding improved performance. Under the adaptive hybrid controllers, both end-effectors are expected to exert the desired forces on the load while simultaneously moving on desired trajectories. The hybrid-hybrid control strategy is most suitable when simultaneous control of both position and force is required.

5. Discussion and Conclusions

Three adaptive control strategies for cooperative dual-arm robots are described in this paper. In these strategies, each robot arm is considered a subsystem of the total system and is controlled independently using an adaptive controller in the low level of the control hierarchy. Each controller ensures that the controlled variables follow desired commands and reject unwanted cross-coupling effects from other subsystems which are treated as "disturbances." The subsystems are coordinated through trajectory generators in the intermediate level, where synchronous desired trajectories for both arms are specified in a common task-related frame of reference. An important feature of the present approach is that the overall control system for N cooperative arms is reduced to N decentralized independent single-arm controllers. The control schemes do not require communication and data exchange among individual controllers, which is an appealing feature from both computational and reliability points of view. Furthermore, available techniques for single-arm control can be utilized directly in multiple-arm environments.

The control strategies described in this paper do not require the knowledge of the load parameters such as mass and stiffness or the robot dynamic parameters such as link masses and inertias, and can therefore cope with uncertainties or variations in the system parameters. Furthermore, the complex dynamic model of the arms is not used in generating the control actions. The control schemes are very simple and extremely fast for on-line implementation with high sampling rates, yielding improved dynamic performance. The control methodology described in this paper can also be utilized in the coordinated control of N-arm robots when N exceeds two.

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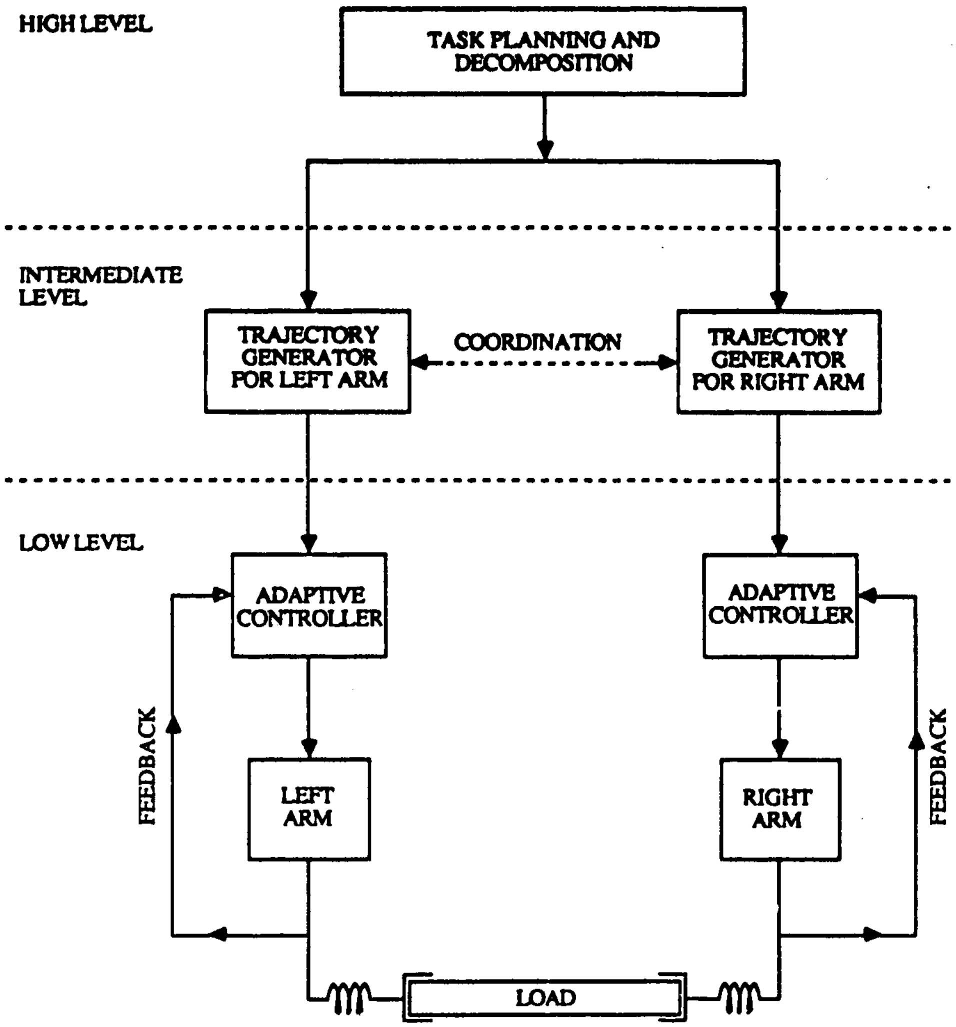

Figure 1. Tri-level Hierarchical Control of Dual-Arm Robot

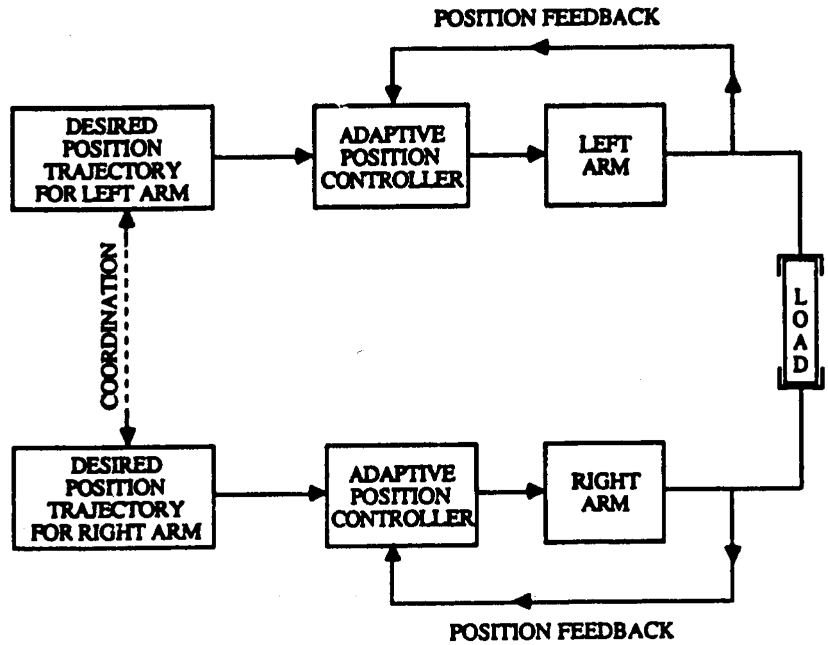

Figure 2. Position-Position Control Strategy

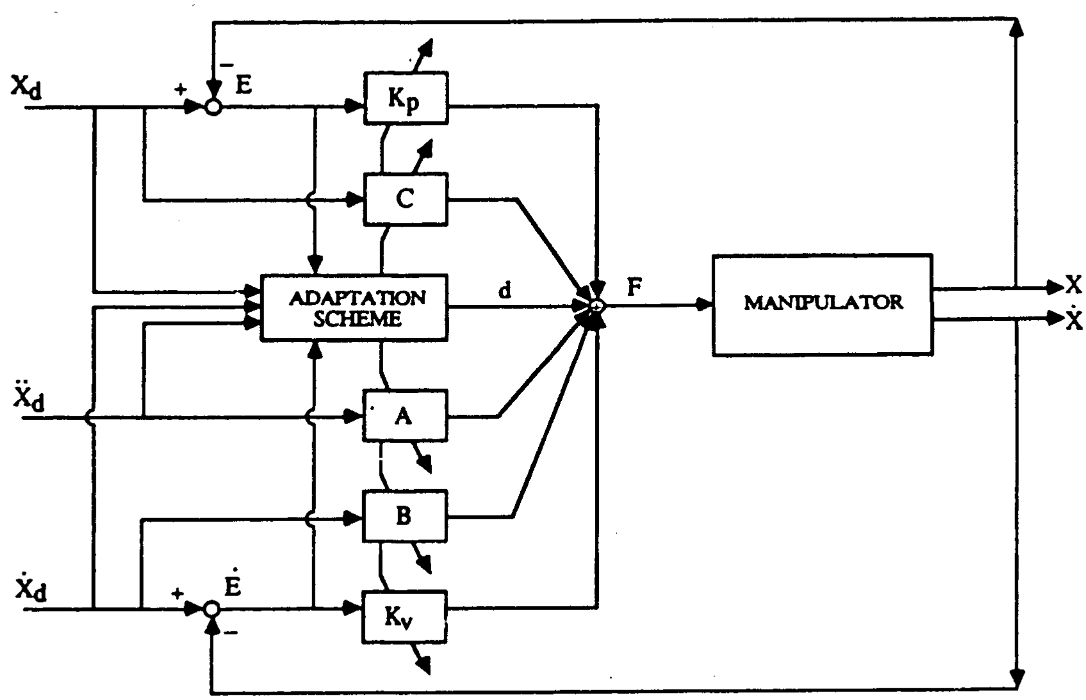

Figure 3. Adaptive Position Control System

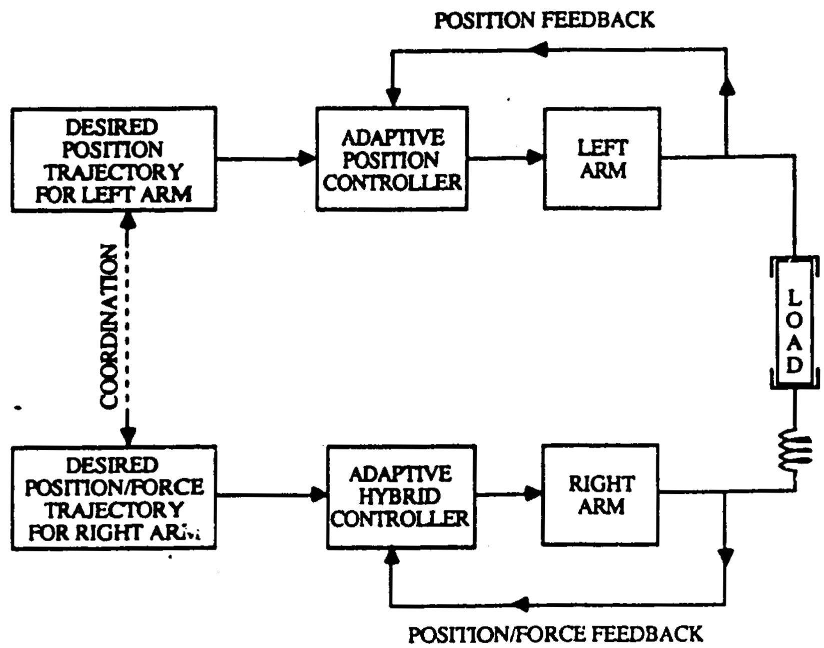

Figure 4. Position-Hybrid Control Strategy

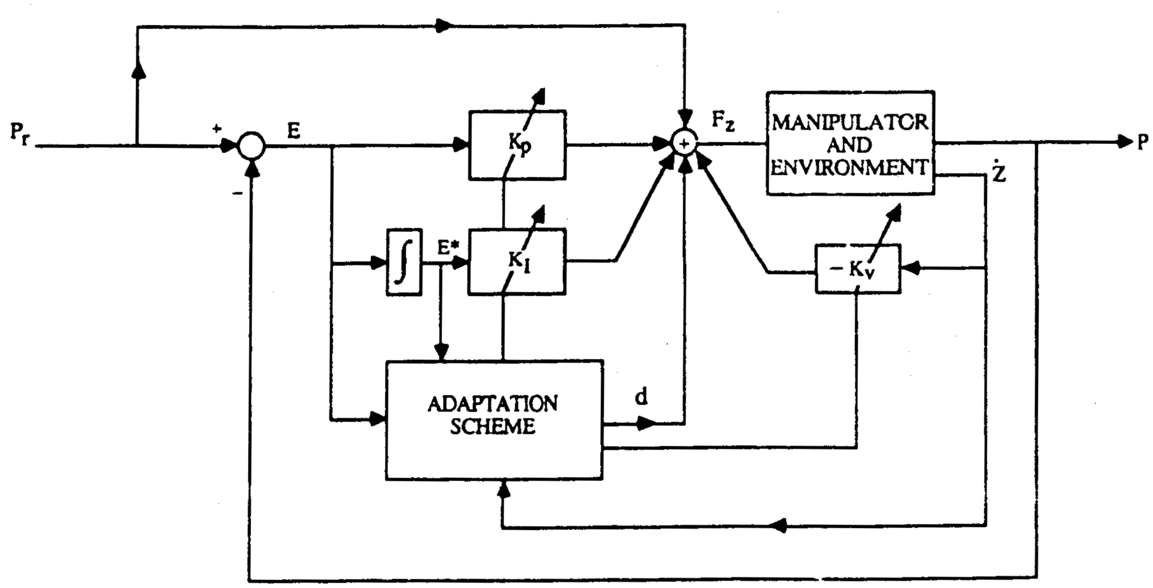

Figure 5. Adaptive Force Control System

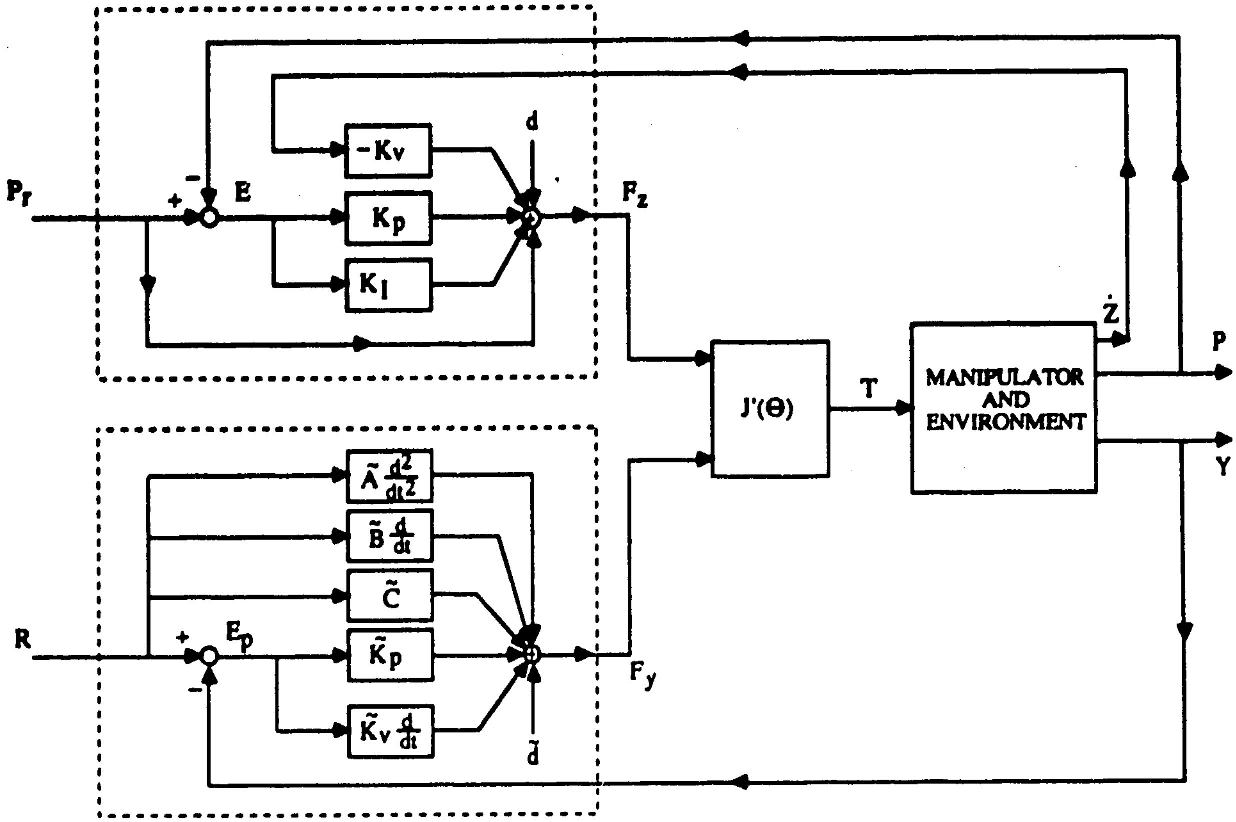

Figure 6. Hybrid Position/Force Control System

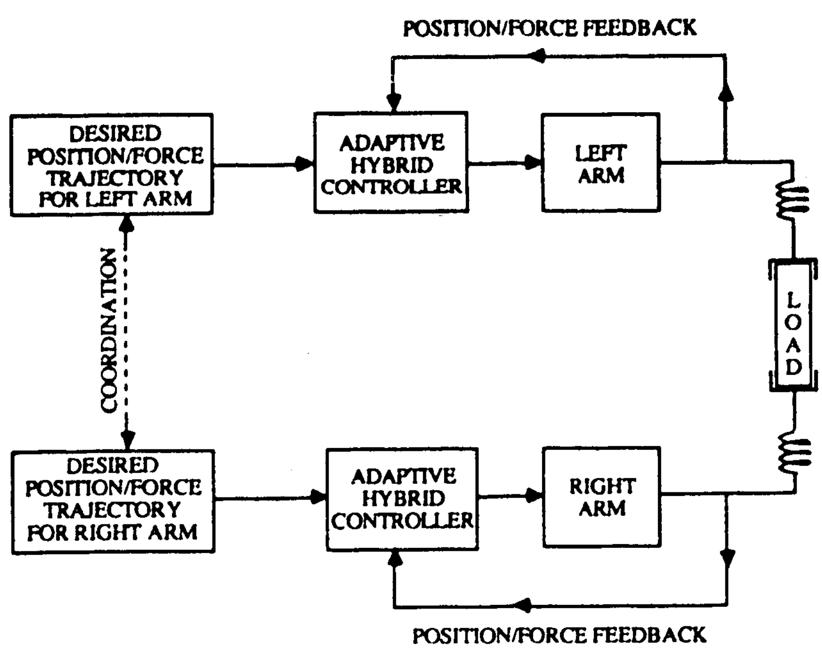

Figure 7. Hybrid-Hybrid Control Strategy