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An overview of robot force control

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SUMMARY

This paper reports on the existing robot force control algorithms and their composition based on the review of 75 papers on this subject. The objective is to provide a pragmatic exposition with speciality on their differences and different application conditions, and to give a guide of the existing robot force control algorithms. The previous work can be categorized into discussion, design and/or application of fundamental force control techniques, stability analysis of the various control algorithms, and the advanced methods. Advanced methods combine the fundamental force control techniques with advanced control algorithms such as adaptive, robust and learning control strategies.

KEYWORDS: Stiffness; Impedance; Admittance; Hybrid; Force control; Adaptive control; Robust control; Learning algorithm.

1 INTRODUCTION

Many tasks performed by a robot manipulator require the robot to interact with its environment, such as pushing, scraping, deburring, grinding, pounding, polishing, twisting, cutting, excavating, etc. Implementation of all these tasks intrinsically necessitates that a robot, besides realizing the predisposed position, provides the necessary force to either overcome the resistance from the environment, or comply with environment. Therefore, robot force control involves integration of task goals like modeling the environment, position, velocity and force feedback, and adjustment of the applied torque to the robot joints. Feedback of various measurement signals of the output of a robot (position, force, velocity) and the choice of command input signals to a robot result in different force control methods. These methods can be further categorized as fundamental robot force control algorithms and advanced robot force control strategies. At the same time, the robotic force control stability issue is also an important subject of investigation in force control, and will be briefly discussed here.

1.1 Fundamental force control

A classification of robot force control algorithms based on application of the relationship between position and applied force or between velocity and applied force, or the application of direct force feedback, or their combinations includes:

1. Methods involving the relation between position and applied force: stiffness control by only position feedback[1,2] and stiffness control by force feedback correction;[3,4]
2. Methods applying the relation between velocity and applied force: impedance control[5–10] and admittance control (or accommodation control);[11]
3. Methods applying directly position and applied force: hybrid position/force control,[12–14] and hybrid impedance control;[15]
4. Methods applying directly applied force feedback: explicit force control.[11,16,17]

1.2 Advanced force control

The advanced force control algorithms are based on adaptive control, robust control, and learning methods integrated or combined with the fundamental methods. Adaptive control methods include: adaptive compliant motion control, adaptive impedance (or admittance) control, adaptive force/position control and adaptive explicit force control. Robust control methods are: robust compliant motion control, robust impedance (or admittance) control, robust force/position and robust explicit force control. Other methods are learning control, neural network techniques[18] and fuzzy control[19,20] for robot force control.

The above classification shows the general approaches to the problem of robot force control. In practice, the implementation of each approach contains details that can be formulated differently. In this paper only the principle of each approach is discussed.

1.3 Stability

Stability is an important factor to application and implementation of robot force control. There are many research results of the stability problems associated with force control. For instance, that a soft force sensor can lead to stable behavior with stiff environment has been shown,[4,21] a stability analysis and design method for an impedance controller using eignstructure assignment has been presented,[22] a remedy for the dynamic stability issues in robot force control has been proposed,[23–25] the stabilizing problems about force control by means of low pass filtering has been discussed,[26] etc. In this paper, the existing stability analysis of robot force control will be classified and briefly discussed. Finally a conclusion will summarize the future developments about robot force control.

2 FUNDAMENTAL FORCE CONTROL ALGORITHMS

A basic endeavor in robot force control is how to determine the interaction forces and efficiently use the feedback signals in order to synthesize the appropriate input signals, so that the desired motion and force can be maintained. The basic variables in robot force control are position, velocity, acceleration and force. The differences in the existing fundamental force control algorithms stem from the different application of these basic variables and their relationships.

2.1 *Stiffness control*

Stiffness control can be passive or active. In passive stiffness control, the end-effector of a robot arm is equipped with a mechanical device composed of springs (or springs and dampers). Its applications are successful in very specific tasks, for instance, handling pegs of a certain length and orientation with respect to the hand. By contrast, active stiffness control[1,2,4,21,27–29] can be regarded as a programmable spring, since through a force feedback the stiffness of the closed-loop system is altered. Figure 1 shows the basic principle of an active stiffness control.

In what follows and the diagrams, J is the robot's Jacobian matrix, X_D is the desired position vector in the task space, X and $\dot{X}$ are position and velocity vectors in the task space, ΔX is the position error vector, $\Delta\theta$ is the joint angle displacement vector, τ_p is the vector of command input to joints associated with stiffness control, N is a vector of nonlinear feedforward compensation for gravity and centrifugal and Coriolis forces, τ is the vector of total joint torque/force input, X_E is the position vector of the contacted environment, K_E is the net stiffness of the sensors and environment, and F is the resulting contact force (or torque) vector in the world space. K_p and K_v are the control gains, usually chosen as diagonal matrices, K_F is the compliance matrix for modifying position command. A nonredundant robot in the 3-D space is considered; thus, the dimension of all the vectors are 6×1, and that of the matrices are 6×6.

For better understanding, Figure 1 is divided into two parts: the controller, in box 1 and the basic system, in box 2. The basic system includes a robot and its environment, velocity feedback and nonlinear compensation for linearizing the robot dynamic system. The stiffness control loop comprising a proportional feedback of force and position in box 1 defines joint torque τ_p of the total joint torque τ due to the contact force. τ_p is thus defined by the following equation

$$\tau_p = K_p \, \Delta\theta \tag{1}$$

The unit of K_p in equation (1) is force/displacement, which is stiffness. Therefore, active stiffness control allows the user to specify arbitrarily the mechanical stiffness of the manipulator by choosing different values for the matrix K_p. If ΔX is not converted to joint displacements through premultiplied by J^{-1}, then the scheme as illustrated in Figure 2 represents a different version of stiffness control, where box 2 is the same as in Figure 1.

The control loop (in box 3) gives the joint torque in the form of

$$\tau_p = J^T K_x \, \Delta X \tag{2}$$

where K_x represents the stiffness matrix. Since $\Delta X = J\,\Delta\theta$, then $\tau_p = J^T K_x J\,\Delta\theta$. That means

$$K_p = J^T K_x J \tag{3}$$

Stability issue. The stability issue for stiffness control has been studied, and the bound for the stability condition has been determined, in general, and investigated on a real system.[22] Furthermore, that a manipulator is kinematically stable under stiffness control has been shown.[23,25,30]

2.2 *Impedance control*

The fundamental philosophy of impedance control, according to Hogan,[8,9] is that the manipulator control system should be designed not to track a motion trajectory alone, but rather to regulate the mechanical impedance of the manipulator. The relationship between the velocity $\dot{X}$ and the applied force F is referred to as

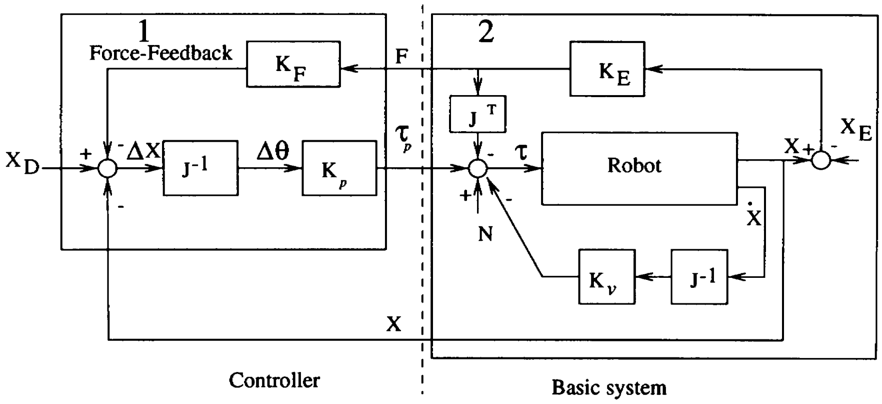

Fig. 1. Active stiffness control, version one.

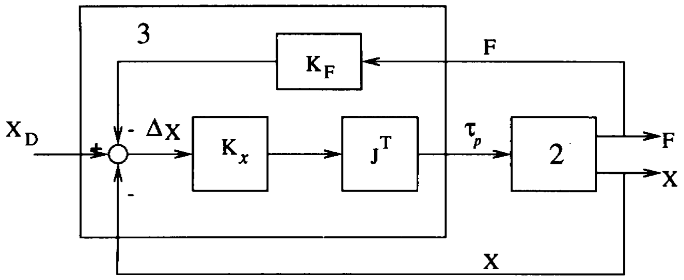

Fig. 2. Active stiffness control, version two.

the mechanical impedance Z_m. In the frequency domain, this is represented by

$$\frac{F(s)}{\dot{X}(s)} = Z_m(s) \tag{4}$$

In terms of position $X(s)$, we may write

$$\frac{F(s)}{X(s)} = sZ_m(s) \tag{5}$$

In a linear case, a desired impedance might be specified as

$$sZ_m(s) = Ms^2 + Ds + K \tag{6}$$

The constant matrices M, D and K represent the desired inertia, damping and stiffness values, respectively. It is the task of impedance control to guarantee the behavior of the controlled system to be as dictated by equation (5). Impedance control has been implemented in various forms,[4–11,24,27,29,31–33] depending on how the measured signals, i.e. velocity, position or force are used. Figure 3 shows the structure of a basic impedance control loop, which determines an appropriate value for $Z_m(s)$.

Figure 3 is, in fact, similar to Figure 1 with the addition of another feedback loop for the incorporation of velocity and the effect of the contact force on the velocity. In this sense, impedance control is a proportional and derivative controller in which the sensed forces give rise to modifications to be made for the position and velocity. The position modification results from multiplying the sensed forces by matrix K_{F1} that has the same role as in the stiffness control. The velocity modification results from multiplying the sensed forces by matrix K_{F2}. In the joint space the command force for error correction, thus, is defined by

$$\tau_{pv} = J^T(K_p\,\Delta X + K_v\,\Delta\dot{X}) \tag{7}$$

In Figure 3, the control loop in box 4.2 has the effect of modifying the damping constant of the manipulator when it is in contact with the environment. Impedance control is normally employed when a robot needs to adapt to the damping characteristics of its environment.

Impedance control may be introduced in a different way, as shown in Figure 4, in which X_F represents the equivalent force-feedback trajectory, X_I is the modified desired trajectory defined as the solution to the differential equation

$$M\ddot{X}_I + D\dot{X}_I + KX_I = -F + M\ddot{X}_D + D\dot{X}_D + KX_D \tag{8}$$

where $X_I(0) = X_D(0)$, $\dot{X}_I(0) = \dot{X}_D(0)$. M, D and K are as defined before. Equation (8) can be obtained by inspection from Figure 4. It implies the same impedance definition as in equations (5) and (6). It is noted that in the impedance control formulation X_I is a function of both the input X_D and the measured contact force F. Since the position-controlled subsystem in box 5 ensures that the end-effector position X closely tracks X_I defined in equation (8), therefore the target impedance of the manipulator is obtained.

Stability issue. The stability properties of impedance control in common implementations have been systematically discussed, and the stability boundaries for the impedance parameters have been obtained.[34]

2.3 Admittance control

Mechanical admittance[4,27,35] is defined as

$$A = \frac{\dot{X}}{F} \tag{9}$$

It is the inverse of the impedance definition in equation (4). Figure 5 shows the structure of a common admittance control, where box 5 is the same as in Figure 4.

In Figure 5, the admittance matrix A relates the force error vector E ($E = F_D - F$) to the end-effector velocity perturbation. For a known environmental stiffness, an admittance A can be constructed to achieve a desired

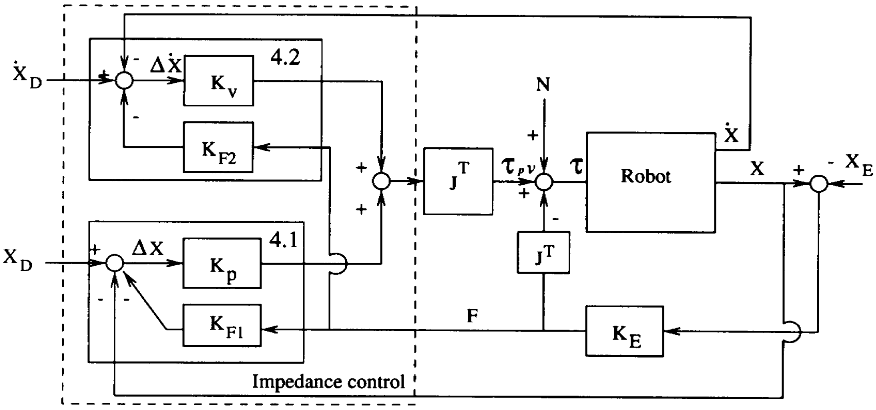

Fig. 3. Basic impedance control.

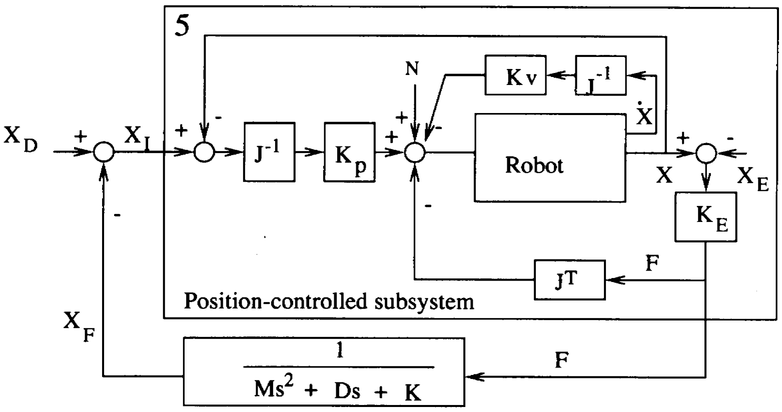

Fig. 4. Position-based impedance control.

force response with small or zero error, low overshoot, and rapid rise time. The command trajectory X_c is defined as

$$X_c = \int A(F_D - F)\,dt \tag{10}$$

From the admittance definition, we know that the concept of admittance is the inverse of impedance. The underlying concept of compliant motion control using admittance is to take a position-controlled robot as a baseline system and to make the necessary modifications of the admittance to this system in order to enable the execution of constrained tasks. To compare with impedance control, admittance control focuses more on desired force tracking control.

Stability issue. The stability and performance limits in admittance control have been studied, and an ultimate performance limit to guaranteed-stable admittance control has been derived.[36]

2.4 Hybrid control

2.4.1 Hybrid position/force control. Hybrid position/force control combines force and torque information with positional data, based on Mason's concept,[13] who defines two complementary orthogonal workspaces on displacement and force. Numerous works have been reported on this subject.[4,12,14,15,27,37–44] In hybrid position/force the position control and force control can be separately considered. The efficiency of this hybrid control method has been first verified on a Scheinman arm.[14] Figure 6 shows the representation of a robot arm, its environment and the control element for gravity compensation. Hereafter the content of this figure is addressed as a box in the following figures. Figure 7 shows the hybrid position/force control scheme.

In Figure 7, $S = \text{diag}(s_j)$ $(j = 1 \cdots n)$ is called the compliance selection matrix, n is the number of degree of freedom. The matrix S determines the subspaces for which force or position are to be controlled, and s_j is selected 1 or 0. When $s_j = 0$, the jth DOF must be force controlled, otherwise it must be position controlled.

The command torque is

$$\tau = \tau_p + \tau_f \tag{11}$$

where τ_p and τ_f are the command torques acting in position and force subspaces, respectively. In this way, position control and force control are decoupled. The control laws for each can be designed independently, so that the different control performance requirements for the desired position and force trajectories tracking are simultaneously realized. Normally, the position control law in Figure 7 consists of a PD action, and the force control law consists of a PI action. This is because for the position control a faster response is more desirable, and for the force control a smaller error is more preferable.

2.4.2 Hybrid impedance control. The hybrid impedance control was proposed by Anderson and Spong,[15] who combine impedance control and hybrid position/force control into one strategy. This allows a designer to obtain more flexibility in choosing the desired impedance of the controlled robotic system. A distinction of impedances in force-controlled and position-controlled subspaces thus can be made. Therefore, in addition to maintaining the velocity (or position) requirements, a controlled force trajectory can be followed. Figure 8 shows the hybrid impedance control block diagram.

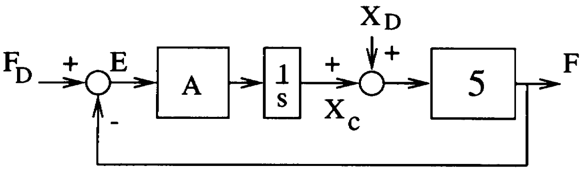

Fig. 5. Admittance control.

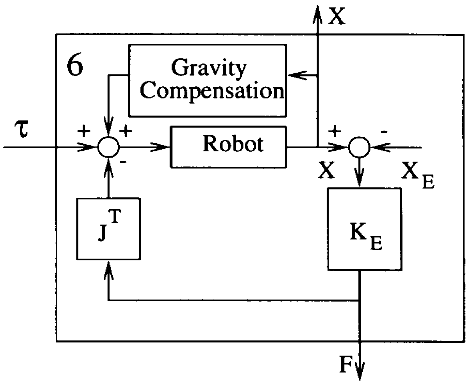

Fig. 6. Representation of a robot, its environment and gravity compensation.

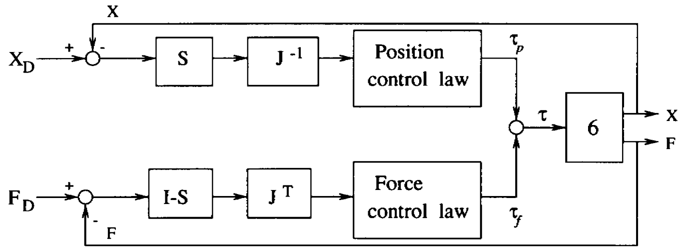

Fig. 7. Conceptional organization of hybrid position/force control.

In Figure 8, Z_{mp} and Z_{mf} are the desired impedance terms that are selected by user. If they are chosen as diagonal matrices, their elements represent the impedance along each degree of freedom. S is the compliance selection matrix, same as the one in the hybrid position/force control. The modified desired trajectory X_i is

$$X_i = X_{pi} + X_{fi} \tag{12}$$

where X_{pi} and X_{fi} are the modified position and force trajectories expressed in position and force subspace, respectively.

Stability issue. Hybrid position/force control stability issues are discussed.[25,27,45–47] A generalized architecture for hybrid position/force control has been given.[35] The nonlinear hybrid control stability using Lyapunov's direct method has been analyzed, and the fundamental stability conditions for hybrid control algorithm has also been shown.[48]

2.5 *Explicit force control*

According to Volpe and Khosla,[16,17] who have investigated this subject and studied various methods, robot explicit force control includes two categories. One is force-based and the other is position-based explicit force control. But, the second category consists of the same structure as the admittance control explained earlier and illustrated in Figure 5. In what follows only the force-based control strategy is going to be discussed. Its schematic diagram is shown in Figure 9.

In Figure 9, the measured force is directly used for feedback in order to form the force error vector. The force control law is normally chosen as one of the subsets of PID. The application of PI explicit force control in hard-on-hard contact tasks has been studied, and how to obtain a stable explciit force control on these tasks has been stated.[49] Obviously, the design of force control law in explicit force control is the key to successful force tracking.

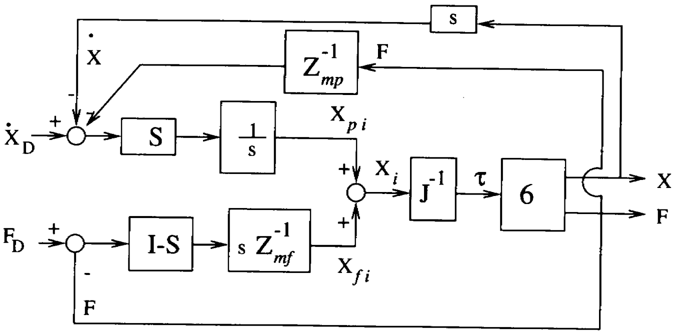

Fig. 8. Hybrid impedance control.

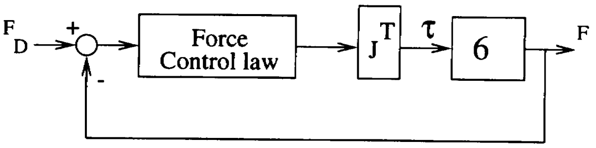

Fig. 9. Explicit force control.

Stability issue. An analytical overview of the dynamics involved in explicit force control has been provided, and the merits and limitations of conventional solutions of explicit force control, such as lead compensator, have been weighed.[40] The role of damping and low pass filtering for stability has been studied.[26] The robustness properties of explicit force control with respect to contact stiffness has been investigated. It has been shown that contrary to the case of P or PD control, the integral control law ensures increasing stability with increasing contact stiffness.[41]

2.6 *Implicit force control*

Implicit force control is proposed,[3] and discussed.[4] Figure 10 shows the implicit force control. Here there is no force feedback. Instead, the position is controlled based on the predefinition of position for a desired force. For this the position feedback gain K_p is determined such that the robot arm can obtain a particular stiffness.

2.7 *Comparison of fundamental force control methods*

To sum up, Table I gives the similarities and differences in the various force control methods.

3 ROBOT ADVANCED FORCE CONTROL ALGORITHMS

The utilization of robot in some complex tasks proposes many challenging problems, such as unknown parameter, unstructured environments and external disturbances, etc. How to achieve a good control performance in the presence of unmodelled dynamics, sensor noise and external disturbances for robot force control stimulates the needs for research on more advanced force control algorithms. An advanced method is about to provide accurate force tracking or perfect task accomplishment in the presence of unknown parameters and uncertainties regarding the robot and environment. Based on the fundamental force control methods in section 2, there are many advanced force control techniques, which are classified as adaptive control, robust control and learning control. These are briefly described here.

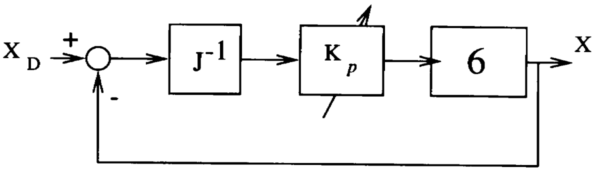

Fig. 10. Implicit force control.

Table I. Various force control method comparison

Algorithm classification		Workspace	Measured variables	Modified variables	Modulated objectives
Active stiffness control	1. Version one	Joint space	Position force	Joint displacement, contact force	Joint stiffness matrix
	2. Version two	Task space[a]		Position error, contact force	Stiffness matrix
Impedance control	1. Basic impedance control	Task Space	Position, velocity, force,	Position and velocity error, contact force	Impedance
	2. Position-based impedance control			Modified desired trajectory, contact force	
Admittance control			force	force error	Admittance
Hybrid control	1. Hybrid position/force	$\{P\}^b$	Position	Position error	Position
		$\{F\}^c$	Force	Force error	Force
	2. Hybrid impedance	$\{P\}$	Force	Velocity error	$Z_{mp}{}^d$
		$\{F\}$		force error	$Z_{mf}{}^e$
Explicit force control	*PI, PD, PID,* etc.	Task space	Force	Force error	Desired force F_D
Implicit force control		Task space	Position	Position error	Predefined stiffness

[a] Task space $=\{P\}\oplus\{F\}$.
[b] $\{P\}$ is Position subspace.
[c] $\{F\}$ is Force subspace.
[d] $\{Z_{mp}\}$ is the impedance expressed in Position subspace.
[e] $\{Z_f\}$ is he impedance expressed in Force subspace.

3.1 Robot adaptive force control

The basic objective of adaptive force control is to maintain consistent performance of a control system in the presence of unknown parameters in robot and environment. Based on the existing definitions of the fundamental force control methods, a robot adaptive force controller incorporates certain adaptive strategy into a controller in order to maintain the proper desired stiffness, impedance, admittance and so forth when unknown parameters of robot and contact environment exist. A desired position and force tracking position and force subspace respectively, thus, is guaranteed.

Normally, there are two categories of adaptive strategies for robotic force control: indirect and direct adaptive methods. In the indirect method there is an explicit parameter estimate for unknown parameters of the dynamic model of the controlled robotic system. Then this parameter estimate is used in control gains. The objective of an indirect adaptive force control is to make parameter error converge to zero. For this reason, its design requires a precise knowledge of structure of the entire robot and environment. In practice, often this is difficult to do. Because of this constraint, direct adaptive strategy is more and more used in robot force control. In direct adaptive force control, an adaptation scheme is applied so that the control gains are self-adjusting. The objective of this self-adjusting is to make the tracking error vector converge to zero. Figure 11 shows the general structure of adaptive force control.

In Figure 11, the box 7 is an adaptation scheme or a parameter estimtor. The former represents a direct adaptive force control and the latter stands for an indirect adaptive method. The existing adaptive force control techniques are indirect adaptive (simply called IA),[47,52] IA explicit force control,[53] IA impedance control,[53,54] Direct Adaptive (DA) admittance control,[35] DA impedance control,[55] DA positon and force control,[56,57] etc.

To sum up, the objective of an adaptive force control is to design a command input for robot, so that either of the following control aims are achieved in the presence of unknown parameters of robot and environment:

a. Stiffness control;

$$\lim_{t\to\infty}(X_D-X)=-K_FF \tag{13}$$

b. Impedance control;

$$\lim_{t\to\infty}(X_D-X)=-[Ms^2+Ds+K]^{-1}F \tag{14}$$

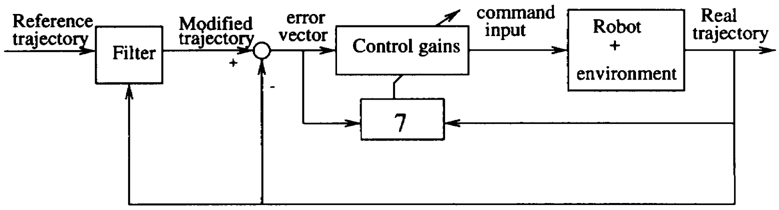

Fig. 11. Adaptive force control.

c. Hybrid control;

$$\lim_{t\to\infty} S(X_D - X) = 0, \text{ in } \{P\};$$

and (15)

$$\lim_{t\to\infty} (I - S)(F_D - F) = 0, \text{ in } \{F\}.$$

d. Hybrid Impedance control;

$$\lim_{t\to\infty} S(\dot{X}_D - \dot{X}) = -Z_{mp}^{-1}F, \text{ in } \{P\};$$

and (16)

$$\lim_{t\to\infty} (I - S)(F_D - F) = 0, \text{ in } \{F\}.$$

e. Explicit control;
including admittance control having an explicit force feedback.

$$\lim_{t\to\infty} (F_D - F) = 0 \qquad (17)$$

f. Implicit control;

$$\lim_{t\to\infty} (X_D - X) = 0, \qquad (18)$$

X_D predefined for a desired force.

Note that all symbols here are as defined before.

3.2 Robot robust force control

The objective robust force control is to achieve the target dynamics such as the target impedance, etc, and to preserve the stability robustness in the presence of bounded model uncertainties (alternatively called modeling errors) in robot and environment. Figure 12 shows the structure of robust force control.

In Figure 12, the command input includes two parts: robust control law and feedback control law. The feedback control normally uses PI, PD or PID, etc. The difficulty is to design a good robust control law. For this reason, the design concept of sliding mode[58] is widely used. In terms of error information and output feedback, robust control law is usually built by employing Lyapunov's direct method. Finally, the designed robust and feedback control laws guarantee the achievement of the predefined target dynamics, while preserving stability in the presence of modeling errors.

Until now, two main categories of robust strategies for robotic force control are: robust hybrid position/force control,[50–66] and robust impedance control.[67–71]

3.3 Learning algorithm for robot force control

Learning control has been independently introduced to robot position control.[52,72] Recently it was implemented for hybrid position/force control.[73–75] Figure 13 shows the learning algorithm principle for robot force control.

Learning algorithm is introduced for hybrid position/force control when a robot performs the same task repeatedly. It can enhance the performance of the controlled robotic system significantly. The algorithm utilizes position, velocity and acceleration errors or force error for learning the command input required to perform tasks. It guarantees the convergence of both position and force tracking errors, as well as robustness, for sufficiently small parameter uncertaintis and disturbances.

3.4 Summary of advanced force control

Table II gives a comparison of similarities and differences in these three robot advanced force control methods.

4 CONCLUSIONS

In this paper, an overview of various robotic force control techniques has been made. The existing

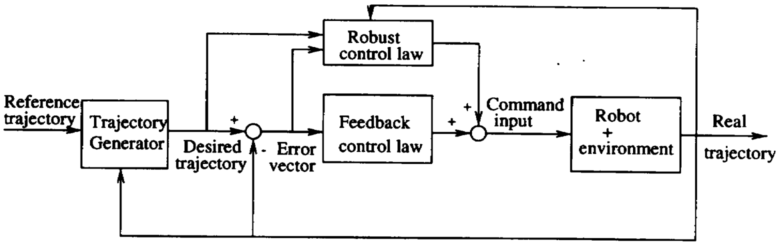

Fig. 12. Robot robust force control.

Table II. Advanced force control method comparison

Algorithm		*Control objective*	*Control techniques*	*Applied theory*	*Applied domain*
Adaptive control	Indirect	parameter error convergence	parameter estimate	Adaptive principle	Having unknown parameters
	direct	tracking error convergence	Adaptation scheme		
Robust		Tracking error convergence	Robust control law	Sliding mode control, Bounded input-output stability	Having model uncertainties
Learning		Complete compensation to unknown	feedforward compensation	Learning principle	Being a period task

fundamental and advanced force control algorithms are discussed. This work is based on the results of 75 papers. In the class of fundamental force control, stiffness control, impedance control, admittance control, hybrid position/force control, hybrid impedance control, explicit control and implicit control techniques are discussed in detail. In the class of advanced force control, the adaptive, robust and learning structure for force control are given. Furthermore, Table I and Table II sum up the similarities and differences in fundamental and advanced force control algorithms, respectively. This gives a guidance of understanding and utilization of the existing results in robotic force control. Based on the existing research results in robot force control, it may be envisaged that more work is needed in the following areas.

- More efficient filter and estimate to allow more sophisticated algorithms;
- Investigation on better stabilization and theory to decide what feedback strategy should be employed for each robot task;
- Faster learning capabilities to cope with unpredictable changes in robot and environment's parameters;
- Stronger robustness to comply with unknown restriction and disturbance imposed by environment.

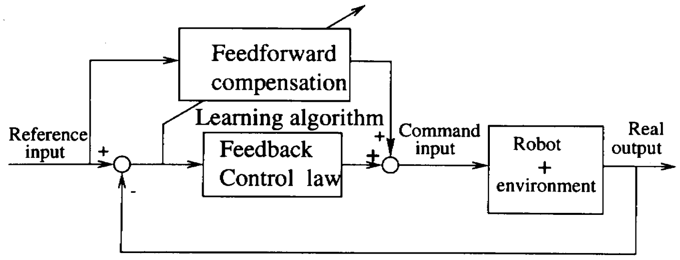

Fig. 13. Schematic drawing of robot learning position/force control.

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