A Fuzzy Adaptive Control Design for Compliant Motion of a Manipulator

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Abstract- **A fuzzy adaptive force controller is designed and integrated with the existing motion control system of a manipulator. This controller works in parallel with the robot controller by calculating the position corrections which allow contact force to be controlled in the desired manner. Fuzzy PI control scheme is used in the force controller design. This intelligent control system features an adaptive feedforward compensation to cope with the variations in the contact environment. Practical implementation has been carried out by integrating a 6D force/torque sensor to an ABB IRB2000 industrial robot. The force controller itself is realized in an PC-AT/486 which has signal interfaces to the robot as well as the force/torque sensor. Some simulation as well as experimental results are presented in this paper.**

INTRODUCTION

Most commercially available robots function solely as position controlled devices, with no means of directly controlling the contact forces between the manipulator and the environment. In a large number of manufacturing applications, control of contact forces is desirable and even in some situations critical. The objective of control during contact with the environment is to regulate the force that the manipulator's end-effector exerts on the environment.

As far as the system structure of compliant motion is concerned, there are two main approaches to the problem of controlling the contact force between the robot's end-effector and workpiece. One approach is the hybrid position/force control [1][2] . In this method, the control problem is divided into a set of position and force constraints that depend on the mechanical and geometrical characteristics of the task to be performed. Force is controlled along those directions constrained by the environment, while position is controlled along those directions in which the manipulator is unconstrained. In general, this control method performs well with simple surface geometries, but needs more modifications and advanced strategies to handle complex workpieces. The second approach is the impedance control [3]. In this method, a relationship is designed between the velocity of the manipulator and the interaction forces in order to generate compliant motion. Impedance control does not attempt to track the motion or force trajectories but rather to regulate the relationship between the velocity and force (i.e. the mechanical impedance). By controlling the manipulator's position and specifying its proper relationship to the interaction forces, this method is able to maneuver in a constrained environment while maintaining appropriate contact forces. However, under the dynamic interaction between the manipulator and the environment, the manipulator can achieve neither accurate position control nor accurate force control. In addition, the environmental stiffness introduced due to contacting might results in an oscillatory behavior of the end-effector. Accordingly, impedance control is not applicable to tasks which require a certain desired contact force trajectory and is not able to assure global dynamic stability [4].

Common to these two methods described above, the problems of stability and robustness with respect to the environmental uncertainties require further attention. Moreover, the implementation of these two methods are based on a precise mathematical model or a physical model obtained from system identification. In case of modelling errors and load disturbances, it will be difficult to find suitable gain parameters. Thus the designed controller might not perform successfully if the gain parameters are not properly tuned. Recently, control schemes based on artificial neural networks have been developed to cope with these uncertainties. In [5] a neural network was trained to learn the parameters of the impedance model to obtain the robustness against the environment uncertainties. However, the performance is normally only acceptable for the trajectories which have been trained in the neural network. Furthermore, torque servos are usually required for each joint to implement these methods. Hence it is difficult to directly apply these methods to most existing industrial manipulators which are equipped with only position servos.

In this article, a control scheme which includes adaptation to variations of contact conditions is proposed. A fuzzy PI controller proposed by MacVicar-Whelan [6] is used to develop the force controller in contrast to conventional control design. In order to take advantage of powerful programming utilities and position control capability of commercial industrial robots, the external force control strategy [7] deserves further investigation. This approach is therefore adopted in the present work for the implementation of the fuzzy adaptive controller on an industrial robot. The rest of this paper is organized as follows: In section 2, a design of the one-dimensional fuzzy force controller will be described. The computer simulation of this control design will be presented in section 3. In section 4, an adaptive scheme will be described to cope with the environment uncertainty. Some experimental results of this fuzzy adaptive controller will be presented in section 5. Section 6 is the conclusion.

FUZZY FORCE CONTROL DESIGN

The configuration with position inner loop and force outer loop

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was chosen for this position/force control design. By using this configuration the complex control problem can be split into two manageable subproblems : The internal position control system takes care of the manipulator dynamics; while the external loops are responsible for the interaction with the environment.

A block diagram of an one-dimensional force control of a manipulator in contact with its environment is depicted in Fig.1. In this figure, $g(s)$ and $h(s)$ are the transfer functions of the force controller and the robot position control system respectively. The contact force f_a is measured and fedback in an external loop closed around the position control system. The contact stiffness k_e is modelled as the total stiffness of robot and environment measured at the contact point. By means of the linear analysis, it can be shown that the force control law $g(s)$ has to contain an integrating factor, $\frac{1}{s}$ [7].

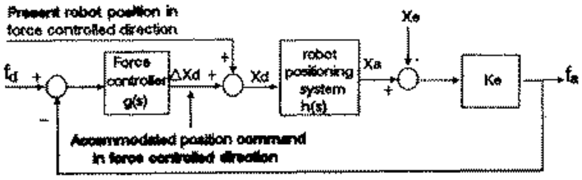

Fig. 1 Block diagram of one-dimensional force control system

However, because the robot dynamic model is a set of nonlinear equations, it would be difficult to directly design a force control law without nonlinear feedback. Besides, for force control system the following characteristics must be considered in practical situations. Firstly, the force data provided by the force/torque sensor are generally disturbed by noise. In spite of the use of filters within the sensor processor, the measured forces still have some uncertainty. Secondly, the detailed mathematical model of the controlled process is difficult to obtain. Thirdly, if the conventional PI controller is used to design the force controller, then the parameters of the PI controller must be tuned to satisfy some performance criteria. However, it would be difficult to correctly find these gain parameters, and thus the designed controller would not give successful performance if the parameters are not properly tuned.

On the other hand, no detailed mathematical model of a process is required in designing a fuzzy logic controller. Instead, it is realized by a set of heuristic decision rules, which are normally derived based on human expert thinking. In addition, the fuzzy controller is more robust for the small variation of system parameters. Therefore the form of the rules used will not need to change due to the small variation of system parameters.

Although the applications of fuzzy control to industrial processes have often produced results superior to classical controller, the design procedure appears to be limited by the acquisition of the heuristic rules for control. MacVicar-Whelan [6] tries to overcome this limitation by providing some general rules for the structure of fuzzy controllers. In the limit as quantization levels of the control and measurement variables become infinitely fine, the fuzzy logic controller proposed by MacVicar-Whelan approaches a deterministic PI controller [8]. Based on the design concepts and the meta rules proposed by MacVicar-Whelan, we design our force controller as a generalized fuzzy PI controller.

The structure of the fuzzy PI force controller is shown in Fig.2. The normalized force error $\hat{f}_e$ and its incremental change $\hat{f}_{ce}$ are chosen as the fuzzy variables. (i.e. the input variables of the force controller). The control action of the force controller (i.e. the output variables of the force controller) is then defined as the accommodated position command, ΔX_d, of the internal position controller in the force-controlled direction. $\hat{f}_e$ and $\hat{f}_{ce}$ are defined as follows:

$$\hat{f}_e(k) = f_e(k)/f_d \tag{1}$$

$$\hat{f}_{ce}(k) = f_{ce}(k)/f_d \tag{2}$$

where $f_e(k) = f_a(k) - f_d$, $f_{ce}(k) = f_e(k) - f_e(k-1)$, f_d is the desired force command, and f_a is the actual force. By means of $\hat{f}_e$ and $\hat{f}_{ce}$, the error and error change are represented as relative percentage of the desired contact force rather than the absolute force difference.

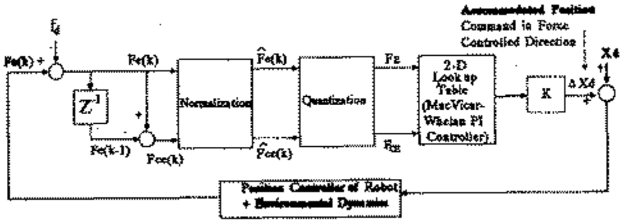

Fig. 2 Structure of fuzzy PI force controller

The seven linguistic variables used are as follows: PB (Positive Big), PM (Positive Medium), PS (Positive Small), ZO (Zero), NS (Negative Small), NM (Negative Medium), and NB (Negative Big). The heuristic rules for this fuzzy logic controller are basically derived from the meta-rules proposed by MacVicar-Whelan [6]. To cope with the measurement uncertainties in practical situations, the fuzzy variables are quantized to 13 levels as shown in Table 1. To get better performance, the quantization levels between levels -2 and +2 are designed to be nonlinear. The discrete membership functions of the linguistic variables are given in Table 2. Finally, the proposed fuzzy PI gain matrix is shown in Table 3. As shown in Fig.2, the accommodated position command in force-controlled direction is obtained by multiplying the controller output with a scaling factor K.

Table. 1 Quantization levels of fuzzy variables

$\hat{F}e(k)$ (%)	$\hat{F}ce(k)$(%)	Quantized Level
~ - 51	~ -25	-6
- 51 ~ - 41	- 25 ~ -20	- 5
- 41 ~ - 31	- 20 ~ -15	- 4
- 31 ~ - 21	- 15 ~ -10	- 3
- 21 ~ - 5	- 10 ~ -5	- 2
- 5 ~ -1	-5 ~ - 0.5	- 1
- 1 ~ +1	- 0.5 ~ +0.5	0
+1 ~ +5	+0.5 ~ +5	+1
+5 ~ +21	+5 ~ +10	+2
+21 ~ +31	+10 ~ +15	+3
+31 ~ +41	+15 ~ +20	+4
+41 ~ +51	+20 ~ +25	+5
+51 ~	+25 ~	+6

Table. 2 Discrete membership functions

	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6
PB	0	0	0	0	0.	0	0	0	0	0	0.3	0.7	1.0
PM	0	0	0	0	0	0.	0	0	0.3	0.7	1.0	0.7	0.3
PS	0	0	0	0	0	0	0.3	0.7	1.0	0.7	0.3	0	0
ZO	0	0	0	0	0.3	0.7	1.0	0.7	0.3	0	0	0	0
NS	0	0	0.3	0.7	1.0	0.7	0.3	0	0	0	0	0	0
NM	0.3	0.7	1.0	0.7	0.3	0	0	0	0	0	0	0	0
NB	1.0	0.7	0.3	0	0	0	0	0	0	0	0	0	0

Table. 3 Gain matrix for fuzzy PI force control

F_{CE}

F_E

	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6
+6	0	0	-1	-2	-3	-4	-5	-5	-5	-5	-5	-5	-5
+5	0	0	-1	-2	-2	-3	-4	-4	-4	-4	-5	-5	-5
+4	1	1	0	-1	-1	-2	-3	-3	-3	-4	-4	-5	-5
+3	2	2	1	0	-1	-2	-2	-3	-3	-3	-4	-4	-5
+2	3	2	1	1	0	-1	-1	-2	-2	-3	-3	-4	-5
+1	3	3	2	2	1	0	0	-1	-2	-3	-3	-4	-4
0	3	3	3	2	1	0	0	0	-1	-2	-3	-3	-3
-1	4	4	3	3	2	1	0	0	-1	-2	-2	-3	-3
-2	5	4	3	3	2	2	1	1	0	-1	-1	-2	-3
-3	5	4	4	3	3	3	2	2	1	0	-1	-2	-2
-4	5	5	4	4	3	3	3	2	1	1	0	-1	-1
-5	5	5	5	4	4	4	4	3	2	2	1	0	0
-6	5	5	5	5	5	5	4	4	3	2	1	0	0

SIMULATION RESULTS

To show the validity of the one-dimensional force control scheme, computer simulations have been carried out for a manipulator with a wrist force/torque sensor. The manipulator was simulated to push against a wall with a constant force f_d. The wall is modelled as an environment with stiffness k_e. There are some assumptions concerning this simulation. First, the control action is directly implemented in the cartesian frame. Secondly, the resolution of the position controller is set to be 0.125mm according to the type of manipulator used in the laboratory. Therefore, the scaling factor K of the force controller in Fig.2 is chosen to be 0.125. Thirdly, the uncertain region of the force sensor is assumed to be 0.5N according to the measured data observed during calibration test of the force sensor. Fourthly, the closed position-loop transfer function $h(s)$ with dc gain equal to 1 and the position loop always reaches steady state for each sample period. Under these assumptions, the simulation results are shown in Fig.3. The performance of the robot system would be overdamped when the end-effector is commanded to push against a wall of low stiffness with a constant force. However, the reaction force may be underdamped and a response with limit cycle will appear when pushing against a wall of higher stiffness. This shows that it is impossible to ensure stable performance of the system for a large range of environmental stiffness if only a fixed gain matrix of the fuzzy PI controller is applied.

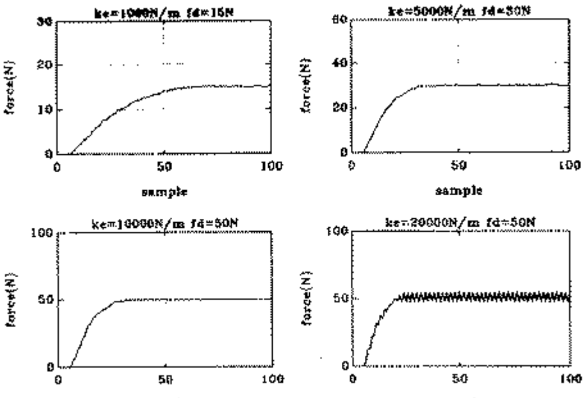

Fig. 3 Simulation results of various environment conditions using fuzzy PI force control

ADAPTIVE SCHEME FOR ENVIRIONMENT UNCERTAINTIES

In order to overcome the shortcomings of the original external force control system and to keep the system stable for contact with both low and high stiffness environment, an adaptive control scheme is developed for the force controller. The basic concept of this design is that an identification module is included in the control scheme to estimate the contact stiffness k_e and adjust the control action accordingly.

Assuming that the force f_a acting upon the end-effector can be modelled as:

$$f_a = k_e(x_a - x_e), \qquad (3)$$

where x_a is the actual position of the end-effector and x_e is the fixed environment position. Since this force is measured by a 6D force/torque sensor, the stiffness of the environment can be estimated in the following manner. Let $f(k-1)$ and $f(k)$ be two consecutive contact forces delivered from the force sensor in the same direction. Let $x(k-1)$ and $x(k)$ be the positions of the contact points at step $(k-1)$ and k respectively. The stiffness of environment can be estimated as:

$$k_e^{est} = [x(k) - x(k-1)]^{-1}[f(k) - f(k-1)], \qquad (4)$$

where $x(k) \neq x(k-1)$. Based on the identified stiffness, the equivalent position x_d^{est} corresponding to the desired force f_d at step k can be determined:

$$x_d^{est} = x(k) - (k_e^{est})^{-1}(f(k) - f_d) \qquad (5)$$

This equivalent position x_d^{est} is used as an input to the position controller in the force controlled direction. A stable position controller is responsible for realization x_d and accordingly the desired contact force f_d.

However, it is clear that the identification of k_e^{est} will not be very accurate and therefore the actual contact force may deviate from the desired contact force f_d. To compensate this deviation, the external force feedback control described in the previous section is still applied. Therefore, the control action in the force controlled direction is the combination of the accommodated position command from the fuzzy PI controller and the feedforward equivalent position command from the adaptive estimation. Fig.4 depicts this fuzzy adaptive control scheme.

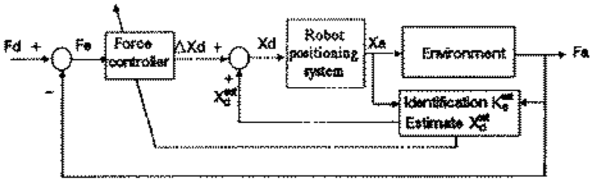

Fig. 4 Fuzzy adaptive force control system

On the other hand, fixed control gains for the fuzzy controller might not ensure a satisfactory maintaining of the desired contact force for obvious changes of environment stiffness. Therefore, the control action has to be modified according to the identified stiffness of the environment. The adaptation rules are as follows: If $log_{10}k_e^{est}(N/m)$ is larger than 4 and smaller than 5, then the accommodated position command is degraded to one half of the original command. And if $log_{10}k_e^{est}$ is larger than 5, then the accommodated position command is degraded to one forth of the original command.

To show the improvement of the one-dimensional adaptive force control scheme, computer simulations have been done with the same conditions mentioned in section 3. Figure 5 shows the simulation results of this fuzzy adaptive controller. It is observed that the speed of the response is improved with a small overshoot and the limit cycle disappears in the high-stiffness case.

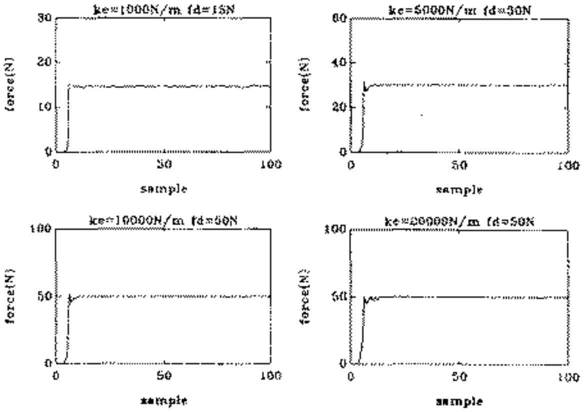

Fig. 5 Simulation results of various environment conditions using fuzzy adaptive force control

EXPERIMENTAL RESULTS

Practical implementation of this control scheme has been carried out in the laboratory using an ABB IRB2000 industrial robot equipped with a JR^3 wrist force/torque sensor. The force controller itself is realized in an 80486 based personal computer with signal interfacing to the robot controller as well as the sensor system. The setup of the experiment is illustrated in Fig. 6. According to the sensing information obtained from the force sensor, the accommodated position command is calculated by the control law resident in the personal computer. It is transmitted to the robot controller through the computer link. The original robot controller is responsible for the manipulator motion control.

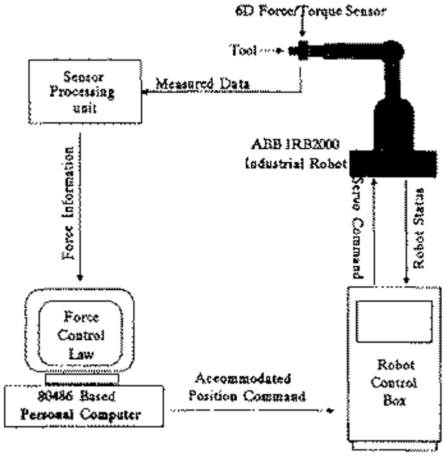

Fig. 6 Experiment setup of the fuzzy force control system

Experiment of tracking a surface

In this experiment the robot is commanded to move along the surface of a workpiece with a prescribed tangential speed and normal force. The workpiece is made from sponge material and its stiffness is about 5000N/m. A special made tool is attached at the robot through the force sensor. It moves along the surface with tangential displacement 1.0mm/sample and maintains the normal reaction force of 10N.

The experimental result of this process without adaptation is shown in Fig.7 and the result with adaptation is shown in Fig. 8. It is observed that the response of the fuzzy adaptive force controller is faster than that of the fuzzy controller without adaptation. The contact forces is controlled and the environment estimator works as expected.

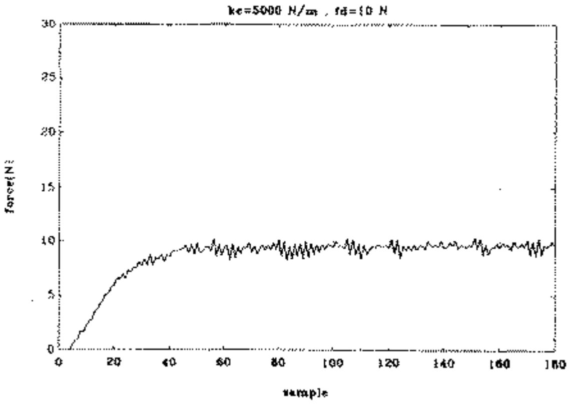

Fig. 7 Experimental result of fuzzy force tracking along a surface without adaptation to the environment

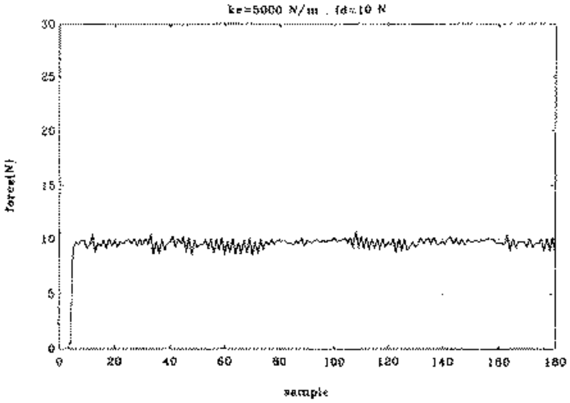

Fig. 8 Experimental result of fuzzy adaptive force tracking

Experiment of tracking a curved surface

In this experiment, the robot is commanded to move along a curved contour of a workpiece with a prescribed tangential speed and normal force. Here the workpiece is again a sponge. The recorded contour after execution is shown in Fig. 9. Figure 10 shows the experimental result of this process when without adaptation to the environment. The experimental result with adaptation is shown in Fig. 11.

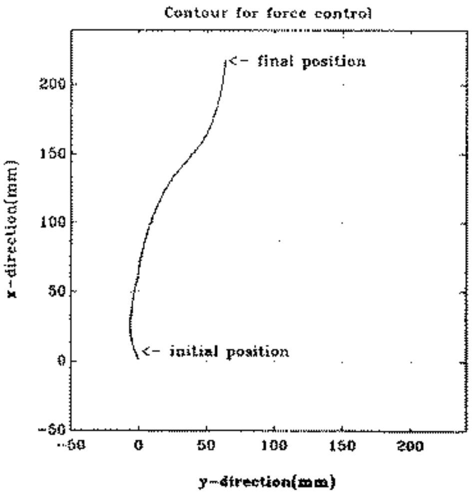

Fig. 9 Experimental result of the executed trajectory when tracking a curved surface

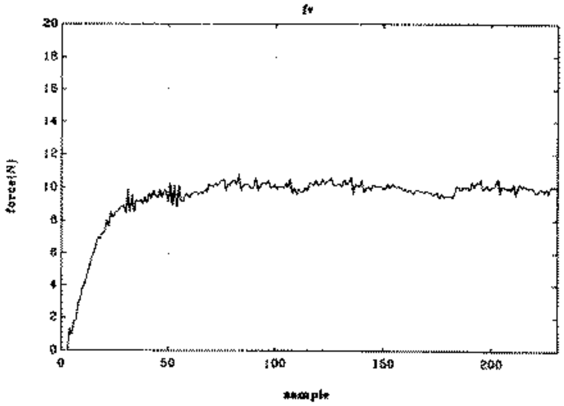

Fig. 10 Experimental result of Fig. 9 using fuzzy force control without adaptation to the environment

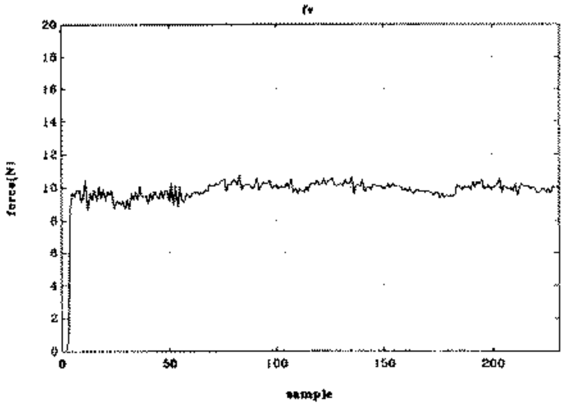

Fig. 11 Experimental result of Fig. 9 using fuzzy adaptive force control

Discussion on the influence of the position resolution

The influence of the position resolution of the manipulator on the performance of the present force control design has been noticed. It is observed from experiment that the practical system has limited position accuracy. This results in limit cycles in force response when a constant contact force is to be controlled. Their peak-to-peak amplitude depends on the resolution of the existing position controller, Δx_{res}, and the environmental stiffness ,k_e. While the actual position, x, of robot takes any value between x_i-$\frac{\Delta x_{res}}{2}$ and $x_i+\frac{\Delta x_{res}}{2}$, the position feedback signal of the robot controller, x_m, remains equal to x_i, and hence the position controller dose not react. Under this condition, a low frequency oscillation will appear with amplitude $k_e\Delta x_{res}$. To improve this condition, a passive compliance may be necessary in order to obtain a satisfactory force resolution and steady state accuracy.

CONCLUSIONS

In this article, a fuzzy force control strategy is developed for a manipulator equipped with a wrist force sensor. This control design combines the advantages of fuzzy logic control and external force control scheme. In order to assure system performance in various contact conditions, a method for estimation of the contact stiffness and also adaptation of force control action accordingly is proposed. The improvement of the force response on the original fuzzy PI controller has been verified. Both simulation and experimental results are presented to show that the proposed control strategy has acceptable performance.

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