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FUZZY ADAPTIVE FORCE CONTROL OF INDUSTRIAL ROBOT MANIPULATORS WITH POSITION SERVOS

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Abstract—A fuzzy adaptive force control algorithm is suggested for commercialized industrial robots equipped with position servo drives in cascade with a software filter for the control of acceleration/deceleration profile to avoid vibrational shocks due to a sudden start or stop, where the control algorithm is composed of a Fuzzy Interpolation Logic Controller (FILC) and a Fuzzy Adaptive Stiffness Estimator (FASE). FILC determines a control action according to the magnitude of an environmental stiffness in such a way that good force response is maintained regardless of changes of environmental stiffness. Specifically, some fuzzy controllers are designed for several representative environmental stiffness values, and then a control action for an estimated environmental stiffness value which is not the same as any representative stiffness values is decided by fuzzily aggregating different control actions of those fuzzy controllers. Here, FASE plays the role of estimating an environmental stiffness value and transfers the estimated stiffness value to FILC. To show the validity of the proposed adaptive fuzzy force controller, several numerical examples and some experimental results are illustrated, where soft, medium and hard environments are considered.

1. INTRODUCTION

Many robotic tasks, such as grinding and precision assembly, require the end-effector of the robot to establish and maintain contact with the environment. For successful execution of such tasks, both the force control and the position control of the manipulator must be simultaneously controlled. In addition, an adaptive algorithm is often required in the force control to successfully perform tasks with changes of environmental constraints.

Control of interaction forces has been investigated by many researchers. Active force control strategies have been classified into two major approaches. One is hybrid position/force control [1] and the other is impedance control [2]. However, these approaches often involve inverse dynamics to compensate nonlinear manipulator dynamics. In particular, impedance control requires the use of accurate manipulator dynamics in its operational space as well as perfect measurements of the external force [3] and thus seems to be difficult to implement because powerful hardware is required to compute manipulator inverse dynamics in real time. In addition, such control laws require direct control of motor torques. This implies that it may be difficult to directly apply such force control methods to most of the commercialized industrial robot manipulators equipped with only conventional position servos, of which inputs should be reference position signals.

In [4], Salisbury proposed a force control technique using only position servos, in which no explicit force sensors were employed. However, the method requires modifications of servo algorithms usually embedded in a controller of the hardware and/or firmware type. This seems to us to be difficult to apply in practice. Furthermore, Salisbury's technique can be applied only to the zero reaction-force regulator. To resolve such problems, a force/position control method based on a fuzzy proportional integral derivative (PID) control action was proposed for a commercialized industrial robot manipulator equipped with position servo drives, where a wrist force/torque sensor was assumed to be employed [5]. However, the proposed algorithm was not actually experimented. In [6], a fuzzy force control algorithm was suggested for commercialized industrial robots equipped with position servo drives, where control rules of the proposed fuzzy controller are changed according to the magnitude of environmental stiffness in such a way that a good force response is maintained regardless of changes of environmental stiffness. However, satisfactory performances can be obtained only under the condition that the actual environmental stiffness value is exactly given by an operator.

In most practical cases, exact environmental stiffness values are not known in advance and thus they should be automatically measured or estimated as a robot contacts with unknown environments. To cope with unknown or changing environment stiffness, many researchers have proposed several sophisticated control schemes which employ complex robot dynamics and adaptation algorithms [7–13]. In [7], Khatib and Burdick reformulated the hybrid control algorithm to include full compensation of the manipulator dynamics and constraining forces. Pelletier and Daneshmend proposed a rather complex adaptive control scheme to compensate for variations of environmental stiffness during compliant motion using damping control [8]. Slotine developed and tested an adaptive controller in Cartesian space that can track position and force trajectories by including in the adaptive model both the robot and environment parameters [9]. On the other hand, force control schemes based on fuzzy logic have recently been proposed [10]. However, their simple fuzzy force control algorithm seems not to completely compensate for the uncertainties of the environment.

In this paper, we will propose a force control algorithm to effectively adapt to changes of environment for the manipulator with position servo drives. For this, a slightly modified version of the Fuzzy Interpolation Logic Controller (FILC) in [6] and a model based Fuzzy Adaptive Stiffness Estimator (FASE) are proposed. Specifically, for several representative linguistic environmental stiffness values, corresponding fuzzy control rules are designed. FILC then determines a control action for an arbitrary environmental stiffness value by fuzzily aggregating different control actions of those fuzzy control rules, where the environmental stiffness value is estimated by FASE. Specifically, fuzzy rules are proposed to determine an exponent implying the degree to which the stiffness value is adjusted, where a second order reference model is employed to evaluate how well the current stiffness value is tuned and to obtain input signals for FASE. The current environmental stiffness value is then updated based on the exponent value given by the fuzzy rules. The proposed scheme can be easily implemented for real time force control purposes with a high sampling rate and does not require any detailed mathematical models when compared with other adaptive schemes. To show the validity of the proposed fuzzy control algorithm, several numerical examples and some experimental results are illustrated, where the PT200V robot, a five-axis articulated robot manipulator, equipped with the wrist force/torque sensor system, and our own prototype dual robot controller [14] are used.

2. FORCE CONTROL ALGORITHM BY FUZZY INTERPOLATION METHOD

In many research works on robot control stability has been discussed [6, 15–19], since it is an essential property of any control system. However, these analyses mostly focused on manipulators with torque servos, and thus may not work on manipulators with only position servos. Recently [6, 15, 16], the stability of the force controlled robot with position servos has been investigated. References [15] and [16] have considered only position servo dynamics. However, to be more practical, it should be taken into account that a filter, such as the exponential filter shown in Fig. 1, is often employed in cascade with a position servo for the control of acceleration/deceleration profile, which is necessary to avoid vibrational shocks due to a sudden start or stop. Since filter dynamics is designed to be dominant over any other dynamics included in the robot with position servo drives, the exponential filter dynamics should be considered in the stability analysis of a force controlled manipulator with position servos, as in [6]. As a result, it is known that stability and force output response of the system with an exponential filter are more dependent on the environmental stiffness values than those of systems without the exponential filter. Therefore, a force controller to be designed should be a function of stiffness values to make the closed loop system be stable and, furthermore, to obtain good force responses regardless of changes in environment.

Now, we will propose a design method of such a force controller which is a slightly different version of the one in our earlier work [6]. To be specific, let $\mathbf{K}_E$ and $\delta\mathbf{X}$ be the diagonal 6×6 stiffness matrix in the Cartesian space and a 6×1 infinitesimal displacement of the end effector in the Cartesian space, respectively. And let $\mathbf{q}$, $\delta\mathbf{q}$ and $\boldsymbol{\tau}$ be the n-dimensional joint position vector, infinitesimal joint displacement vector and joint torque vector, respectively. Also, let matrix $\mathbf{J(q)}$, $\mathbf{F}_d$ and $\mathbf{F}_a$ be the Jacobian matrix relating $\delta\mathbf{q}$ and $\delta\mathbf{X}$, a six dimensional desired force vector and a six dimensional actual force vector. Then, from the basic stiffness formulation in [4], we can obtain that

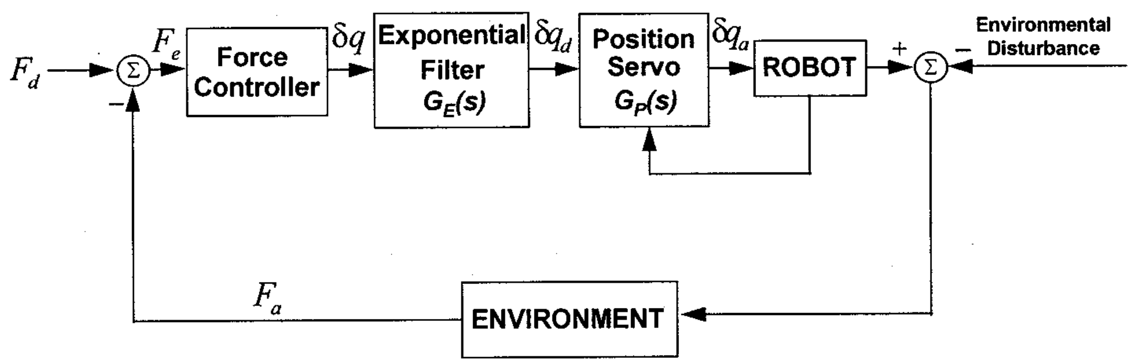

Fig. 1. Block diagram of typical force control for robot manipulator with position servos.

$$\boldsymbol{\tau} = \mathbf{J}(\mathbf{q})^T \mathbf{K}_E \mathbf{J}(\mathbf{q}) \delta \mathbf{q}. \tag{1}$$

For force feedback controls without modifications of position servos, $\delta\mathbf{q}$ should be obtained from the explicit force error signal. For this, note that $\boldsymbol{\tau} = \mathbf{J}(\mathbf{q})^T\mathbf{F}$. Then $\delta\mathbf{q}$ can be written as $\delta\mathbf{q} = (\mathbf{K}_E\mathbf{J}(\mathbf{q}))^{-1}\mathbf{F}$ or $\delta\mathbf{q} = \mathbf{J}(\mathbf{q})^{-1}\delta\mathbf{X}$. Here, the controller design problem is to find $\delta\mathbf{X}$ as a function of error signals and system parameters. Now, denote $\mathbf{F}_e$ and $\mathbf{F}_{et}$ as $\mathbf{F}_e \triangleq \mathbf{F}_d - \mathbf{F}_a$ and $\mathbf{F}_{et} \triangleq d(\mathbf{F}_d - \mathbf{F}_a)/dt$, respectively. And note that a control action for a given environmental stiffness value should be modified to successfully react for the environment with a different stiffness value. This implies that control action should be decided based on the environmental stiffness value. Therefore, the control input $\delta\mathbf{X}$ should be a function of $\mathbf{F}_e$, $\mathbf{F}_{et}$ and $\mathbf{K}_e$ given as $\mathbf{h}(\mathbf{F}_e, \mathbf{F}_{et}, \mathbf{K}_E)$, which will be implemented by fuzzy rules. Then, we obtain that

$$\delta\mathbf{q} = \mathbf{J}(\mathbf{q})^{-1}\mathbf{h}(\mathbf{F}_e, \mathbf{F}_{et}, \mathbf{K}_E). \tag{2}$$

Now, without loss of generality, the force control algorithm to be proposed will be explained for a single-axis force control among six end effector coordinate axes. Six-axis force controls can be easily extended since multi-axis force control can be separated into a group of single-axis force controls by using the selection matrix in the hybrid position/force control algorithm proposed in [1]. For this, let K_E^i, $\hat{K}_E^i$, F_e^i and F_{et}^i, repectively, be a scalar valued stiffness value, an estimated stiffness value, force error and force error change of the ith axis in task space. For notational simplicity, superscript i will be dropped out whenever no confusion will occur.

Figure 2 shows the block diagram for a fuzzy force control of the commercialized industrial robot controller equipped with position servos in cascade with an exponential filter. Note that the control law in Eqn (2) should be designed to obtain output force response with good transient behavior. However, it appears that $h(F_e, F_{et}, K_E)$ is difficult to obtain analytically in a closed form. Thus, $h(F_e, F_{et}, K_E)$ will be estimated by fuzzy rules. For generating the necessary fuzzy control rules, a control knowledge base must be developed which uses the linguistic description of the main parameters. In modeling the human expert operator's knowledge, fuzzy control rules of the form

If F_e is positive small, F_{et} is positive small and K_E is hard, then the control action is negative small

may be generally used. Suppose that numbers of linguistic values for input variables, F_e, F_{et} and K_E, are given as L, M, N, respectively. Then $L \times M \times N$ fuzzy rules

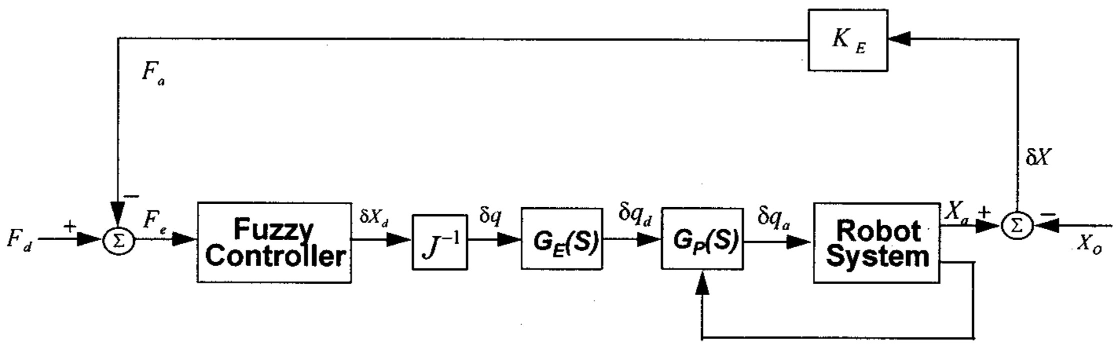

Fig. 2. Block diagram for the fuzzy force control algorithm.

should be determined by an heuristic choice. However, it appears difficult to design such fuzzy rules as a whole. Hence, instead of designing a fuzzy controller with $L \times M \times N$ fuzzy rules, N fuzzy controllers with $L \times M$ fuzzy rules are independently designed. Then, a control action is determined by fuzzily aggregating different control actions from N fuzzy controllers. This approach has been proposed in [6, 20, 21] as a fuzzy interpolation method. Here, $h(F_e, F_{et}, K_E)$ will be determined by the fuzzy interpolation technique.

Specifically, to design $h(F_e, F_{et}, K_E)$ by the fuzzy interpolation method, let $h(F_e, F_{et}, K_E)$ be a function to be approximated and be represented by a weighted sum of N representative functions $g_i(F_e, F_{et}) \triangleq h(F_e, F_{et}, K^*_{E,i})$ for $i = 1, 2, \ldots, N$, where $g_i(F_e, F_{et})$ can be obtained by assigning a constant value $K^*_{E,i}$ to K_E of the function $h(F_e, F_{et}, K_E)$. Let $\hat{K}_E$ be an estimated stiffness value. If $\hat{K}_E$ is different form $K^*_{E,i}$ for all i, the output value of $h(F_e, F_{et}, \hat{K}_E)$ needs to be newly estimated using $g_i(F_e, F_{et})$, for $i = 1, 2, \ldots, N$. For this, let ω_i be the weight which informs how much $\hat{K}_E$ is similar to $K^*_{E,i}$. Then, the function $\tilde{h}(F_e, F_{et}, \hat{K}_E)$, which is an approximation of $h(F_e, F_{et}, \hat{K}_E)$, can be represented as

$$\tilde{h}(F_e, F_{et}, \hat{K}_E) = \frac{\sum_{i=1}^{N} \omega_i g_i(F_e, F_{et})}{\sum_{i=1}^{N} \omega_i}. \tag{3}$$

For example, to obtain the similarities between $\hat{K}_E$ and $K^*_{E,i}$, three linguistic values can be employed as HARD, MEDIUM and SOFT, and their membership functions denoted by $\mu_i(K_E)$ can be given as depicted in Fig. 3. The weight is then given by

$$\omega_i = \mu_i(\hat{K}_E). \tag{4}$$

In Eqn (3), $g_i(F_e, F_{et})$ can be designed by fuzzy rules in such a way that some performance criteria such as small overshoot and fast settling time are satisfied [6]. For this, consider a typical step response as shown in Fig. 4, where the response is divided into eight regions I–VIII according to its characteristics. If the control action is properly determined in each region, then the response is expected to be improved. Such control rules are to be made based on the "prediction" of response as described in [5]. For example, as in the case of Regions II and VI, if the response shows overshooting behavior, the control action should be negative small regardless of the

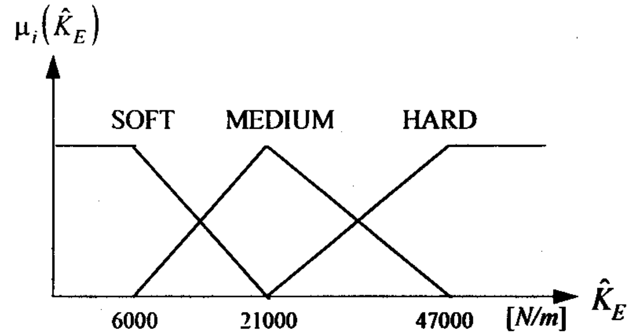

Fig. 3. Fuzzy membership function of FILC.

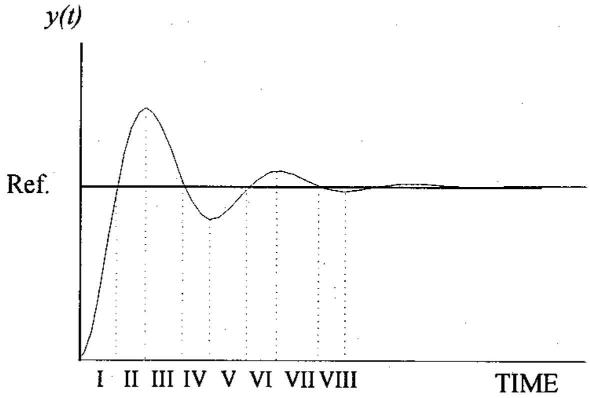

Fig. 4. A typical step response.

magnitude of the error and its rate of change to prevent the response from further overshooting. And, as in Region I, if the rate of error change is too large, the response is expected to show overshooting behavior, and thus the control action should be positive small. From these observations, the following control rules are here proposed.

Region I, V (Region III, VII). The output response is increasing (decreasing) to reach the reference input. If the error is positive (negative) large, then the control action should be positive (negative) large enough to force the system to track the reference input quickly. And if the error is small and the rate of the error change is positive (negative) large, then control action should be negative (positive) medium enough to suppress the system output inasmuch as the system output should not diverge from the desired value. If the error is almost zero, zero control action should be applied to keep the system in a current state.

Region II, VI (Region IV, VIII). The output response has already crossed over the reference input and tends to further increase (decrease). Thus, the control action should be negative (positive) small enough to force the output to get quickly back to the reference value.

An example of the proposed fuzzy tuning rules is tabulated with linguistic values as shown in Table 1. Table 1 represents the control rules to obtain good force step

Table 1. The fuzzy rules for SOFT environment (K_E = 6000 [N/m])

F_e \ F_{et}	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NM	NM
NM	NM	NM	NM	NS	NS	NS	PS
NS	NS	NS	NS	NS	ZE	PS	PM
ZE	NS	NS	NS	ZE	PS	PS	PS
PS	NM	NS	ZE	PS	PS	PS	PS
PM	NS	PS	PS	PS	PM	PM	PM
PL	PM	PM	PL	PL	PL	PL	PL

response, when stiffness value is given as 6000 [N/m]. These fuzzy control rules are to be used for the SOFT stiff environment whose membership function is depicted in Fig. 3. It is observed from Table 1 that the control actions are made to be less sensitive to the rate of error changes. This is mainly due to the fact that the force feedback signal is very noisy. If the derivative of the force feedback signal is used as an input of the controller, then control actions may amplify noise and may produce oscillations of the resonant frequency. This might drive an underdamped system into oscillation. Thus, it is not advisable to take the derivatives of such a signal.

Figure 5 shows a block diagram of the fuzzy interpolation logic controller (FILC), where FLC_i implies $g_i(F_e, F_{et})$ designed by fuzzy logic for the ith representative stiffness value. As in the design procedure of determining the number of linguistic values in general fuzzy logic controllers [23], the number of FLCs can be determined. It is remarked that in some real applications the number of membership functions seems to be well-selected by careful observation of data structure rather than an arbitrary selection.

The FILC scheme is now applied to the robot manipulator with position servos in cascade with exponential filters as shown in Fig. 2, where an exponential filter and a position servo dynamics are given by

$$G_E(s) = \frac{\delta q_d(s)}{\delta q(s)} = \frac{6.5}{s + 6.5} \tag{5}$$

and

$$G_p(s) = \frac{\delta q_a(s)}{\delta q_d(s)} = \frac{555{,}000\ (s + 50)}{s^3 + 5550s^2 + 333{,}000s + 2{,}775{,}000}, \tag{6}$$

respectively. It is remarked that in the case of industrial manipulators with high gear ratio, manipulator dynamics can be neglected. From Eqns (5) and (6), it is observed that the filter dynamics is dominant over position servo dynamics. Figure 6 shows force responses when (i) FILC, (ii) FLC for SOFT environment or (iii) FLC for HARD environment is applied to a MEDIUM stiff environment. It is observed from

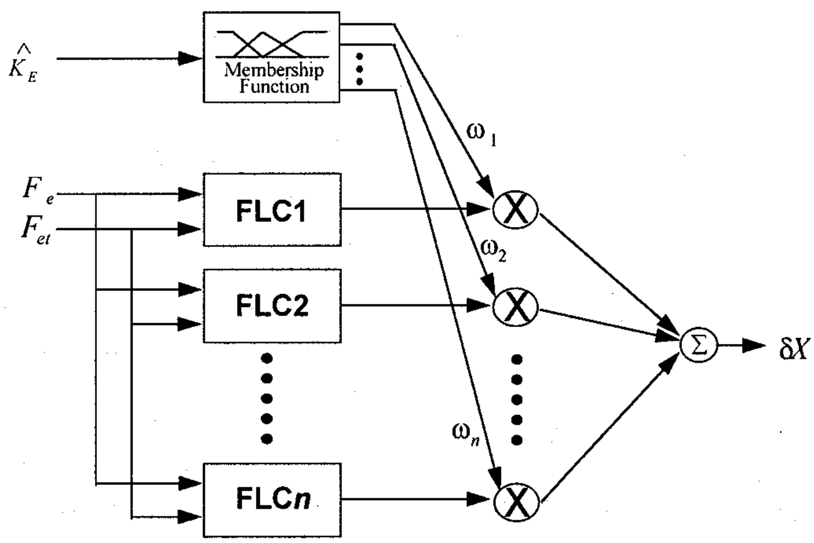

Fig. 5. Block diagram of FILC.

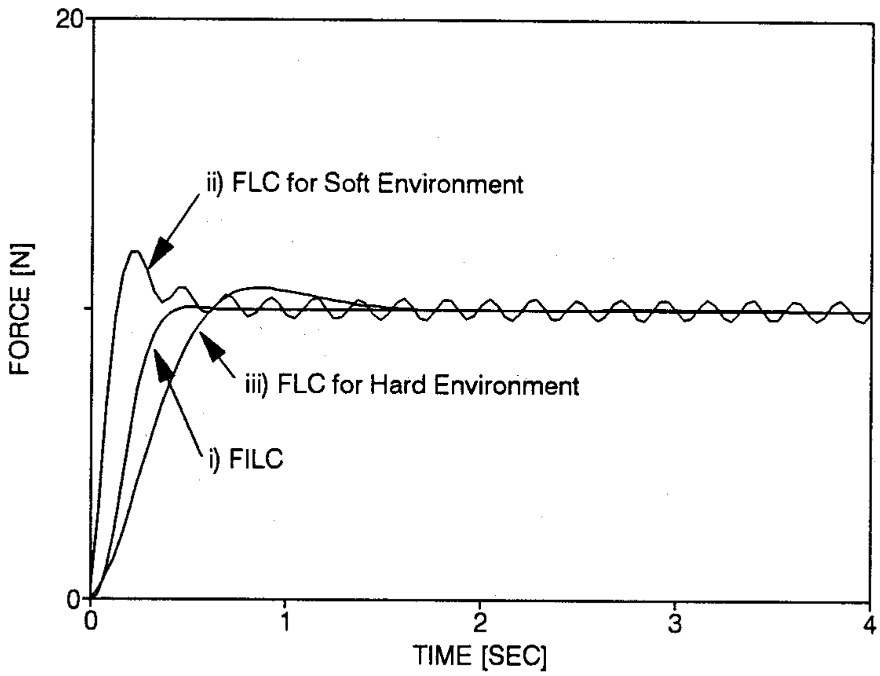

Fig. 6. Force responses when (i) FILC, (ii) FLC for SOFT environment or (iii) FLC for HARD environment is applied to a MEDIUM stiff environment.

Fig. 6 that when FLC for SOFT environment is applied to a MEDIUM stiff environment, the force response shows chattering behavior, and when FLC for HARD environment is applied to the MEDIUM stiff environment, the force response shows relatively slow rising time. On the other hand, FILC provides a good performance in the sense of almost zero overshoot and fast rising time.

3. FUZZY ADAPTIVE ESTIMATION OF ENVIRONMENTAL STIFFNESS VALUES

It is recalled from section 2 that if the environmental stiffness value, $\hat{K}_E$, is accurately given to the input of FILC, good force output response can be obtained by use of FILC. However, it is difficult to accurately know the environmental stiffness value in the case of a changing environment. For example, when the magnitude of force applied to an environment, such as a hard rubber, is increased to a threshold level, the stiffness value is often suddenly increased. However, the rate of increase becomes different according to the shape of an object, such as thickness. Thus, the Fuzzy Adaptive Stiffness Estimator (FASE) is here proposed to estimate environmental stiffness values. FASE is then combined with FILC to obtain good force responses.

In order to evaluate goodness of a force response from which a stiffness value is to be estimated, a reference model is employed. It should be noted that, in practice, where some theoretical requirement may not be satisfied, the reference model should be chosen sensibly in the sense that the process output can actually follow the reference model [22]. For this, a good actual force response is obtained for a fixed stiffness value. And then, the reference model is chosen in such a way that output of the reference model is almost similar to the good actual force response. It is remarked that if environmental stiffness is changed, the force response for a fixed stiffness value may be getting worse. Thus, fuzzy rules for FASE should be designed in such a way that FASE can completely determine the changing stiffness value, and thus the force output can follow the reference model output by using the estimated stiffness value. For example, consider a force response of a well-tuned fuzzy controller for a fixed stiffness value, where overshoot and rising time are observed to be almost zero and 0.25 [s], respectively, as shown in Fig. 7. In this case, the reference model is taken as a prototype second order system given by

$$H_r(s) = \frac{F_r(s)}{F_d(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \tag{7}$$

where F_r, ζ and ω_n are reference model output, damping ratio and natural frequency, respectively. $\zeta = 0.707$ and $\omega_n = 10\,[\mathrm{rad\,s^{-1}}]$ in Eqn (7) show a similar response to the force response as shown in Fig. 7.

FASE is composed of a set of fuzzy rules and a stiffness updating law as shown in Fig. 8. Fuzzy rules determine an exponent implying the degree to which the stiffness value is adjusted. And then, the stiffness value is computed by a simple stiffness updating law based on the exponent.

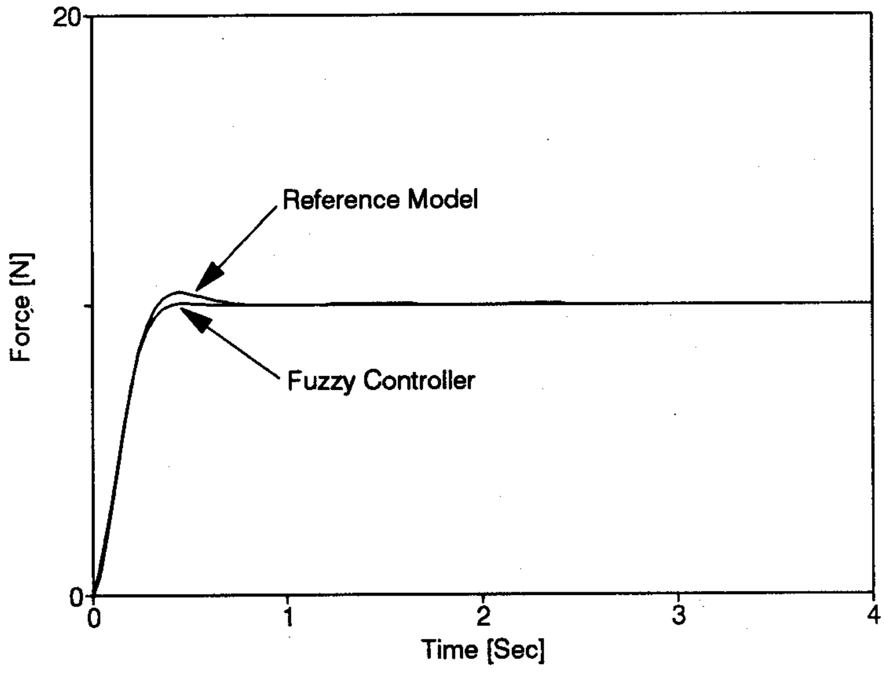

Fig. 7. The response of reference model with $\zeta = 0.707$ and $\omega_n = 10$ [rad s^{-1}] and the force step response for a well-tuned fuzzy controller.

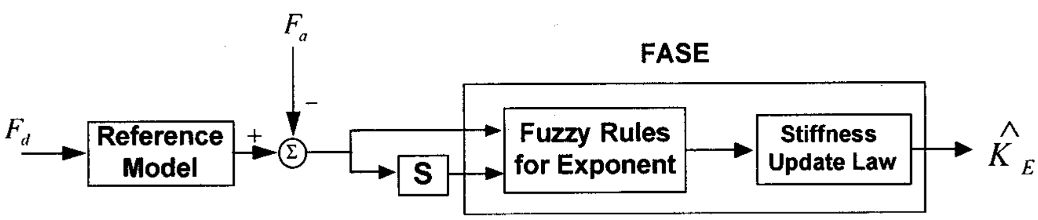

Fig. 8. Block diagram of FASE.

To design the fuzzy rules for determining the exponent, let $\tilde{F}_{re} \triangleq F_r - F_a$ and $\tilde{F}_{ret} \triangleq d(F_r - F_a)/dt$. And let F_{re} and F_{ret} be the normalized $\tilde{F}_{re}$ and $\tilde{F}_{ret}$, respectively. Also, let them be two input variables for the fuzzy rules and let γ be the output of the fuzzy rules. Seven linguistic values of F_{re}, F_{ret} and γ are employed as follows: PL (Positive Large), PM (Positive Medium), PS (Positive Small), ZE (Zero), NS (Negative small), NM (Negative Medium), NL (Negative Large). Their fuzzy membership functions are depicted in Fig. 9, where the triangle fuzzy membership functions are employed for the "IF" part and the singleton fuzzy membership functions for the "THEN" part.

Let $\hat{K}_E$ be the estimated value of an environmental stiffness. In the case that $\hat{K}_E$ is given as the same as the stiffness value of the real environment of object, K_E, the actual transient response is approximately similar to the reference model output. However, if $\hat{K}_E$ is estimated to be smaller than K_E, a large control ouput will be produced and thus the force output shows overshoot behavior. On the contrary, when $\hat{K}_E$ is estimated to be larger the K_E, a small control output is issued and a sluggish force output response will be generated. Here, types of transient behavior can be detected by monitoring F_{re}. Specifically, negative F_{re} implies overdamped behavior. In this case, FASE should increase $\hat{K}_E$. On the other hand, for positive F_{re}, FASE should decrease $\hat{K}_E$ since $\hat{K}_E$ is currently larger than K_E. The heuristic rules for determining the exponent are basically derived from the above concept and the fuzzy rules are given in Table 2. The output of fuzzy logic of FASE, γ, is generated by the sup-min inference mechanism and the center-of-gravity defuzzifier [24]. For fast computation in experimental implementation, a look-up table for fuzzy logic [25] of FASE is generated as shown in Fig. 10.

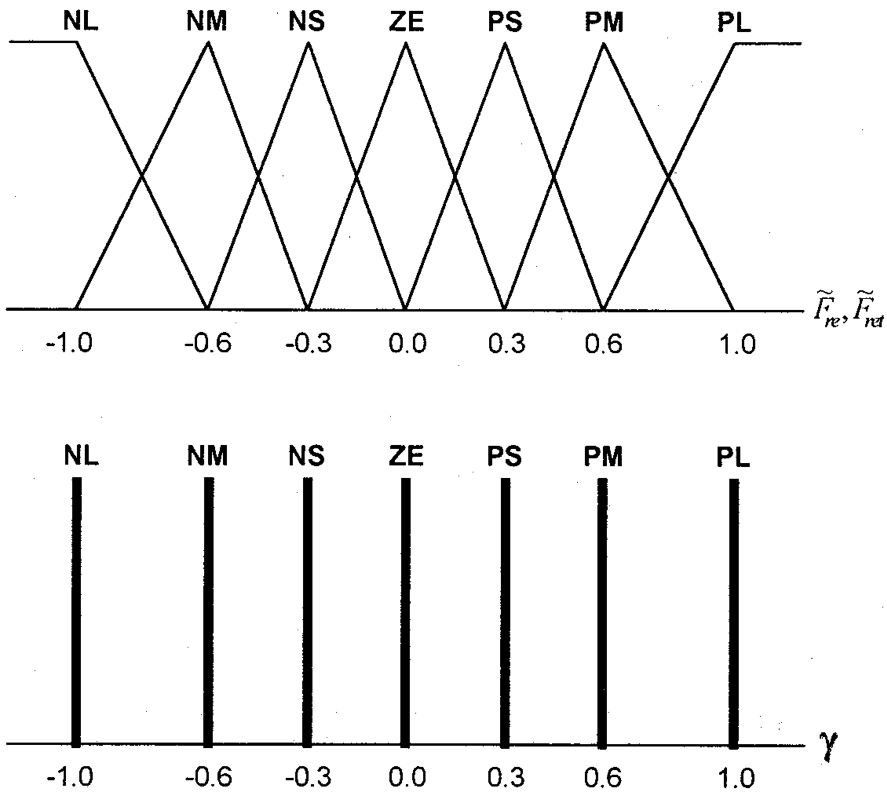

Fig. 9. Fuzzy membership functions of F_{re}, F_{ret} and γ.

Table 2. The fuzzy rules for FASE

F_{re} \ F_{ret}	NL	NM	NS	ZE	PS	PM	PL
NL	PL	PL	PL	PL	PM	PM	PM
NM	PM	PM	PM	PS	PS	PS	PS
NS	PS	PS	PS	PS	NS	NS	NM
ZE	PS	PS	PS	ZE	ZE	NS	NS
PS	NS	ZE	NS	NS	NS	NS	NS
PM	NS	NS	NS	NM	NM	NM	NM
PL	NM	NM	NL	NL	NL	NL	NL

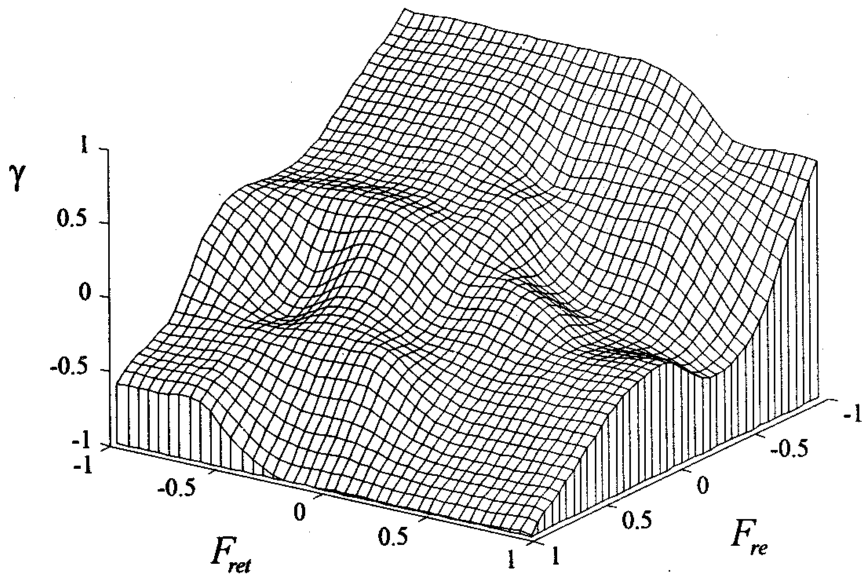

Fig. 10. Look-up table of fuzzy rules for FASE.

Now, to estimate $\hat{K}_E$, the stiffness updating law is given as

$$\hat{K}_E(t) = \hat{K}_E(t - t_s) \cdot (\lambda)^{\lambda(F_{re}(t-t_s),F_{ret}(t-t_s))}, \tag{8}$$

where t_s and λ are sampling time and learning rate, respectively. In Eqn (8), $-1 \leq \gamma(F_{re}, F_{ret}) \leq 1$, where negative (positive) γ means that current stiffness value should be decreased (increased). If a γ is issued, a new estimated stiffness value is updated as much as $(\lambda)^\gamma$ times the previous stiffness value, where λ is chosen as a constant between 1 and 2. For example, in our experiment, λ is heuristically given as 1.25, since with $\lambda = 1.25$ the estimated stiffness value can quickly converge to the actual stiffness value. It is remarked that noisy force signals may cause a stiffness estimator to issue wrong stiffness values, as is often the practical case. And wrong estimated stiffness values may be very different from the current stiffness values. Thus, new estimated stiffness values are here to be dependent on previous stiffness values to avoid such a sudden change of stiffness values due to noisy signals. It is also remarked that in practice the fuzzy adaptive scheme should be applied only in transient period, since during a steady state noisy signals may cause the estimator in Eqn (8) to frequently change the stiffness values. Thus to avoid such an undesirable action of the estimator, Eqn (8) is corrected as

$$\hat{K}_E(t) = \begin{cases} \hat{K}_E(t - t_s) \cdot (\lambda)^{\gamma(F_{re}(t-t_s), F_{ret}(t-t_s))}, & 0.1 < F_r < 0.9 \\ \hat{K}_E(t - t_s), & \text{otherwise}, \end{cases} \tag{9}$$

where F_r is the normalized $\tilde{F}_r$. Figure 11 shows the block diagram of the whole force control system which consists of reference model, FILC and FASE.

To show the validity of FASE, the following two cases are considered for the system in Eqns (5) and (6), where no noisy force signals are assumed for convenience. Noisy signal cases will be handled in section 4.

Case 1: $\hat{K}_E$ and K_E are given as 40,000 [N/m] and 10,000 [N/m], respectively.
Case 2: $\hat{K}_E$ and K_E are given as 3000 [N/m] and 10,000 [N/m], respectively.

Figure 12 shows simulation results for Case 1. Repetitive trials are performed to find the correct environmental stiffness value. It is observed from Fig. 12 that at the first trial the force output response shows sluggish behavior since FASE action finished at $t = 0.6$ [s] and $\hat{K}_E$ (0.6) is still greater than K_E. Now, $\hat{K}_E(0)$ for the second trial is given as $\hat{K}_E$ (0.6), which is finally obtained by the first trial. Then, the force output response becomes similar to the reference model output, since $\hat{K}_E$ converges to K_E. In a similar way as for Case 1, simulations for Case 2 are performed. Figure 13 shows simulation results for Case 2. The force response initally shows overshoot behavior because $\hat{K}_E$ is smaller than K_E. However, because the actual stiffness value is found by FASE as the trials are repeated, the force response follows the reference model output. These simulation results show that FASE can successfully adapt to unknown or changing stiffness values.

4. EXPERIMENTAL RESULTS

All experiments were performed by employing a five-axis articulated robot manipulator (PT200V) equipped with a force sensor system [26]. The control algorithm is

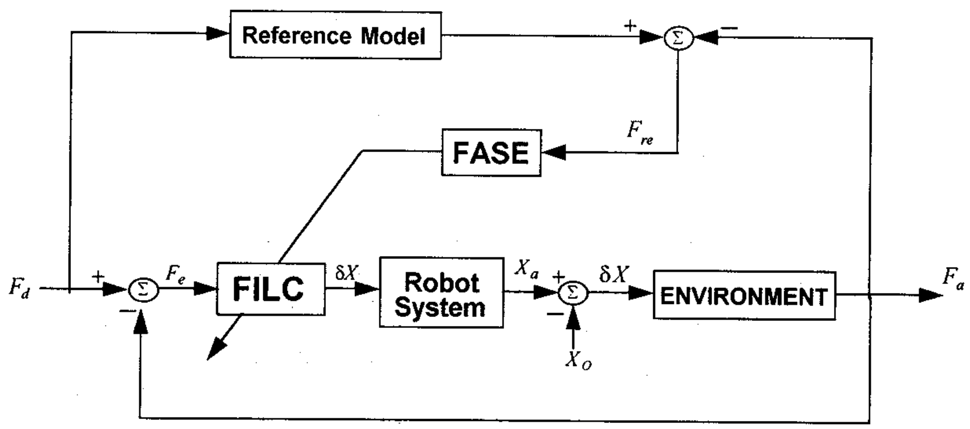

Fig. 11. Block diagram of force control algorithm by FASE.

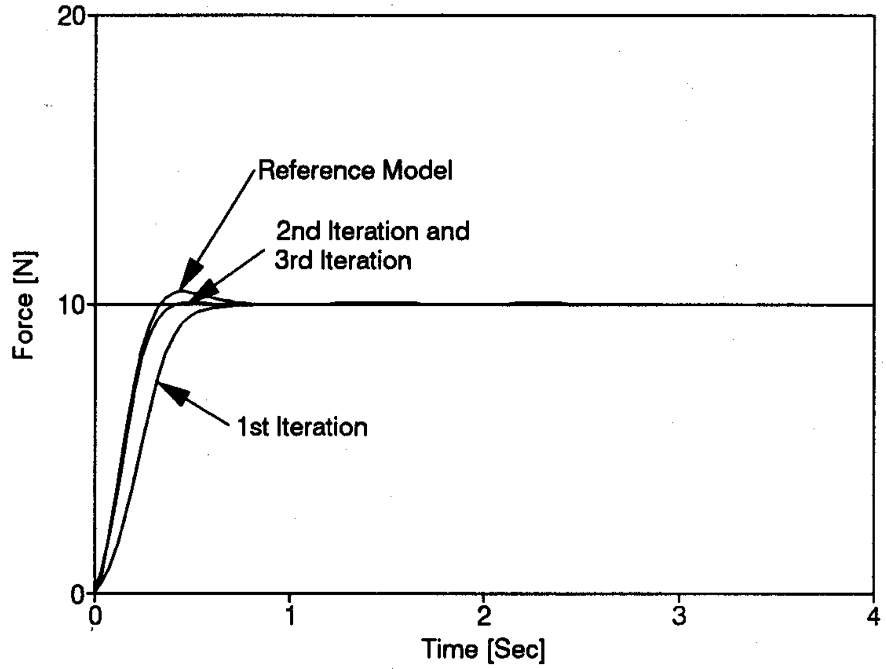

Fig. 12. Force step response for Case 1.

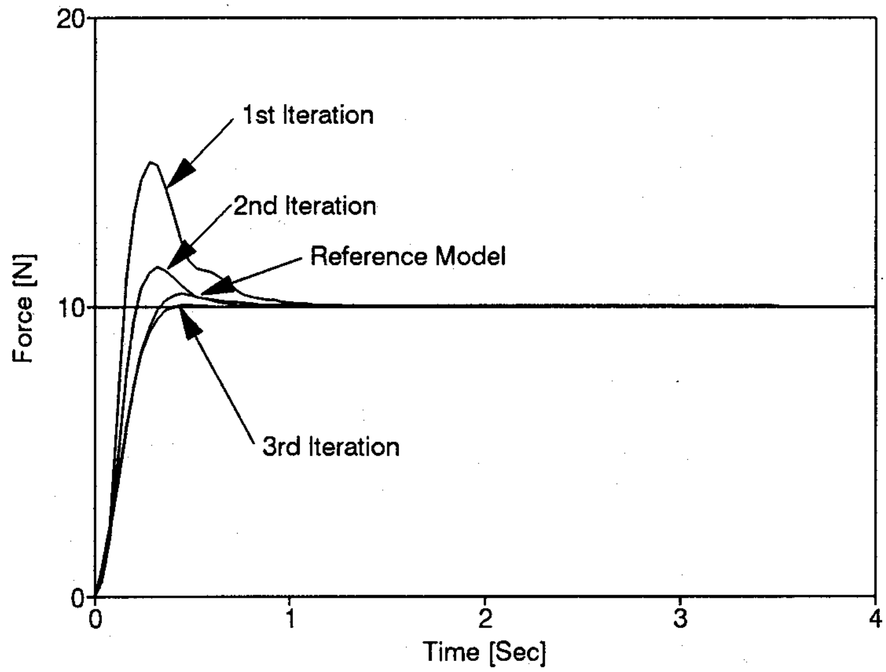

Fig. 13. Force step response for Case 2.

written in C language and tested in our prototype dual robot controller [14], where two 32-bit microprocessor boards (FORCE30 [27]) are used (Fig. 14). The experimental set-up for our force control experiment is depicted in Fig. 15.

The sampling time chosen is 40 [ms] in which data transmission from the F/T sensor system to our prototype controller can be completed and the control algorithm can be performed based on the sensor data. For our experiments, three different rubber materials are used and their stiffness values are measured as shown in Table 3.

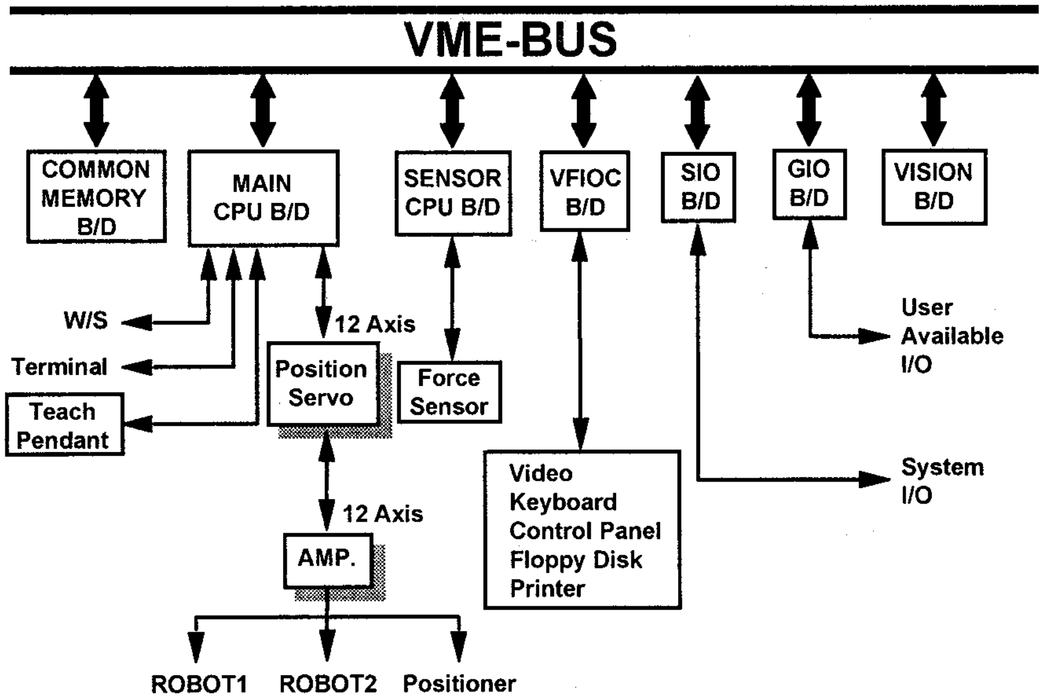

Fig. 14. Hardware structure of the overall systems.

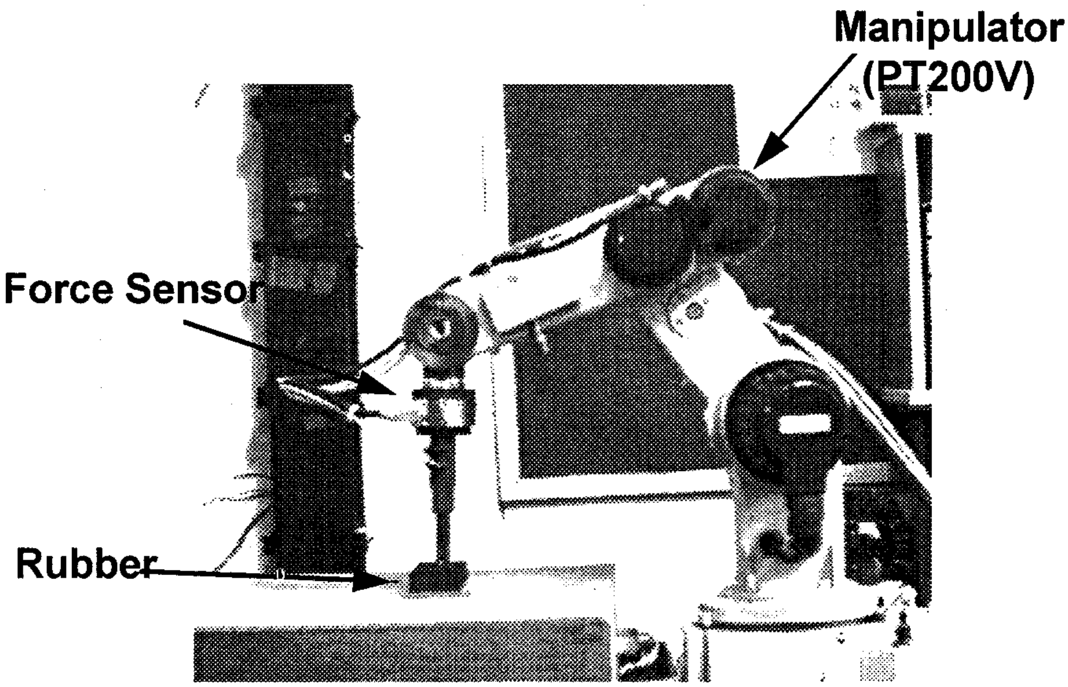

Fig. 15. Experimental set-up for force control experiments.

Table 3. Environmental stiffness values

Object	Linguistic Value	Measured Stiffness [N/m]
rubber1	SOFT	6000
rubber2	MEDIUM	21000
rubber3	HARD	47000

Three FLCs for SOFT, MEDIUM and HARD environments are designed, and their look-up tables are generated as shown in Fig. 16, where the sup-min inference mechanism and the center-of-gravity defuzzifier [24] are employed. It is observed from Fig. 17 that the output responses are satisfactory in the sense of small overshoot and fast settling time.

It is recalled that a fuzzy controller for a fixed environment cannot guarantee good force responses when it is applied to other environments. To experimentally show such a phenomenon, we applied FLCs for rubber1 and for rubber3 to an environment with a MEDIUM stiffness value, rubber2, where desired force is given as 10 [N]. Figure 18a and b show the unsatisfactory force output responses which are too underdamped or too sluggish, respectively, due to undesired control actions. Note that if the stiffness value for rubber2 is known, then FILC consisting of FLCs only for SOFT and HARD rubbers can play a similar role to FLC for the rubber with MEDIUM stiffness, as shown in Fig. 18c. This implies that FILC can successfully work for an arbitrary environmental stiffness.

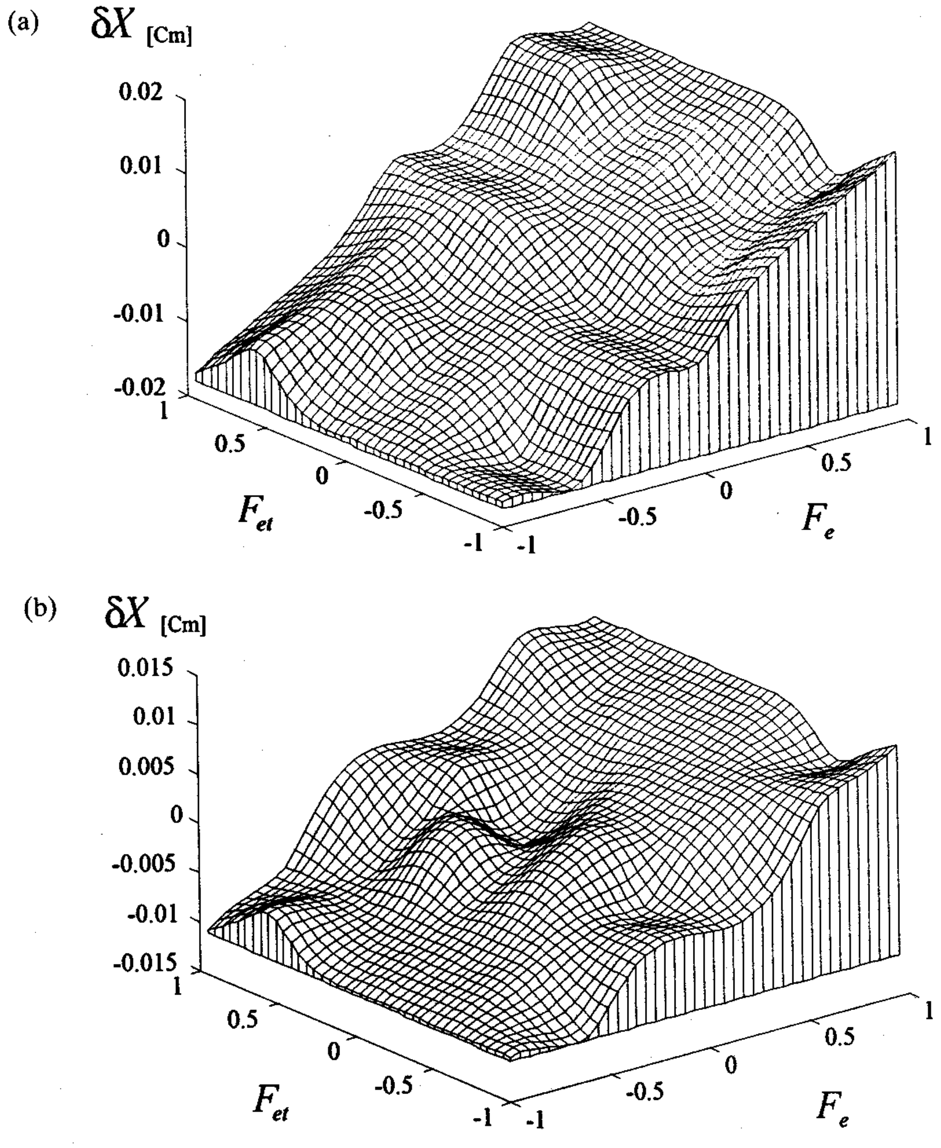

Fig. 16a and b. *Caption overleaf*.

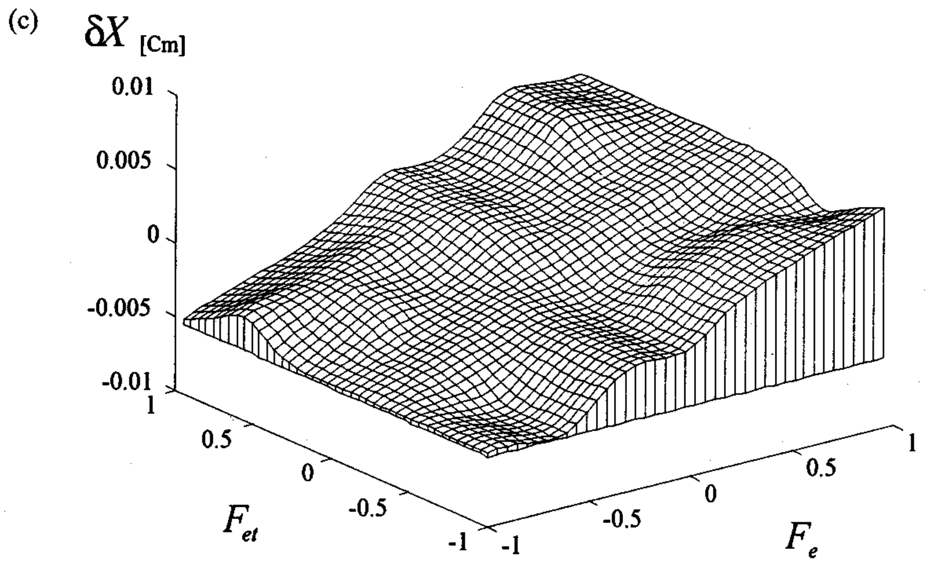

Fig. 16. Look-up tables of the fuzzy control rules for (a) SOFT, (b) MEDIUM and (c) HARD environments.

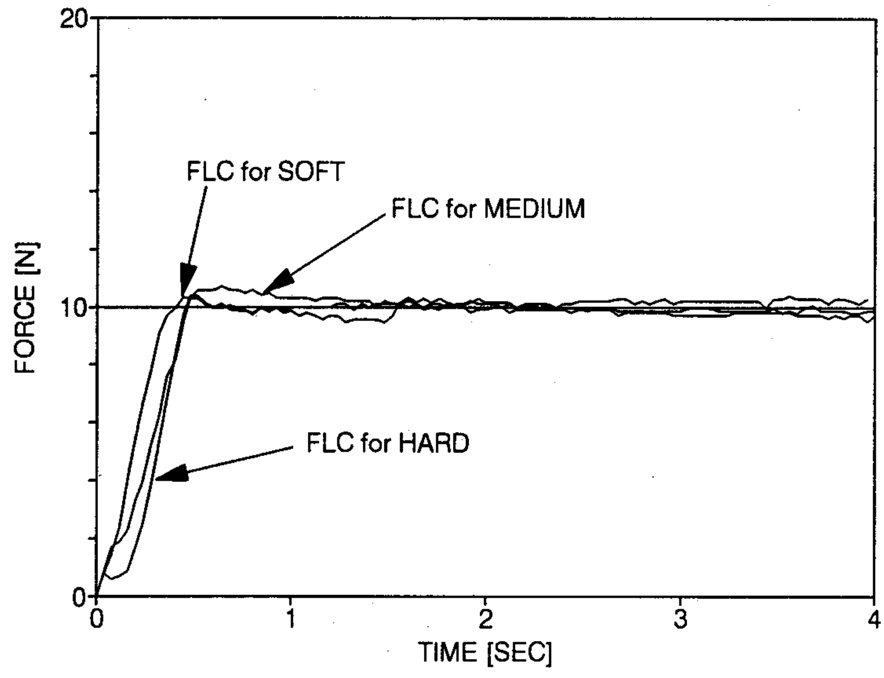

Fig. 17. Force step responses by FLCs for SOFT, MEDIUM and HARD environments.

Now, assume that the stiffness value of rubber1 is not correctly known as 47,000 [N/m]. Then, FILC consisting of three FLCs for SOFT, MEDIUM and HARD environments will act as the FLC for HARD environment, even though the actual environment is SOFT. For this case, FASE is applied to see how a true stiffness value is effectively found, and its corrresponding output performances are improved, where initial $\hat{K}_E$, $\hat{K}_E(0)$, at the start of a repetitive trial is given as $\hat{K}_E$ at the end of its previous trial. And to avoid an incorrect estimation due to noisy force signals, Eqn (9) is employed for experiments. Experimental results are shown in Fig. 19. It is observed from Fig. 19a that at the first trial the force output response shows

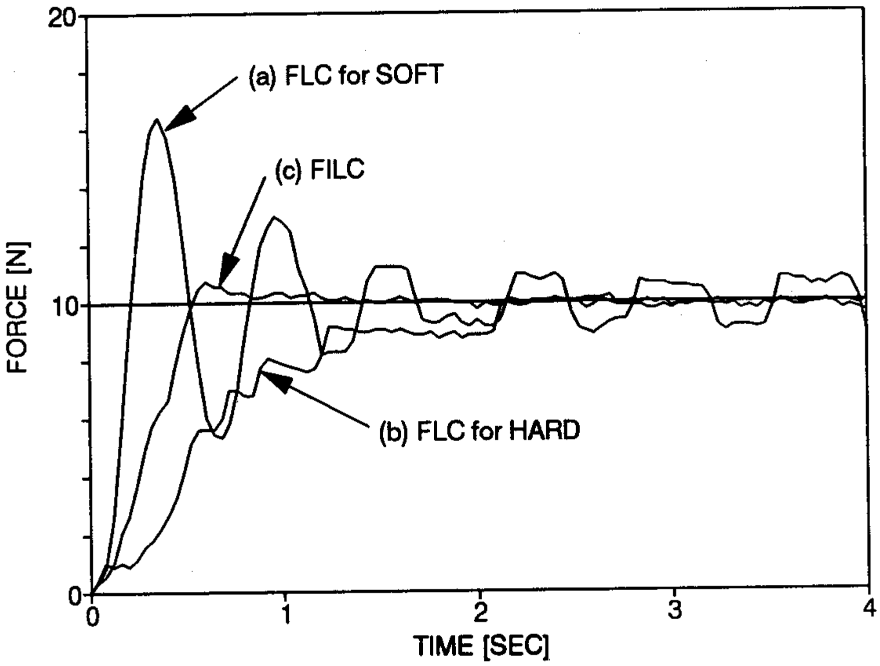

Fig. 18. Force step responses when the FLC for (a) SOFT, (b) HARD and (c) FILC is applied to the case of rubber2.

oscillatory behavior because when FASE action is finished, $\hat{K}_E$ is still smaller than K_E. However, as the number of trials is increased, force output responses become similar to the reference model output and $\hat{K}_E$ converges to K_E as shown in Fig. 19b, where t_i means end of the ith trial and start of the $(i + 1)$th trial. On the other hand, when the stiffness value of rubber3 is not correctly known as 6000 [N/m], force output responses show sluggish behavior at first attempt due to small control actions as

(a)

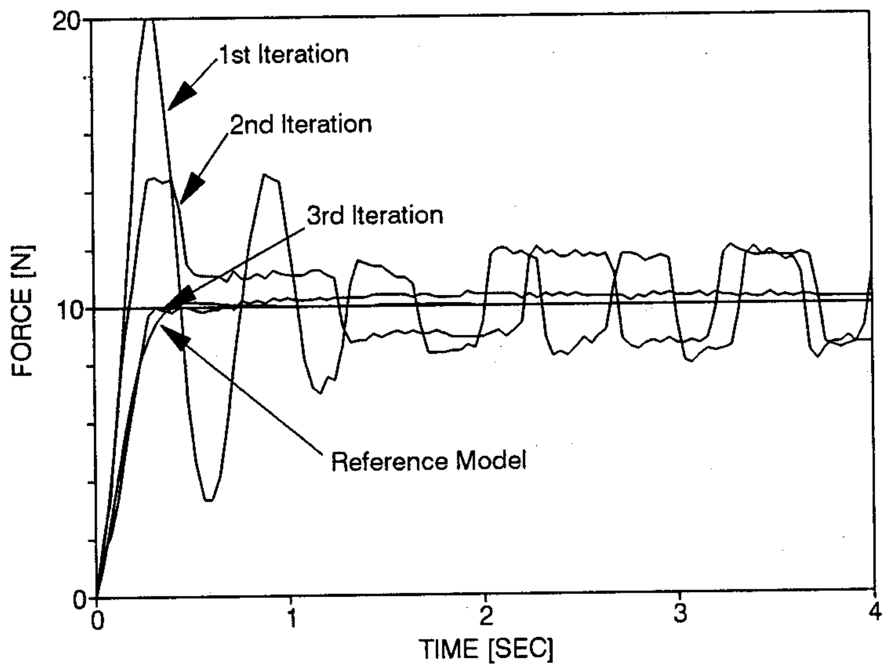

Fig. 19a. *Caption overleaf*.

(b)

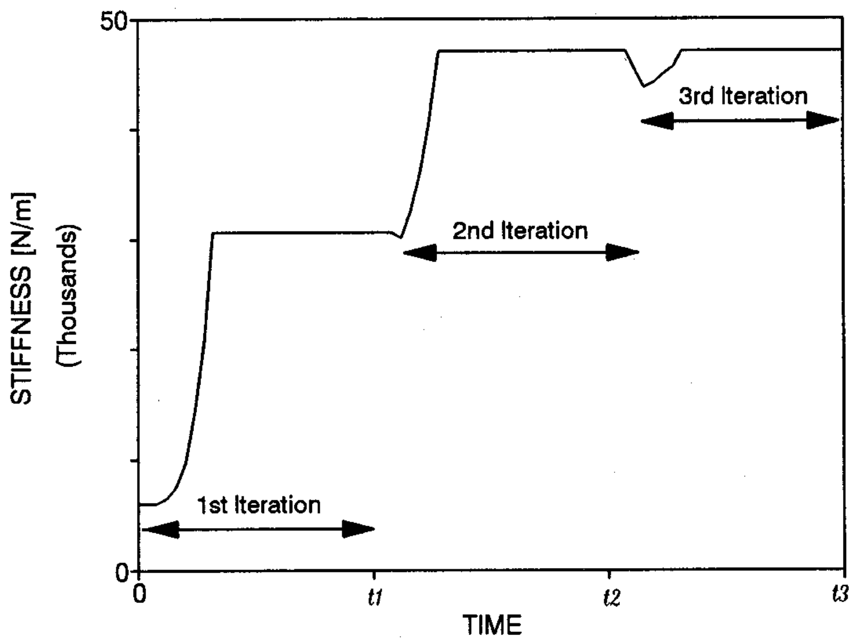

Fig. 19. Experimental force output responses and estimated stiffness value when FASE is applied for the case that $\hat{K}_E(0) = 6000$ [N/m] and $K_E = 47{,}000$ [N/m]. (a) Force output responses. (b) Estimated stiffness value.

shown in Fig. 20. However, repetitive trials make the actual force output follow the reference model output by decreasing $\hat{K}_E$. It is remarked that the number of trials for the experiments may be required to be greater than that for simulations described in section 3 due to noisy force signals. Nevertheless, experimental output performances seem to be quite similar to output performances obtained from simulations. From these experimental results, it may be concluded that our proposed fuzzy adaptive force control scheme can be a good way to respond to unknown or changing environmental stiffness values.

(a)

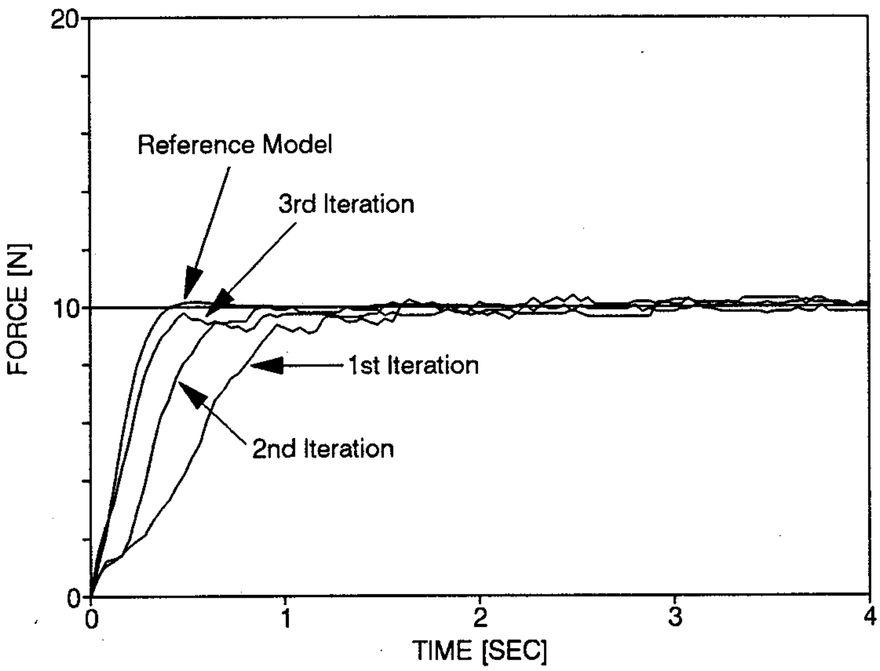

Fig. 20a. *Caption opposite.*

(b)

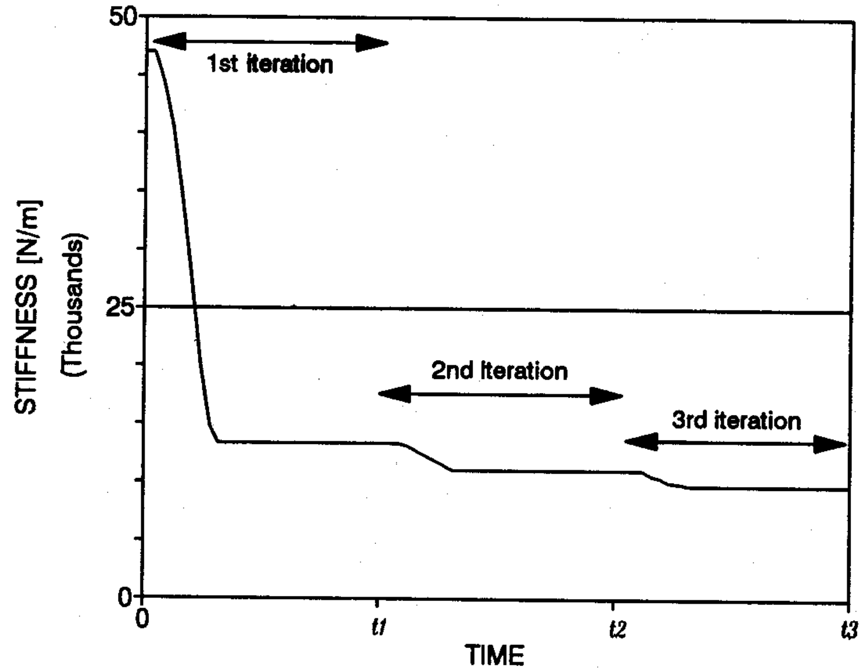

Fig. 20. Experimental force output responses and estimated stiffness value when FASE is applied for the case that $\hat{K}_E(0) = 47{,}000$ [N/m] and $K_E = 6000$ [N/m]. (a) Force output responses. (b) Estimated stiffness value.

5. CONCLUDING REMARKS

A fuzzy force control algorithm was proposed to obtain good force output responses regardless of changes of environmental stiffness, in which some fuzzy control rules were designed for several representative environmental stiffness values, and then a control action was determined by a fuzzy interpolation method. Specifically, to cope with changes of environment, an adaptive logic using a fuzzy algorithm was employed for the estimation of environmental stiffness values. The proposed algorithm was implemented in C language and tested by using a five-axis commercialized industrial robot equipped with the position servo drives in cascade with an exponential filter. From the experimental results, the fuzzy adaptive scheme is believed to successfully respond to changes of environmental stiffness.

Stability analysis of the fuzzy control system has been known to be quite difficult and is unsolved as yet. Hence, we will consider such a stability analysis in future work.

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