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Simultaneous precision positioning and vibration suppression of reciprocating flexible manipulators

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Abstract. Simultaneous precision positioning and vibration suppression of a reciprocating flexible manipulator is investigated in this paper. The flexible manipulator is driven by a multifunctional active strut with fuzzy logic controllers. The multifunctional active strut is a combination of a motor assembly and a piezoelectric stack actuator to simultaneously provide precision positioning and wide frequency bandwidth vibration suppression capabilities. First, the multifunctional active strut and the flexible manipulator are introduced, and their dynamic models are derived. A control strategy is then proposed, which includes a position controller and a vibration controller to achieve simultaneous precision positioning and vibration suppression of the flexible manipulator. Next, fuzzy logic control approach is presented to design a fuzzy logic position controller and a fuzzy logic vibration controller. Finally, experiments are conducted for the fuzzy logic controllers and the experimental results are compared with those from a PID control scheme consisting of a PID position controller and a PID vibration control. The comparison indicates that the fuzzy logic controller can easily handle the non-linearity in the strut and provide higher position accuracy and better vibration reduction with less control power consumption.

Keywords: flexible manipulator; motion control; vibration suppression; fuzzy logic control; smart structure.

1. Introduction

Robotic arms or manipulators have been proposed for space applications, medical or nursing care jobs, and nuclear waste cleanup in recent years. In these applications, slim, light-weighted, and flexible manipulators become essential in order to achieve high accuracy, high speed, large workspace, and low power consumption. The flexibility of manipulators challenges the control design of flexible manipulators and leads to two tasks in motion control of flexible manipulators: 1) tracking a desired trajectory, and 2) vibration suppression.

Most manipulators are slewing manipulators driven by different joint motors such as DC/AC motors (Ge, *et al*. 1998) and artificial pneumatic muscle actuators (Park, *et al*. 2002), where the rotational angles and/or angular speeds of the motors are fed back to the controllers to position the manipulators. For vibration suppression of manipulators, there are two actuation approaches. The most popular and convenient approach is directly employing the actuators that position the manipulators, i.e., joint motors (Ge, *et al*. 1998, Park, *et al*. 2002). In this case, the vibration information, acquired on-line or off-line, of the flexible manipulators is also used to design the joint motor controllers. In the on-line

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vibration information acquisition, sensors are directly used to measure the flexible manipulator vibration, for example, bonding strain gages to the flexible manipulators (Ge, *et al*. 1998, Park, *et al*. 2002). The vibration can be monitored all the time, and the vibration control part of the joint motor controller may respond to any change of vibration environment by employing proper control strategies such as adaptive control (Feliu, *et al.* 1990), robust control (Lenz, *et al.* 1991), variable structure control (Thomas and Bandyopadhyay 1997), and intelligent control (Park, *et al*. 1999, Hesselroth, *et al*. 1994). The off-line vibration information acquisition is based on the understanding of the flexible manipulator dynamics including natural frequencies, damping ratios, etc., and the vibration control part of the joint motor controller is designed based on this known dynamics. A typical example of the off-line vibration information acquisition is the command or input shaping control (Tzes and Yurkovich 1993, Mohamed and Tokhi 2004). This technique works by altering the shape of either the actuator commands or the reference outputs to reduce the manipulator oscillation. Input shaping refers to a particular command shaping technique that exploits the convolution of the reference signal with a sequence of an impulse to reduce the manipulator vibration. Since actuators that provide position control of the manipulators are concurrently used for vibration suppression, the obvious advantages of this actuation approach include hardware-saving and compact architecture; however, the actuator must have sufficient frequency bandwidth and motion range to satisfy both vibration suppression and positioning requirements that may not always be possible. Another actuation approach for vibration suppression is to use a separated actuator, e.g., bonding/embedding PZT patches onto/into the flexible manipulators (Shin and Choi 2001, Xu and Yao 2001, Ma 2003). In this case, complex wiring has to be handled (Ghasemi-Nejhad and Pourjalali 2003, Ghasemi-Nejhad and Russ 2003). In addition, if the motion range of a flexible manipulator is not too large, simultaneous precision positioning and vibration suppression can be achieved by using bonded/embedded PZT actuators directly (Ma, *et al.* 2002, Ma and Ghasemi-Nejhad 2003, 2004).

This paper focuses on the trajectory tracking and vibration suppression of a flexible reciprocating manipulator by employing a multi-functional active strut and fuzzy logic control strategy. Compared to slewing manipulators, reciprocated manipulators require less power or driving moment for the same tip motion of the manipulator. The multi-functional active strut developed in this work is a combination of a motor assembly and a PZT stack actuator in series. The motor assembly can reduce the effect of model uncertainties such as parameter variations and external disturbance (Xu and Yao 2001) and provides trajectory tracking. The PZT actuator possesses high frequency bandwidth to meet the requirement of vibration reduction. Therefore, this strut configuration is compact with a desirable frequency bandwidth and stroke. Fuzzy logic control is a model-free intelligent control method and can easily handle the non-linearity that exists in the motor assembly. This paper is organized as the following. First, the manipulator driven by the multi-functional active strut is described. Then, modeling is performed, a control strategy is presented, and the fuzzy logic control is briefly explained. Finally, the experiments and discussions are followed.

2. Flexible manipulator with active strut

Fig. 1 shows the schematic of the flexible manipulator driven by the multifunctional active strut. The manipulator consists of a polymer beam with 580 mm in length, 25 mm in width, and 1.6 mm in thickness, and is clamped at one end that is mounted onto the multifunctional active strut, resulting in its first natural frequency of 1.013 Hz. The active strut has the dual-functionalities of positioning and vibration suppression by combining the motor assembly with the piezoelectric stack actuator in series.

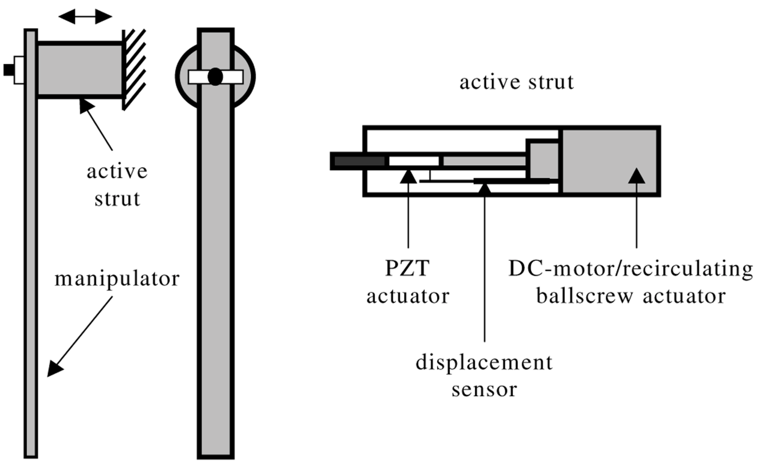


Fig. 1 Flexible manipulator with multifunctional active strut

The motor assembly consists of a DC-motor, a gearhead and a recirculating ballscrew. The gearhead reduces the DC-motor speed, and the recirculating ballscrew transforms the DC-motor rotation to translation, resulting in the elimination of the torque-induced rotation of the manipulator and the cosine error that occurs when a drive system is misaligned with the driven part. Compared with traditional leadscrews, recirculating ballscrews reduce the sliding friction of leadscrews to rolling friction, showing significantly reduced wear and friction, long lifetime, and high velocity. This motor assembly has a high resolution and low power consumption. Its maximum velocity, unidirectional repeatability, maximum stroke, backlash, and maximum push/pull force are 1 mm/s, 0.1 µm, 50 mm, 2 µm, and 40 *N*, respectively. To control the vibration beyond the frequency bandwidth of the motor assembly, the piezoelectric stack actuator, due to its high frequency bandwidth, is integrated into the strut. The piezoelectric stack pre-load, maximum load, resolution, maximum stroke, and maximum input voltage are 150 *N*, 1000 *N*, 0.02 nm, 20 µm, and 150 V, respectively. In addition, a displacement sensor with a resolution of 1.5 µm is integrated to measure the locomotion of the motor assembly. The free-end of the manipulator can be precisely positioned by employing the DC-motor assembly, and the induced vibration can simultaneously be suppressed by using the PZT stack actuator.

3. Dynamic models

3.1. Manipulator

Fig. 2 show the manipulator model, where the manipulator is a cantilevered beam with a moving clamped-end driven by the multifunctional active strut. In this figure, $y_b(x, t)$ and $y_a(t)$ are the displacement relative to the neutral axis of the manipulator at position x and the motion of the multifunctional active strut, respectively. The absolute displacement of the manipulator is then:

$$y(x, t) = y_b(x, t) + y_a(t) \tag{1}$$

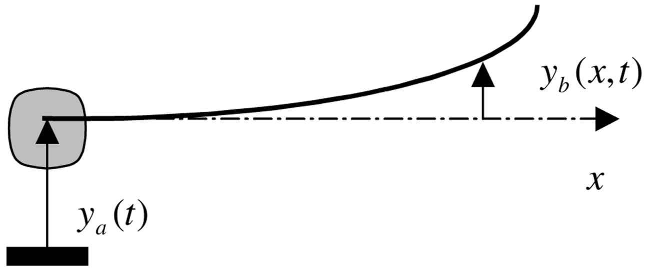


Fig. 2 Model of manipulator driven by multifunctional active strut

The differential equation of the manipulator is as the following:

$$EI\frac{\partial^4 y_b(x,t)}{\partial x^4} + m[\ddot{y}_a(t) + \ddot{y}_b(x,t)] = 0 \tag{2}$$

in which EI is the flexural stiffness, and m is the mass per unit length. Rearranging Eq. (2) yields:

$$EI\frac{\partial^4 y_b(x,t)}{\partial x^4} + m\ddot{y}_b(x,t) = -m\ddot{y}_a(t) \tag{3}$$

Assuming the solution in the following form:

$$y_b(x,t) = \sum_i \varphi_i(x) q_i(t) \tag{4}$$

where $q_i(t)$ is the modal coordinate, and $\varphi_i(x)$ is the i-th modal shape at position x, Eq. (3) in the modal coordinate becomes:

$$\ddot{q}_i(t) + \omega_i^2 q_i(t) = -\ddot{y}_a(t)\frac{m}{M_i}\int_0^l \varphi_i(x)dx \tag{5}$$

where l is the entire length of the manipulator, M_i is the i-th modal mass, $M_i = \int_0^l m\varphi_i^2(x)dx$, ω_i is the i-th modal frequency, $\omega_i^2=(\beta_i l)^2\sqrt{\frac{EI}{ml^4}}$, and β_i depends on the boundary conditions. Taking the structural damping into account and defining that $D_i=\frac{m}{M_i}\int_0^l \varphi_i(x)dx$, Eq. (5) can be rewritten as:

$$\ddot{q}_i(t) + 2\xi_i\omega_i\dot{q}_i(t) + \omega_i^2 q_i(t) = -\ddot{y}_a(t)D_i \tag{6}$$

In fact, the motion of the multifunctional active strut, $y_a(t)$, consists of two components: the motion of the motor $y_m(t)$ and the motion of the PZT actuator $y_p(t)$. Due to the low damping property of the manipulator, the motor position change will induce the manipulator vibration that has to be suppressed by using the PZT stack actuator.

$$\ddot{q}_i(t) + 2\xi_i\omega_i\dot{q}_i(t) + \omega_i^2 q_i(t) = -[\ddot{y}_m(t) + \ddot{y}_p(t)]D_i \tag{7}$$

The displacement at the free end of the manipulator is

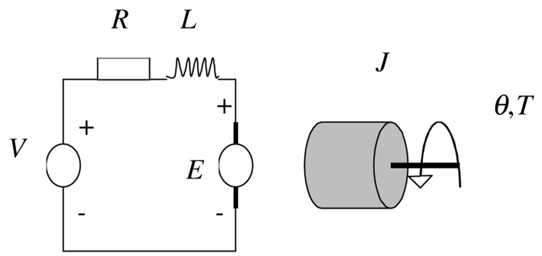


Fig. 3 DC-motor and dive circuit

$$y(l,t) = y_b(l,t) + y_m(t) + y_p(t) \tag{8}$$

From Eq. (8), if $y_b(l, t) = -y_p(t)$, then $y(l, t) = y_m(t)$, i.e., if the PZT stack actuator fully suppresses the manipulator vibration, then the displacement at the free-end of the manipulator equals the motion of the motor assembly.

3.2. Motor assembly

Fig. 3 shows the schematic of a DC-Motor and its drive circuit. The motor torque is related to the armature current by an electromotive force constant. The back electromotive force is related to the rotational velocity by the following equations:

$$T(t) = K_t I(t) \tag{9}$$

$$E(t) = K_e \dot{\theta}(t) \tag{10}$$

where T is the motor torque, I is the armature current, E is the back electromotive force, θ is the motor shaft angle, and K_t and K_e are the electromotive force constants. Based on Newton's law and Kirchhoff's law, the following equations can be obtained:

$$J\ddot{\theta}(t) + B\dot{\theta}(t) = K_t I(t) \tag{11}$$

$$L\dot{I}(t) + RI(t) = V_m(t) - K_e\dot{\theta}(t) \tag{12}$$

where J is the moment of inertia of the motor rotor, B is the damping of the motor and its payload, L and R are the electric inductance and resistance of the motor and its drive circuit, and V_m is the input voltage.

The translation of the motor assembly is as follows:

$$y_m(t) = K_g \theta(t) \tag{13}$$

in which K_g is the transformation constant between the DC-motor rotational angle and the translation of the DC-motor assembly.

In view of non-linearity due to the existing friction and backlash of the motor, Eq. (12) can be rewritten as the following.

$$L\dot{I}(t) + RI(t) = f\, V_m(t) - K_e\dot{\theta}(t) \tag{13}$$

where f is a nonlinear function that describes the existing non-linearity. In general, a dead-zone and/or hysteresis can be used to describe the non-linearities due to the backlash and friction in the motor assembly.

3.3. Piezoelectric actuator

The relationship between the input voltage and the motion of the PZT stack actuator can be assumed as the following:

$$y_p(t) = K_p V_p(t) \tag{14}$$

where K_p is a constant, and V_p is the input voltage of the PZT stack actuator.

4. Control strategy and fuzzy logic control

4.1. Control strategy

To accomplish simultaneous precision positioning and vibration suppression of the manipulator, the following control strategy, as shown in Fig. 4, is proposed. This control strategy includes two controllers. One of them, namely the motor (position) controller, is used to control the motor for positioning, and the other one, namely the piezo-actuator (vibration) controller, is used to drive the piezoelectric actuator for suppressing the vibration induced by the motion of the manipulator itself. The motor controller uses the translation of the motor assembly, i.e., $y_m(t)$, as the feedback signal and the piezo-actuator controller uses the velocity at the free-end of the manipulator as the feedback signal.

Applying Laplace transform to Eqs. (7) and (8), the following can be obtained:

$$Y(s) = [1 + H(s)][Y_m(s) + Y_p(s)] \tag{15}$$

where $Y(s)$, $Y_m(s)$, $Y_p(s)$ are the Laplace transforms of $y(t)$, $y_m(t)$, and $y_p(t)$, respectively, s is the Laplace

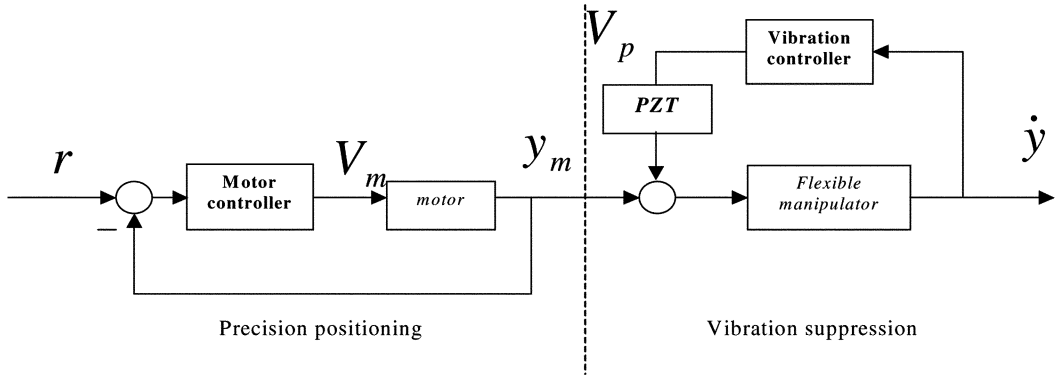


Fig. 4 Control strategy for the manipulator

factor, and $H(s)$ is the transfer function between $Y_b(s)$ and $Y_p(s)$ or $Y_m(s)$, $H(s)=\sum_{i=1} \frac{-D_i\phi_i s^2}{s^2+2\xi_i\omega_i s+\omega_i^2}$, $Y_b(s)$ are the Laplace transforms of $y_b(t)$. From Eq. (15), assuming that $Y(s)=Y_m(s)$, then

$$Y_p^*(s) = -\frac{H(s)}{1+H(s)}Y_m(s) \tag{16}$$

where $Y_p^*(s)$ is the optimal $Y_p(s)$ for achieving full vibration suppression of the manipulator.

According to Fig. 4 and Eqs. (14) and (15),

$$Y_m(s) = \frac{C_m(s)G(s)}{1+C_m(s)G(s)}R(s) \tag{17}$$

$$Y_p(s) = \frac{C_P(s)K_p[1+H(s)]s}{1-C_P(s)K_p[1+H(s)]s}Y_m(s) \tag{18}$$

where $C_m(s)$, $C_p(s)$, and $G(s)$ are the transfer functions of the motor controller, the piezo-actuator controller, and the motor assembly, respectively. Eqs. (15) and (17) indicate that the motor controller and the desired trajectory affect the free-end position of the manipulator. From Eqs. (16) and (18), the optimal vibration controller, $C_p^*(s)$, can be obtained:

$$C_p^*(s) = -\frac{H(s)}{K_p[1+H(s)]s} \tag{19}$$

which implies that the optimal vibration controller is only dependent on the dynamics of the manipulator, meaning that the motor controller and the piezo-actuator controller can be designed separately.

4.2. Fuzzy logic control

Fuzzy logic control (FLC) can be applied in developing both linear and non-linear systems. By using fuzzy logic, designers can realize lower development costs, superior features, and better end product performance. Furthermore, products can be brought to market faster and more cost-effectively. The FLC is capable of providing the high degree of accuracy required by high-performance systems, without the need for detailed mathematical models (Li, *et al.* 2002, Yen and Langari 1999, Verbruggen and Babuska 1999).

FLC uses a form of quantification of imprecise information (input fuzzy sets) to generate an inference scheme, which is based on a knowledge base of control signals to be applied to a system (Yen and Langari 1999, Verbruggen and Babuska 1999). The benefit of this quantification is that the fuzzy sets can be represented by a unique linguistic expression, such as small, medium, or large. The linguistic representation of a fuzzy set is known as a term, and a collection of such terms defines a term-set, or a library of fuzzy sets. A fuzzy controller converts a linguistic control strategy, typically based on expert knowledge, into an automatic control strategy. A FLC is comprised of four primary components: (1) fuzzifier (the values of the state variables monitored during the process are fuzzified into fuzzy linguistic terms); (2) a knowledge base that contains fuzzy IF-THEN rules and membership functions; (3) fuzzy reasoning (the result of which is a fuzzy output for each rule), and (4) a defuzzification interface. Clearly, the FLC is rule-based controllers in which a set of so-called fuzzy rules represents a control decision mechanism to adjust the effects of certain system stimulus. The goal of the FLC is normally to replace an experienced human operator with a fuzzy rule-based system. Fuzzy processing enables the quantification of an irregular input by sets that can be treated according to their significance. A rule in the knowledge base can be defined, such that the control signal will be zero, without detrimentally affecting the system. Similarly, any set can be treated differently from any other sets.

Therefore, the first step in designing a FLC is to decide which state variables of the controlled system can be taken as the input signals to the controller. The position error of the motor is used as the input to the motor controller in this work. Likewise, the velocity at the free-end of the manipulator is used as the input to the piezo-actuator controller. Further, choosing the fuzzy sets to formulate the fuzzy control rules are also significant factors in the performance of the FLC. Empirical knowledge and engineering intuition play an important role in choosing fuzzy sets and their corresponding membership functions. After choosing proper fuzzy variables as inputs and outputs of the FLCs, the fuzzy sets must be determined. These sets transform the numerical values of the inputs to fuzzy quantities. The number of these fuzzy sets specifies the quality of the control, which can be achieved using FLCs. As the number of the fuzzy sets increases, the management of the rules is more involved and the tuning of the controller is less straightforward. Accordingly, a tradeoff between the quality of control and computational time is required to choose the number of fuzzy sets. A number of fuzzy sets for each of the input variables are chosen to represent the drive system under study. In the motor controller, seven fuzzy sets are defined for the position error and five fuzzy sets are defined for the output of the motor controller. Similarly, in the piezo-actuator controller, seven fuzzy sets are defined for the velocity of the free-end of the manipulator and five fuzzy sets are defined for the output of the piezo-actuator controller. The seven input fuzzy sets are Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Large (PL), and the five output fuzzy sets are Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Large (PL). After specifying the fuzzy sets, their membership functions are then determined. Functional definition, which express the membership function of a fuzzy set, is a functional form. In this paper, triangular-shaped, trapezoidal-shaped, and Gaussian-shaped functions are employed to fix the limits of the membership functions (Mathworks 2001), i.e.,

Gaussian membership function (GAUSS_MF):

$$f(x, \sigma, c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \tag{20}$$

Trapezoidal membership function (TRAP_MF):

$$f(x, a, b, c, d) = \max\left(\min\left(\frac{x-a}{b-a} \quad 1 \quad \frac{d-x}{d-c}\right), 0\right) \tag{21}$$

Triangular membership function (TRI_MF):

$$f(x, a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \tag{22}$$

where a, b, c, d, and σ are given constants, and x is a variable.

The third step of designing a FLC is the choice of the fuzzy rules. The decision-making logic is the way in which the controller output is generated. The decision-making uses input fuzzy sets, and the decision is governed by the values of the inputs. Furthermore, the knowledge base consists of knowledge of the application domain and the attendant control goals. It includes a database and a fuzzy control rule base.

After the input and output values are assigned to the defined fuzzy sets, each possible input condition must be mapped onto an output condition. Such mapping is commonly expressed as IF-THEN rules. For the motor controller and the piezo-actuator controller, these rules are as simple as the followings:

IF (input is (NL or NM)) THEN (output is NL);
IF (input is NS) THEN (output is NS);
IF (input is Z) THEN (output is Z);
IF (input is PS) THEN (output is PS);

and

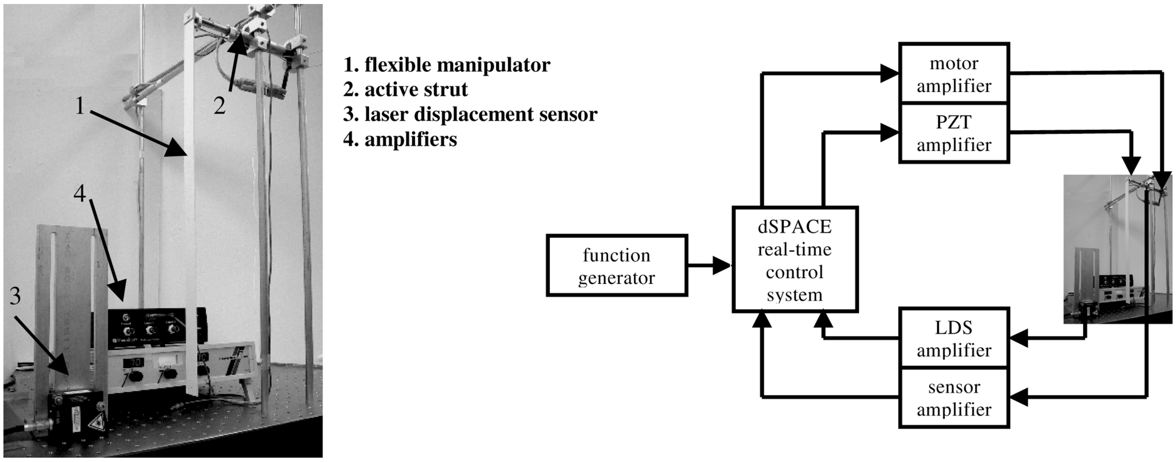
IF (input is (PL or PM)) THEN (output is PL).

For FLCs with several inputs, the fuzzy rule base can be illustrated as a look-up table. The more the inputs are, the more complex the fuzzy rule base is, and the longer time it takes for the decision-making.

The last step is the defuzzification. Defuzzification is the conversion of a fuzzy quantity represented by a membership function, into a precise or crisp value. Commonly used strategies may be described as maximum criterion, mean of maximum, and centroid methods (Yen and Langari 1999). The centroid method is employed in this paper.

5. Experimental system and results

Fig. 5 illustrates an experimental system and setup for simultaneous precision positioning and vibration suppression of the reciprocating flexible manipulator. It consists of the flexible manipulator, the multi-functional active strut, a laser displacement sensor (LDS), amplifiers of sensors and actuators, a function generator, and a real-time control system. The LDS is used to measure the free-end displacement of the manipulator. The sampling rate is 100 Hz. The control code is programmed in Matlab-Simulink,



(a) Setup. (b) Control system.

Fig. 5 Experimental setup and control system

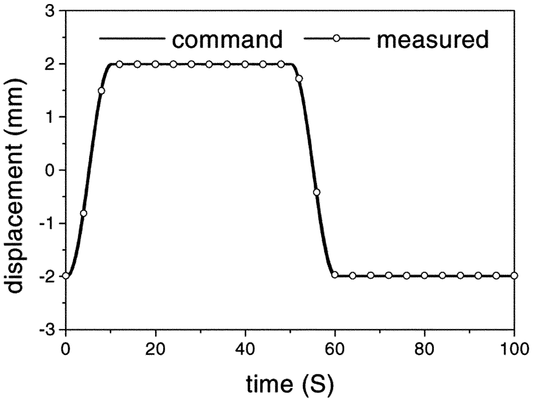


Fig. 6 Motor displacement (PID)

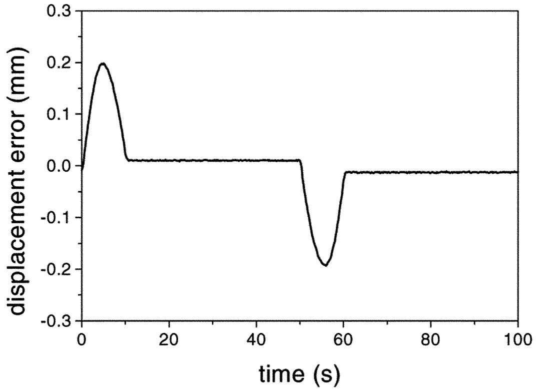


Fig. 7 Motor displacement error (PID)

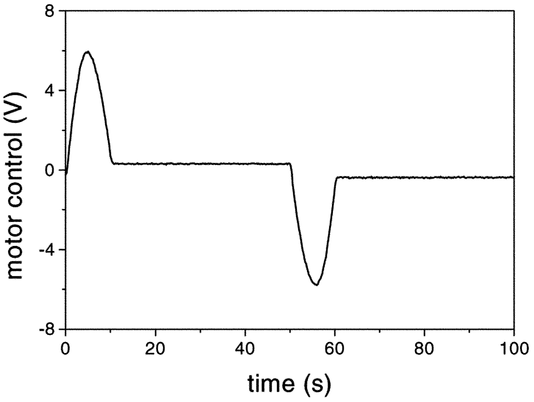


Fig. 8 Motor control (PID)

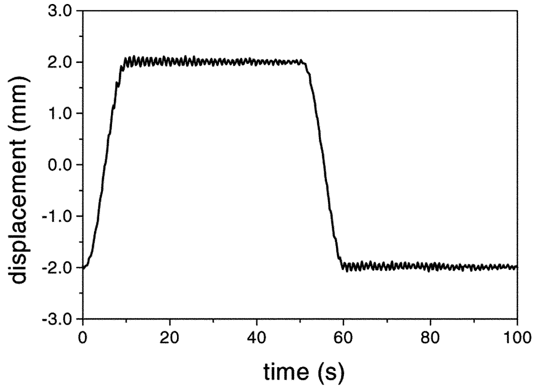


Fig. 9 Free-end displacement

compiled and downloaded to the real time control system.

The feature of the multifunctional active strut is characterized. It is found that the motor assembly behaves as an integrator with dead-zone nonlinerity due to the existing backlash and friction. The width of deadband is 0.6 V from -0.3 V to 0.3 V, and the integral constant is 0.2765.

Firstly, two PID controllers are designed for the motor controller and the piezo-actuator controller, respectively. The PID motor controller is a typical PI controller with the proportional and integral gains of 30 and 0.001, respectively. For the piezo-actuator controller, the displacement signal of the LDS is differentiated, i.e., the velocity of the free-end is fed back to the piezo-actuator controller. The piezo-actuator controller is a proportional controller where the proportional gain is carefully adjusted to achieve maximum vibration reduction, and the final proportional gain is set as 5. In addition, for decreasing the vibration of the flexible manipulator, the input-shaping technology is also employed; therefore, the command shown in Fig. 6 is not a step but a saturated sinusoidal wave. Figs. 6 and 7 demonstrate the motor displacement and error showing that the maximum error and the steady state error are 0.2 and 0.01 mm, respectively, i.e., the relative steady state error is 0.5%, and the settling time for a 1% steady state error tolerance is 10.3 seconds. Fig. 8 shows the motor control signal. Fig. 9 shows the free-end displacement without the piezo-actuator controller resulting in the vibration amplitude of -27.19 dB at the first natural frequency of the manipulator. Fig. 10 demonstrates the free-

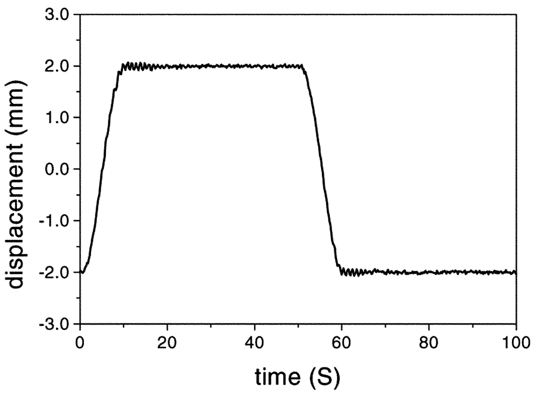


Fig. 10 Free-end displacement (PID)

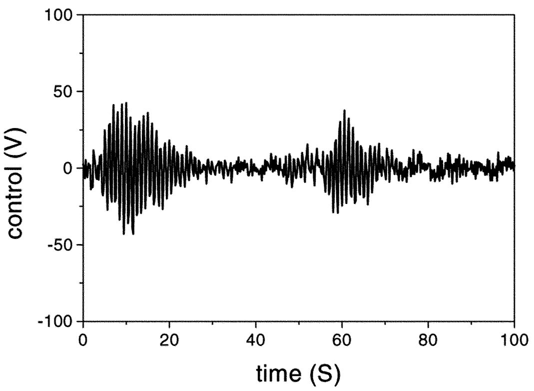


Fig. 11 PZT control (PID)

Table 1 Fuzzy sets of the position error (motor controller)

Fuzzy sets	Membership functions
NL	GAUSS_MF (x, 0.5, -2)
NM	GAUSS_MF (x, 0.261, -1.09)
NS	GAUSS_MF (x, 0.083, -0.68)
Z	TRAP_MF (x, -0.00529, -0.000529, 0.000529, 0.00476)
PS	GAUSS_MF (x, 0.088, 0.532)
PM	GAUSS_MF (x, 0.18, 1.06)
PL	GAUSS_MF (x, 0.5, 2)

Table 2 Fuzzy sets of the motor controller output

Fuzzy sets	Membership functions
NL	GAUSS_MF (x, 1.8, -10)
NS	GAUSS_MF (x, 0.639, -4.75)
Z	TRI_MF (x, -0.0794, 0.132, 0.238)
PS	GAUSS_MF (x, 0.908, 5.17)
PL	GAUSS_MF (x, 1.8, 10)

end displacement with the piezo-actuator controller, and the vibration amplitude at the first natural frequency of the manipulator is -37.63 dB, i.e., a 10.42 dB reduction is achieved. The control signal of the piezo-actuator controller is shown in Fig. 11.

The FLC performance is also evaluated experimentally. Tables 1 to 4 list the fuzzy sets and their membership functions for the inputs and outputs of the motor controller and the piezo-actuator controller. Tables 1 and 2 indicate that the position error of the motor assembly translation is set in the range of [-2, 2] mm, and the motor control voltage is in the range of [-10, 10]V. Similarly, Tables 3 and 4 imply that the velocity of the free-end of the manipulator is set in the range of [-1, 1] mm/s, and the output of the piezo-actuator controller is in the range of [-5, 5] V before amplification, equivalent to [-200, 200] V after amplification.

Some results are shown in Figs. 12 to 17. Figs. 12 and 13 demonstrate the motor displacement and error showing that the maximum error and the steady state error are decreased, compared to the PID

Table 3 Fuzzy sets of the velocity (piezo-actuator controller)

Fuzzy sets	Membership functions
NL	GAUSS_MF (*x*, 0.25, -1)
NM	GAUSS_MF (*x*, 0.1305, -0.545)
NS	GAUSS_MF (*x*, 0.0798, -0.234)
Z	TRAP_MF (*x*, -0.156, -0.000264, 0.000264, 0.167)
PS	GAUSS_MF (*x*, 0.044, 0.24)
PM	GAUSS_MF (*x*, 0.09, 0.53)
PL	GAUSS_MF (*x*, 0.25, 1)

Table 4 Fuzzy sets of the piezo-actuator controller output

Fuzzy sets	Membership functions
NL	GAUSS_MF (*x*, 0.9, -5)
NS	GAUSS_MF (*x*, 0.598, -1.69)
Z	TRI_MF (*x*, -0.675, 0.066, 0.939)
PS	GAUSS_MF (*x*, 0.454, 2.585)
PL	GAUSS_MF (*x*, 0.9, 5)

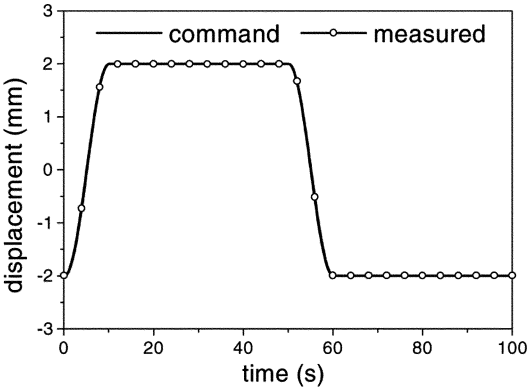


Fig. 12 Motor displacement (FLC)

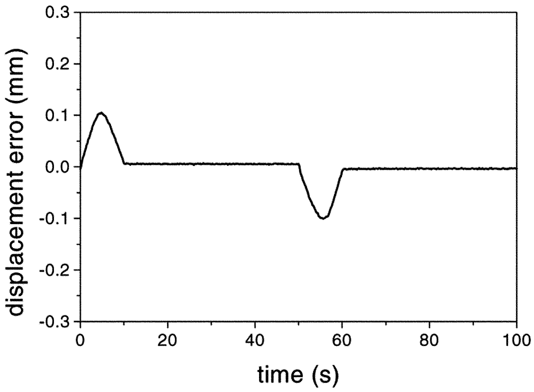


Fig. 13 Motor displacement error (FLC)

control, to 0.1 and 0.005 mm, respectively, i.e., the relative steady state error is 0.25%, and the settling time for a 1% steady state error tolerance is shortened to 9.5 seconds. Fig. 14 shows the motor control signal. Fig. 15 shows the free-end displacement without the piezo-actuator controller resulting in the manipulator vibration amplitude of -29.52 dB, at the first natural frequency, which is 2.33 dB less than that in the PID control case. Fig. 15 demonstrates the free-end displacement with the piezo-actuator controller, where the vibration amplitude at the first natural frequency of the manipulator is -39.29 dB, i.e., 9.77 dB reduction is achieved. Compared with the PID controllers, the controlled vibration of the manipulator employing the fuzzy logic controllers is 1.66 dB less. The control signal of the piezo-actuator controller is shown in Fig. 17.

The presented results show that the fuzzy logic intelligent controllers provide more accurate motor position, shorter settling time, and faster vibration decay of the flexible manipulator, compared with those in the PID control case. The FLC motor controller even induces less vibration amplitude of the

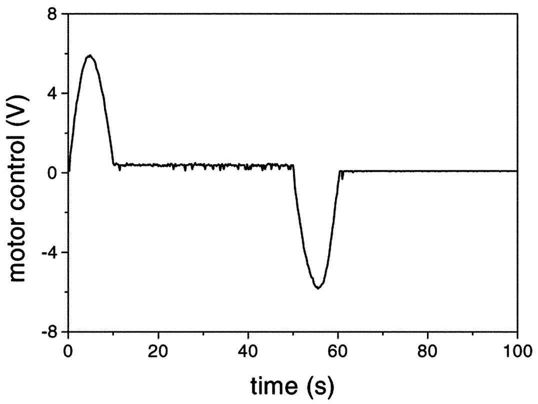


Fig. 14 Motor control (FLC)

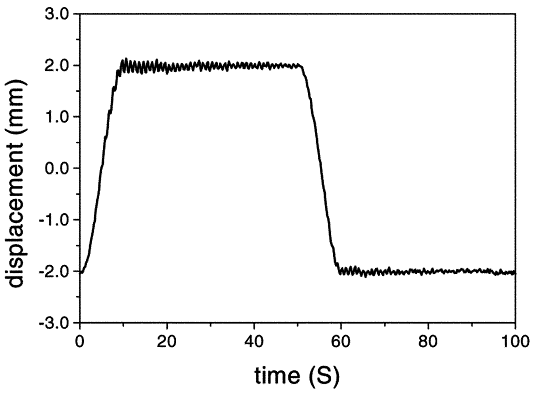


Fig. 15 Free-end displacement

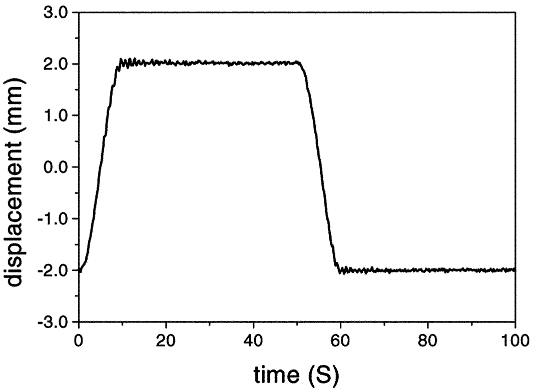


Fig. 16 Free-end displacement (FLC)

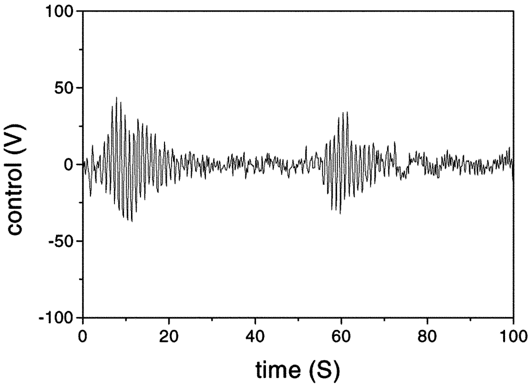


Fig. 17 PZT control (FLC)

Table 5 Vibration displacement amplitude of the manipulator at its 1st natural frequency (dB)

PID motor	PID motor/PZT	FLC motor	FLC motor/PZT
-27.19	-37.63	-29.52	-39.29

flexible manipulator. This can be attributed to the fact that fuzzy logic control is a nonlinear and intelligent control method that is different from linear PID control, and can easily handle the existing non-linearities by adjusting the types and parameters of the membership functions.

Table 5 summarizes the vibration levels of the flexible manipulator for the PID and fuzzy logic controllers.

In order to compare the power consumptions, the following power index, J, is defined:

$$J(t) = \int_0^t V^2(t)dt \tag{23}$$

where $V(t)$ is the control voltage, i.e., $V_m(t)$ for the motor controller or $V_p(t)$ for the piezo-actuator controller. Figs. 18 and 19 illustrate the power indexes of the motor controller and the piezo-actuator controller, respectively, for both the PID and FLC, revealing that the fuzzy logic motor controller consumes slightly less power than the PID motor controller; however, the fuzzy logic

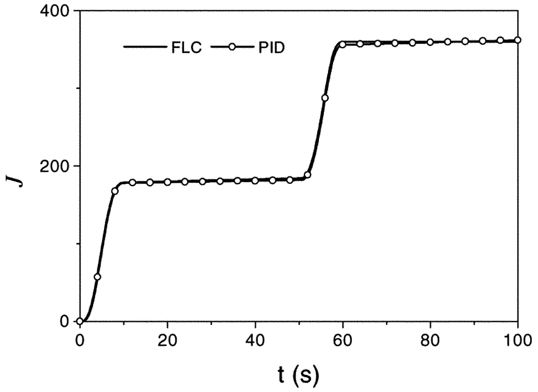


Fig. 18 Motor power index

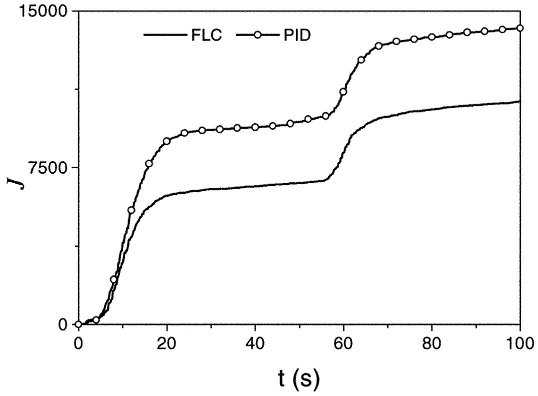


Fig. 19 PZT power index

piezo-actuator controller consumes much less power than the PID piezo-actuator controller. This is because the fuzzy logical motor controller induced less vibration of the manipulator and the fuzzy logical vibration controller works more effectively than the PID vibration controller.

6. Concluding remarks

Positioning and vibration suppression of a flexible manipulator simultaneously depend on the positioning controller and the vibration controller. The desired positioning controller should not only provide high position accuracy in various conditions such as variable payload and non-linearities, but also should induce less vibration of the manipulator, i.e., vibration reduction would also be considered while designing the positioning controller. The vibration controller is then used to further dampen unwanted vibrations.

The multifunctional active strut can successfully achieve simultaneous precision positioning and vibration suppression of flexible manipulators. The position controller and the vibration controller can be designed separately. Compared with the PID control, the fuzzy logic controller can easily handle the non-linearity of flexible manipulators and the active strut, and provide higher position accuracy with less control power consumption.

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