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Gain Tuning Fuzzy Controller for an Optical Disk Drive

Shiuh-Jer Huang, and Ming-Tien Su

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Abstract**—**Since the driving speed and control accuracy of commercial optical disk are increasing significantly, it needs an efficient controller to monitor the track seeking and following operations of the servo system for achieving the desired data extracting response. The nonlinear behaviors of the actuator and servo system of the optical disk drive will influence the laser spot positioning. Here, the model-free fuzzy control scheme is employed to design the track seeking servo controller for a d.c. motor driving optical disk drive system. In addition, the sliding model control strategy is introduced into the fuzzy control structure to construct a 1-D adaptive fuzzy rule intelligent controller for simplifying the implementation problem and improving the control performance. The experimental results show that the steady state error of the track seeking by using this fuzzy controller can maintain within the track width (1.6 μm). It can be used in the track seeking and track following servo control operations.

Keywords**—**Fuzzy control, gain tuning and optical disk drive.

I. INTRODUCTION

OPTICAL disk drive is one of the important component of personal PC for optical recoding and data extracting. Since the track width is reduced in response to the memory capacity increasing, and the operation speed is increased dramatically, the control performance of the disk drive is strictly limited. Usually, the sled mechanism of an optical disk drive system includes a voice coil motor for tracking servo control and a dc motor for seeking servo control. The high frequency voice coil finely tunes the laser spot to track the data track in disc. The coarse tuning dc actuator is used to generate the large radial motion for seeking a specified data track. The positioning and tracking accuracy of these operations are limited to μm range. For the precise positioning control, the motor deadzone and stick friction nonlinear behaviors will influence the control performance. Doh et al. [1-3] employed the repetitive control and a disturbance observer quantitative feedback theory to reduce the external disturbance influence for improving the tracking errors of HDD track following operation. Dong et al. [4] proposed an optimal model prediction control for optical disk drive track following operation. Ohili et al. [5] proposed a robust feed forward track following control for an optical disk drive to improve the precise tracking response. However, it is difficult to estimate the system nonlinearity for model based controller design. Hence, the model-free fuzzy control algorithm has gained the attention of the controller designers.

Yeng et al. [6] employed fuzzy control algorithm on a dual actuator optical disk drive system. Liou et al. [7] used the fuzzy control scheme to solve the nonlinear problem of the signal pickup head of a hard disk driver. Boling et al. [8] employed fuzzy logic control to improve the seeking time of a hard disk. However, the design of a traditional fuzzy controller depends fully on an expert or the experience of an operator to establish the fuzzy rule bank. Generally, this knowledge is difficult to obtain. A time-consuming adjusting process is required to achieve the specified control performance. Its application still presents certain difficulty. Hence, the robustness and self adjustment advantages of a sliding mode control are introduced into the fuzzy controller in recent researches.

Yager and Filev [9] and Lo and Kuo [10] employed a fuzzy control to substitute the boundary layer term of a sliding surface in order to improve the chattering behaviour of a sliding mode control. Hwang and Lin [11] and Wang [12] employed the switch function as the fuzzy input variables and proposed a fuzzy sliding mode controller. Lu and Chen [13] extended this approach and developed a self-organizing fuzzy sliding mode controller to smooth the chattering phenomenon. However, these approaches still depend on certain mathematic model for a sliding mode to operate. In addition, the fuzzy rule bank design and calculation are still complicated. Those factors hinder its applications and implementation. Here a fuzzy sliding mode controller (FSMC) is employed to monitor an dc motor actuating optical disk drive for track following and seeking control operations. Since this approach has learning ability for establishing and regulating the fuzzy rule bank and parameters continuously, its control implementation can be started with zero initial fuzzy rules. In addition, its only need seven rules for various operations. This approach can reduce significantly the database burden and computing time, thereby increasing the sampling frequency and implementation possibility.

II. EXPERIMENTAL SYSTEM STRUCTURE

The optical mechanism of an optical disk drive system structure includes optical pickup head, sled mechanism and spindle motor Mecha module and disk tray loader for rotating the disk and pickup data through laser spot. The function of its electronic control part is to generate the servo signal for control the optical mechanism and decoding/coding the read/write

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Shiuh-Jer Huang is with the National Taiwan University of Science and Technology, Taipei, Taiwan 106 (corresponding author: phone 886-2-27376449; fax: 886-2-27314990; e-mail: sjhuang@mail.ntut.edu.tw).

Ming-Tien Su is with the Chi-Mei Optical and Electronics Com. Industrial Park, Tainan, Taiwan (e-mail:hd3601@ntut.edu.tw).

data. In this study, we are focused on the servo control development of the optical mechanism. Generally, the optical disk drive servo control tasks include spindle motor servo control, track following control, track seeking servo control and the optical focus servo control. The function of the spindle motor servo control is to monitor the disk under constant linear velocity (CLV) or constant angular velocity (CAV) rotation for the optical pickup head to read the data from the spiral magnetic track of the memory disk. The CLV type servo control has varying rotation speed with respect to the optical pickup head radial position for following. The function of the track following control is to manipulate the optical pickup head for projecting the laser spot on the spiral data track. In order to accurately project the laser spot on the data track, the servo control system needs to adjust the pickup head radial position continuously for compensating the spindle axis offset and the disk radial oscillation. The function of the track seeking servo control is to extract the specified track by actuating the radial motion of a sled mechanism. The function of the optical focus servo control is to monitor the distance between the lens and the disk surface within the fixed focus length.

A PC based control structure is constructed in this experiment for controller implementation and performance evaluation. This retrofitted dc motor actuating optical disk drive has two dc motors for spindle speed control and the track seeking and following control. The PCL-726D/A and ADIO-113 interface cards are used to convert the control command into the dc motor control voltage. The BA-6849FP IC is adopted as the driver IC of the dc motor. It has FG pin to provide the square wave with different frequencies in response to the motor rotation speed. That can be used as the rotational speed feedback signal. The sled mechanism radial position is measured by using optical linear scale and HCTL-2020 IC for the track seeking and following operations. The control program is written as Turbo C language. The PC is used as the CPU to handle all the I/O data and the control voltage calculation. The resolution of optical linear encoder is 0.1 μm, and the maximum measuring range is 100mm. In this study, the servo controllers are designed to monitor the spindle motor rotation speed and regulate the sled actuator track seeking and following operations.

III. FUZZY LOGIC CONTROLLER DESIGN

Since, this experimental system has dc motor deadzone nonlinear behaviour, it is difficult to establish an appropriate dynamic model for the precise model based controller design. The dead-zone offset voltage will influence the track seeking and following accuracies of the optical disk drive. Hence the model free fuzzy control structure is employed to solve this problem. The control block diagram of single axis fuzzy controller is shown in Fig. 1.

Usually the motivation of a fuzzy approach is that the knowledge is insufficient and the dynamic model has uncertainty. Fuzzy set theory was employed to simulate the logic reasoning of human beings. The major components of a fuzzy controller are a set of linguistic fuzzy control rules and an inference engine to interpret these rules. These fuzzy rules offer a transformation between the linguistic control knowledge of an expert and the automatic control strategies of an activator. Every fuzzy control rule is composed of an antecedent and a consequent, a general form of the rules can be expressed as

$$R_i : \text{IF X is } A_1 \text{ and Y is } A_2\text{, THEN U is } C_1 \qquad (1)$$

Where R_i is the i^{th} rule, X and Y are the states of the system output to be controlled and U is the control input. A_1, A_2 and C_1 are the corresponding fuzzy subsets of the input and output universe of discourse, respectively.

The output importance of each rule depends on the membership functions of the linguistic input and output variables. In this system, two input indices of the fuzzy controller are displacement error e and error change ce, and the output index is control voltage u. In order to simplify the computation of fuzzy controller, seven equal span triangular membership functions are employed for fuzzy controller input variables e and ce. They are NB, NM, NS, ZO, PS, PM, and PB. The membership functions of these fuzzy variables are shown in Fig. 2. The divisions of this membership functions can be expanded or shrunk by changing the scaling parameter of membership functions. The scaling parameter is used to map the corresponding variables into this nominal range. In human beings' intuition, when the displacement error is large, the control voltage will be increased to reduce the displacement error. On the other hand, when the error is approaching to the zero subset of membership functions, the controller should provide fine tuning to correct the little change of displacement error. These two conditions can be traded off, by scaling the divided spans of membership functions with a parameter. These mapping parameters are specified as ge, gce and gu for the error, error change and control voltage, respectively, whose values are shown in Table I. The parameters ge and gce are scaling factors selected to specify the fuzzy input variables operating ranges of position error and error change, respectively. The parameter gu is a gain designed to adjust the fuzzy logic control voltage and simplify the trail-and-error effort for designing the fuzzy rule table. The values of these parameters are not critical for this fuzzy logic controller. They can be roughly determined by simple experimental tests. Hence the same values can be chosen for spindle motor and the track following motor and used in different motion situations.

In this study, the whole universe of discourse of the membership function were divided into three divisions, they are named as fine-tuning area, coarse-tuning area, and transitional area. Fig. 3 shows the individual spans of these different membership functions and the whole membership functions in ratio. For instance, in the beginning of a step response, the controller will choose the biggest division of membership (coarse-tuning area) in response to the large error. Finally, the controller will switch the range of membership function to the fine-tuning area to correct the steady state error, when the displacement is converged and approached to the steady state. Between these two states, a transitional area membership function was designed for reducing the control voltage big variation. This control strategy can switch automatically between these different scales and divisions of

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membership functions, by changing the scaling factor of membership function only. In addition, the dead-zone offset starting control voltage is induced into the fuzzy rule table to reduce the discontinuous variation during the controller switches between these three areas.

In this paper, 49 fuzzy rules are employed to control the spindle and track searching d.c. motors of the optical disk drive. Those fuzzy rules are listed in Table II. These rules are established base on the testing response of a PID control and certain trial-and-error process. The value of dead-zone offset voltage is added into these fuzzy rule tables directly. The fuzzy controller will automatically calculate the control voltage, which is including the offset control voltage. However, a PID controller needs to add a constant control voltage into the control law to compensate the dead-zone offset voltage after control law calculation. The membership function used in this paper for the fuzzification is of a triangular type. The function can be expressed as

$$\mu(x) = \frac{1}{w}(-|x-a| + w) \tag{2}$$

where w is the distribution span of the membership function, x is the fuzzy input variable and a is the parameter corresponding to the value 1 of the membership function. The height method is employed to defuzzify the fuzzy output variable for obtaining the control voltage of the dc motor of this optical disk drive positioning system. The relevant equation is

$$y = \frac{\sum \omega_i y_i}{\sum \omega_i}, \omega_i = \prod_j \mu_{A_{ij}}(x_j) \tag{3}$$

where $\mu_{A_{ij}}(x_j)$ is the linguistic value of the fuzzy set variable and ω_i is the weight of the corresponding rule which has been activated. y_i is the resulting fuzzy control value of the i^{th} fuzzy rule and y is the net fuzzy control action. The fuzzy controller output calculated from this equation determines the control voltage of a dc motor in each control step.

IV. 1-D FUZZY SLIDING VARIABLE CONTROLLER

Since the 2D fuzzy control rule table is difficult to establish and find the optimal rules, the 1-D fuzzy control structure is proposed to control the dc motors motion of a optical disk drive. The sliding mode control concept is adopted to define a sliding variable $s = ce + \lambda e$, which combines the system output error and change of error with a weighting factor λ. Then the one dimensional fuzzy controller can be derived [11,14] to make the system output satisfying the sliding surface reaching condition $s \cdot \dot{s} < 0$. The sliding surface variable s is the unique fuzzy input of the 1-D fuzzy control. The un-equal span fuzzy membership functions of the input variable and control rules are shown in Fig. 4. Where parameters gs and gu are the adjustable variables used to map the input variable into the fuzzy universe of discourse and modify the control gain, respectively. The scaling factor gs is switched from 3 to 1 between the coarse tuning area and fine tuning area. The gain factor gu is switched from 0.28 to 0.3 between the coarse tuning area and fine tuning area for improving the positioning accuracy. In order to equalize the influence of output error and error change, the weighting factor λ is selected as 1.

V. EXPERIMENTAL RESULTS

In this paper, the model-free intelligent controllers are designed to control the spindle motor rotation speed and the optical pickup head track seeking and following operations of an optical disk drive. In order to investigate the control performance of the intelligent fuzzy controller, a commercial optical disk drive is converted into a PC based control structure as explained in section 2. Since the optical disk need micro level precise positioning to optically read/write the data information from the disk, a sub-micro optical scale is added to feed back the track seeking and following position response. Both the spindle motor and the track seeking actuator are direct current (dc) actuated servo motors. The sampling frequency in the following experiments was 1 KHz.. The dynamic responses of this d.c. actuating optical disk drive system with the fuzzy controller are compared with that of a PID controller. Seven equal span triangular membership functions are employed for fuzzy controller input variables e and ce, and output variable u, respectively. The divisions of this membership functions can be expanded or shrunk by changing the scaling parameter of membership functions. The scaling parameter is used to map the corresponding variables into this specified range listed in table 1.

Generally, the dc motor needs a small starting offset voltage to compensate the dead-zone behavior. It is difficult to estimate this accurate value for model based control compensation. Here, the dead-zone effect is directly designed in the fuzzy rules table.

A. PID Control

The appropriate control gains of this PID controller are chosen as $K_p = 0.5$, $K_i = 0.008$ and $K_d = 0.007$ after a trial-and-error test. For a 20 mm track step change, the output response and error history are shown in Fig. 5(a) and 5(b), respectively. The final steady state error is 0.3 μm without overshoot. The settling time is about 0.32 sec. However, the steady state error is enlarged to 63 μm when the track step change is 10 mm. That means the optimum PID gains depend on the motion situation. It is difficult to implement. The speed control response of spindle motor is shown in Fig. 6. The rotation speed is changing from 130 rps to 113rps. The speed error is under 2 rps for all tracking process.

B. 2-D Fuzzy Control

The fuzzy control block diagram and the scaling fuzzy parameters are shown in Fig. 1 and Table I, respectively. These fuzzy control parameters and rules bank of Table II are employed to execute the following experiments without any change. The dead-zone offset voltage is embedded into the fuzzy rules bank. The fuzzy control interference output is employed to control both dc motors of the optical disk drive directly without the introducing of extra constant offset voltage. That means this fuzzy controller can be used as a general purpose controller for various operating conditions instead of a PID controller needs a specific gains for each case. For a 20 mm track step change, the output response and error history are shown in Fig. 7 (a) and 7 (b), respectively. It can be observed that the steady state error and the settling time are -0.8 μm and 0.41 sec, respectively. For a 10 mm track step change, the output response and error history are shown in Fig. 8 (a) and 8 (b), respectively. The steady state error and the settling time are -0.7 μm and 0.22 sec, respectively. It can be concluded that the fuzzy parameters and control rules can be used for different motion situations.

C. 1-D Fuzzy Sliding Control

The 1-D fuzzy input and output membership functions and the control rules are shown in Fig. 4. For a 10 mm track step change, the output response and error history are shown in Fig. 9(a) and 9(b), respectively. The steady state error and the settling time are -0.3 μm and 0.28 sec, respectively. Other track step change experimental results are listed in Table III. It can be concluded that the 1-D fuzzy parameters and control rules can be used for different motion situations. The pickup head position response and the track following error are shown in Fig. 10 (a) and 10(b), respectively. The track tracking error is always within 1 μm of design specification except at the initial learning period.

VI. CONCLUSION

The model free fuzzy controllers are designed to control a d.c. motors actuating optical disk drive system by using a switching factor for adjusting the universe of discourse range of membership functions. The dead-zone offset control voltage is embedded in the fuzzy rule bank for automatic adjustment. The track seeking steady state error can be kept within 1.0 μm for the pickup head to accurate read/write the information. The fuzy parameters can be used for different track seeking and following operation. However, the gains of a PID controller should be individually searched for each case. It is not convenient for the real implementation. In addition, the 1-D fuzzy sliding controller has simplified the fuzzy control structure and the practical implementation problem. The experimental results based on a converted PC based optical disk drive system have evaluated the dynamic performance improvement of the proposed intelligent controller.

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TABLE I
FUZZY VARIABLES SCALING FACTORS

	fuzzy gain parameter		
parameter	g_e	g_ce	g_u
fine tuning	0.001	0.0015	0.05
transient	0.008	0.012	0.05
coarse tuning	1.0	1.5	0.35

TABLE III
TRACK SEEKING PERFORMANCE OF FSMC

Step (mm)	Steady state error (μm)	Settling time (sec)	Overshoot (mm)
35	-1.3	0.61	0.47
30	0.3	0.52	0.68
20	0.8	0.43	0.39
10	-0.3	0.28	0.11

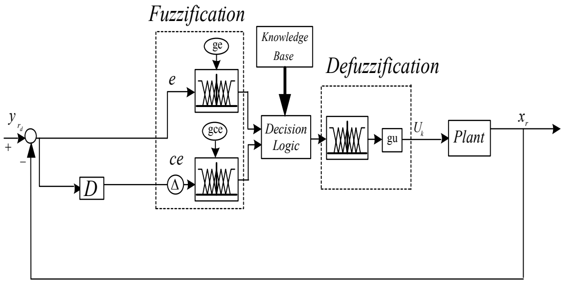


Fig. 1 Fuzzy control block diagram of dc motor

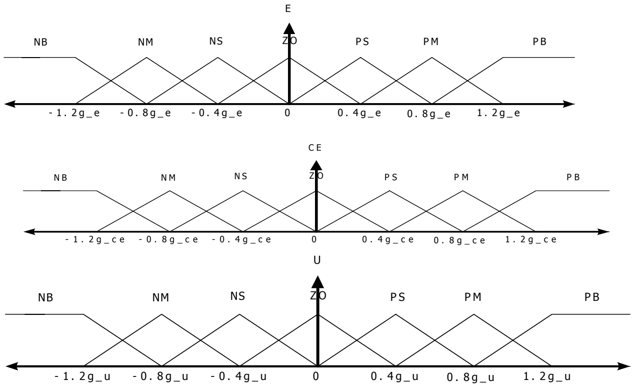
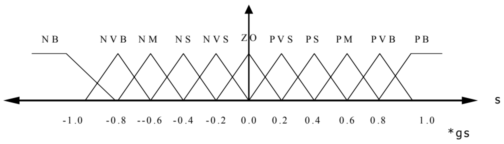


Fig. 2 Fuzzy input and output variables membership functions



Sliding Surface	s										
	NB	NVB	NM	NVS	NS	ZO	PS	PVS	PM	PVB	PB
Control Rule	-1.0	-0.8	-0.6	-0.4	-0.2	0.55	0.6	0.7	0.8	0.9	1.0

Fig. 4 1-D fuzzy membership function and control rules

TABLE II
FUZZY RULES TABLE FOR THE DC MOTOR

		E						
	CU	NB	NM	NS	ZO	PS	PM	PB
	NB	-1.0	-0.8	-0.8	-0.6	-0.6	-0.6	-0.6
	NM	-0.8	-0.8	-0.6	-0.6	-0.6	-0.6	-0.6
	NS	-0.8	-0.6	-0.7	-0.7	-0.6	-0.6	-0.6
CE	ZO	-0.8	-0.6	-0.7	0.0	0.5	0.8	0.8
	PS	0.6	0.6	0.6	0.5	0.6	0.8	0.8
	PM	0.6	0.6	0.6	0.8	0.8	0.8	1.0
	PB	0.6	0.6	0.8	0.8	0.8	1.0	1.0

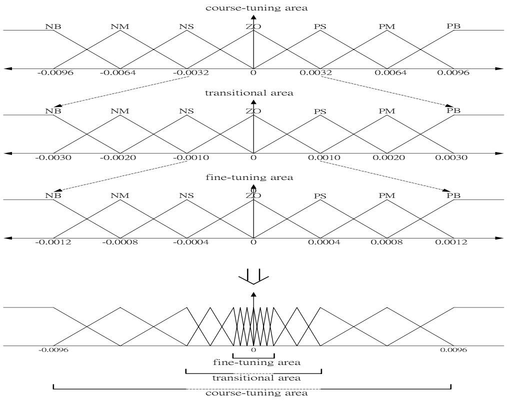


Fig. 3 Membership functions division

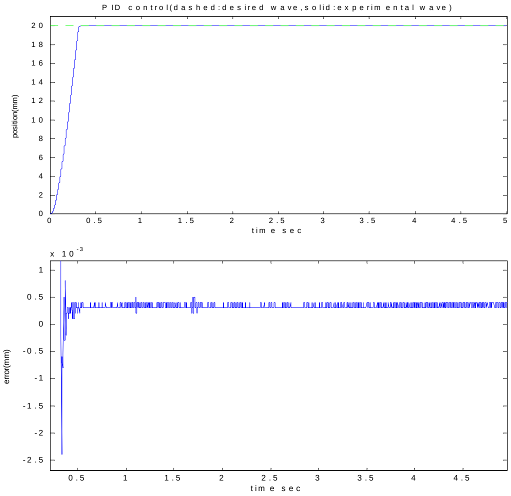


Fig. 5 PID control step response and error history

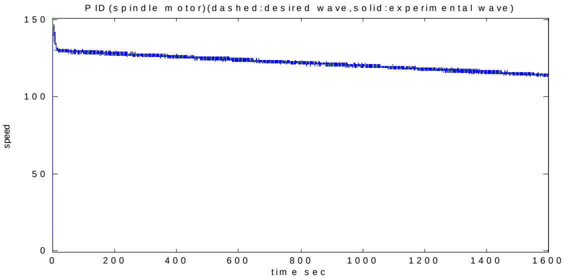


Fig. 6 Spindle motor rotation speed control

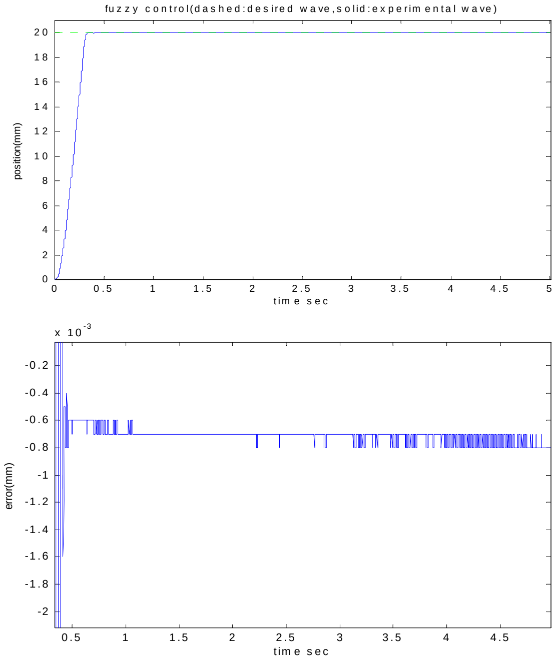


Fig. 7 Fuzzy control step response and error history

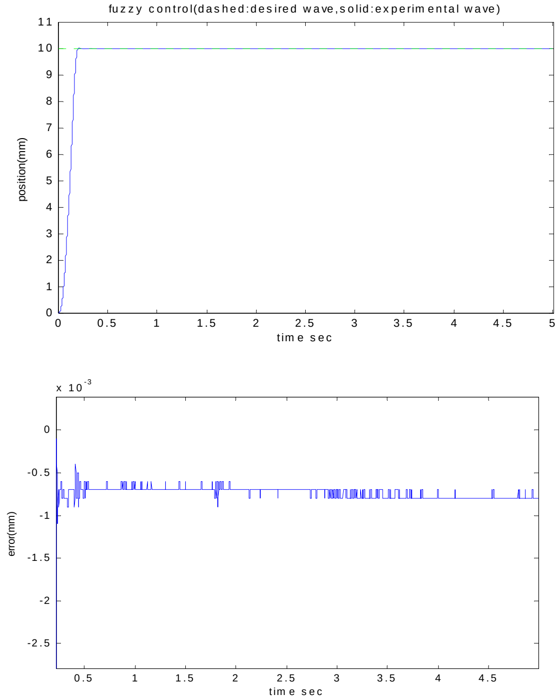


Fig. 8 Fuzzy control step tracking response and error history

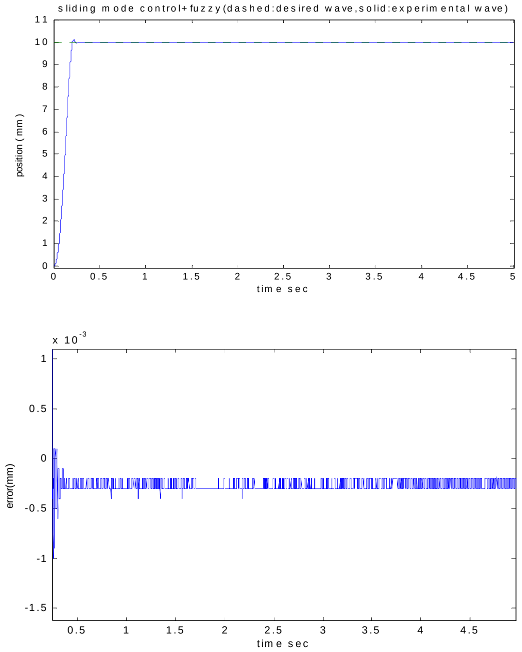


Fig. 9 1-D Fuzzy sliding control step response and error history

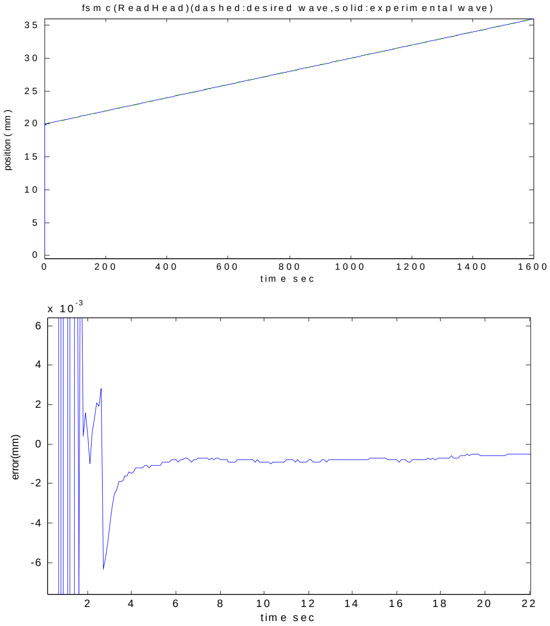


Fig. 10 (a) Pickup head position response and (b) track following error history