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Fuzzy Logic Simulation to Process Control Systems

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Abstract: This paper presents simulation of two process control systems using Fuzzy Logic Controller. The aim of this paper is to create a convenient adaptable simulation system that can model particular control system and obtain solution by application of the fuzzy logic technology. The performance of the process control system with fuzzy logic controller is compared with that of the conventional Proportional Integral and Derivative (PID) controller. This fuzzy logic based process control system needs design of the appropriate rule base. It is shown that the response of the system with Fuzzy Logic Controller (FLC) is better in comparison with the system performance using the conventional PID control method.

Keywords: Fuzzy Logic Control, Proportional Integral and Derivative Controller, Cart System, Shower System, Temperature Control, Flow Control.

Introduction

Control systems are becoming increasingly sophisticated with many systems particularly, process control, installation and commissioning. For a long time, the PID controller was considered sufficient for most control applications. However with specialized control strategies such as robust control and adaptive control, they are being integrated with fuzzy logic techniques (Lennon *et al.*, 1995 and Lennon *etal.*, 1999) At this stage of the technology, a convenient adaptive simulation system using FLC (Lee, 1990) that can model and obtain solution has been presented in this paper.

Control system design is frequently concerned with models of dynamic systems. A parametric model describes how a real system behaves both as a function of time and external inputs. An important part of system modeling is the validation phase, where it is decided whether the model approximates the true system to an acceptable degree of accuracy. However, there are physical systems, which cannot be approximated to the required degree of accuracy by a linear model. Many control system theories have been developed based on linear systems theory. This has proved to be a successful approach, because, although all physical systems are non-linear to some extent, most systems can be approximated using linear relationships (Shinskey, 1996).

The main appeal of fuzzy logic in control systems engineering is that they offer the potential of a generic approach to the modeling and control of non-linear systems. It compresses data by using linguistic variables (Bezdek, 1981) a fuzzy system can be created to match any set of input-output data using adaptive techniques like ANFIS (Adaptive Neuro Fuzzy Inference Systems). Fuzzy systems don't necessarily replace conventional control methods. In many cases, fuzzy systems augment them and simplify their implementation (Tsoukaras *et al.*, 1997)

Design of a fuzzy controller requires more design decisions than usual, for example regarding rule base, inference engine, defuzzification, and data pre-processing and post-processing. The design choices related to single-loop fuzzy control are identified and described, based on an international standard (Jang and Sun, 1995). The design approach uses a PID control as the starting point. The approach proposed in this paper is applied to two process control systems namely, a cart system and a shower system.

Fuzzy Logic Control: Fuzzy controllers are being used in various control schemes. The most obvious one is direct control, where the controller is in the forward path of a feedback control system. Fig.1 shows the block diagram of a direct control system. The controller here is a fuzzy controller, and it replaces the conventional controller. The process output is compared with a reference, and if there is any deviation, the controller takes action according to the control strategy. Fuzzy rules are also used to correct tuning parameters in parameter adaptive control scheme as shown in Fig.1. The gain scheduling block contains a linear controller whose parameters are changed as a function of the operating point in a preprogrammed way.

In the block diagram of fuzzy logic controller shown in Fig.2 the fuzzy controller is between a preprocessing block and a post-processing block. The pre-processor conditions the in puts before they enter the controller. The fuzzification block converts each piece of input data to degrees of membership by a lookup in one or several membership functions. Thus it matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to the input variable.

Collections of rules is called a rule base. The rules may use several variables both in the condition and conclusion of the rules. The controllers can therefore be applied to both Multi Input Multi Output (MIMO) problems and Single Input Single Output (SISO) problems.

The typical SISO problem is to regulate a control signal based on an error signal. The controller may actually need the error, the change in error, and the accumulated error as inputs, but it is considered as single-loop control, because in principle all three are formed from the error measurement. The presentation is thus limited to single-loop control. The rules are presented in a tabular format, a more compact representation as shown in Table.1, where, Pos, Neg, NB, NM, PM, and PB represent Positive, Negative, Negative Big, Negative Medium, Positive Medium, and Positive Big respectively.

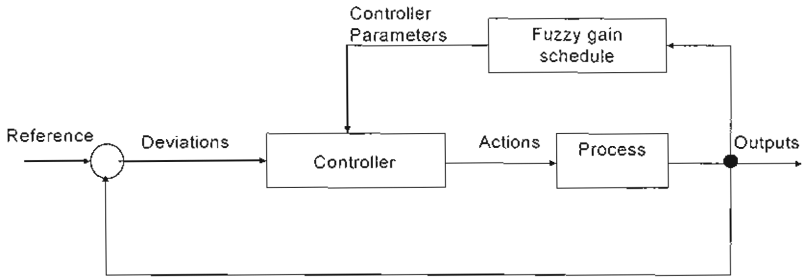


Fig.1: Direct Fuzzy Parameter Adaptive Control

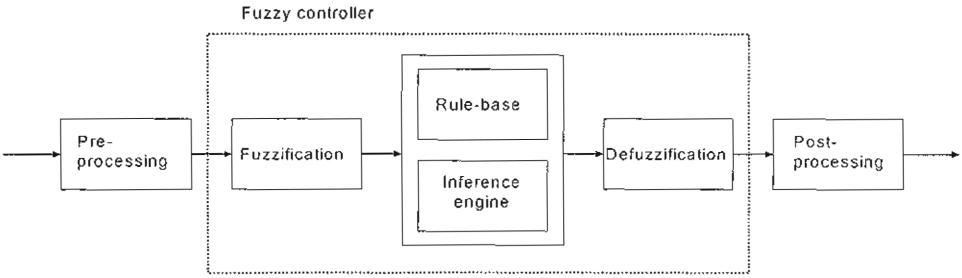


Fig.2: Block Diagram of Fuzzy Logic Controller

The idea behind fuzzy inference is to interpret the values in the input and, based on some set of rules, to assign values to the output vector. For each rule, the inference engine looks up the membership values according to the condition of the rule. The resulting fuzzy set must be converted to a number that can be sent to the process as a control signal (crisp control signal). The crisp control value u can be obtained as

Table 1: Fuzzy Rules

		Change in error		
		Neg	Zero	Pos
Error	Neg	NB	NM	Zero
	Zero	NM	Zero	PM
	Pos	Zero	PM	PB

$$u = \frac{\sum_i \mu(x_i)x_i}{\sum_i \mu(x_i)} \tag{1}$$

Where, x_i is a running point in a discrete universe, and μ (x_i) is the membership value of x_i in the membership function.
The post-processor scales the output to the required format and hence can be considered as an output scaling unit. The post-processing block consists of an output gain that can be tuned.
PID Controller: The control signal u is obtained from a PID controller. The PID controller provides the excitation for the plant and is designed to control the overall system behavior. The transfer function of the PID controller is

$$K_p + \frac{K_i}{s} + K_d s \cdot \tag{2}$$

Where, K_p = proportional gain
K_i = integral gain
K_d = derivative gain.
The term deviation in Fig.1 represents the tracking error, the difference between the desired input value (Reference) and the actual output value. This error signal is sent to the PID controller, and the controller computes both the derivative and the integral components of this error signal. The control signal (action) u is

$$u = K_p e + K_i \int e\,dt + K_d \frac{de}{dt} \tag{3}$$

Case Study
A. Cart System: A simple control system, which is spring-mass-damper system, is shown in Fig.3. While a basic PID controller can do a fine job of making it behave, fuzzy logic can provide a convenient way to meet stringent

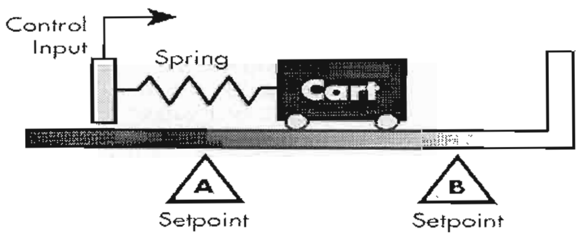


Fig.3: The Cart System to be Controlled

control objectives. The objective is to move the cart back and forth between points A and B in response to a square wave. Near point B there is a wall, a hard stop that the cart is to be kept away from. On the other hand, at point A there is more leeway. It is assumed that the control power and mechanical wear and tear are conserved by using looser and more relaxed controls at point A. The design goal is relaxed control at point A, and tight control (specifically, fast response with no overshoot) at point B. This situation is similar to the operation of a robot arm in an application where precise movement in one position and energy conservation elsewhere is necessary. Both the precise and the relaxed controls can be implemented with a basic PID controller because the plant is a simple one. Nevertheless, to meet both criteria, some kind of gain scheduling to alternate between the two controllers, each of which has gain parameters tuned for its specific control objectives are needed. A fuzzy controller can be designed to handle the gain scheduling. The cart system is being designed using MATLAB-SIMULINK and supplied with a square wave signal.

PID Controlled Cart System: The SIMULINK model of the cart system is shown in Figs. 4 and 5 the controller gains are chosen as

Tight control : $K_p = 60$, $K_i = 4$, and $K_d = 14$
Loose control: $K_p = 5$, $Ki = 1$, and $K_d = 2$
The natural frequency $\omega = 1$ rad/sec and the damping (zeta) ζ is $= 0.1$.

The system is being supplied with a square wave signal whose amplitude is 1. The output gains are summed up to give input for the cart system. The system output is then fed back to the whole system to create an error signal. The input signal from the generator and the cart system output are connected to a scope via a multiplexer mux1. This provides us with the comparison of both the input and output signals in the same graph.

The main design constraint to be guaranteed with the tight control is zero overshoot near set point B. On the other hand, the main consideration for the loose control is minimizing the control effort (while providing a small degree of damping).

Fuzzy Controlled Cart System: The model of fuzzy controller can be realized using Sugeno fuzzy inference system. In a Sugeno fuzzy system, the output membership function is a linear function of the inputs. The fuzzy controller is built with four inputs: cart position and the P, I, and D signals. The two rules used are:

Rule 1 : If cart is near_A then control is loose [$K_p = 5$, $K_i = 1$, and $K_d = 2$]
Rule 2 : If cart is near_B then control is tight [$K_p = 60$, $K_i = 4$, and $K_d = 14$]

One output membership function implements all three gains simultaneously. The system switches between the two different controllers (tight and loose controllers), and so there are two output membership functions and two rules.

The window shown in Fig.6 is the Fuzzy Inference System (FIS) editor that is used to create inputs and outputs for the fuzzy controller. The Membership Function (MF) for the cart system is shown in Fig.7. Point A corresponds to the numerical value 0 and point B corresponds to the value 1. Fig.8 shows the surface plot of the fuzzy controller. This plot depicts the controller's output signal variation as a function of the cart's position and the proportional signal.

The SIMULINK block diagram of the fuzzy controlled cart system can be drawn by replacing the three PID gains in Fig.4 with a fuzzy controller block and including the cart position as an extra input. The system is being supplied with a square wave signal with amplitude of 1 and frequency of 0.6283 rad/sec.

B. Shower System: This system provides an automatic control of the temperature and water flow of a shower. The shower system consists of a hot-water tap and a cold-water tap, each of which supplies water at a particular temperature and at a certain rate. The initial settings for both cold tap and hot tap of the shower are randomly selected and the target temperature is between -20 and +20 degrees Celsius and the target flow rate is between -1 and +1 litres/sec. Upon each successive iteration, the controller receives the composite flow rate and temperature of the current combination, and must recommend adjustments to the taps in order to achieve the optimum flow and temperature in as few iterations as possible.

The shower system uses the Mamdani's fuzzy inference method. Mamdani-type inference expects the output membership functions to be fuzzy sets. After aggregation process, there is a fuzzy set for each output variable that needs de-fuzzification. In many cases, it is much more efficient to use a single spike as the output membership function rather than a distributed fuzzy set. This can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method.

The fuzzy controller for shower system switches between the two input controllers (namely, temperature and flow controllers) and produces two required outputs (cold and hot). This output will control the valve opening. The Fuzzy Inference System (FIS) is shown in Fig.9.

The Membership Functions (MFs) for all the input and output controllers are shown in Fig.10 (a to d). There are 9 rules defined in this fuzzy logic controller. The rules used are:

Rule-1 IF temp is cold and flow is soft THEN cold is openSlow, hot is openFast.
Rule-2 IF temp is cold and flow is good THEN cold is closeSlow, hot is openSlow
Rule-3 IF temp is cold and flow is hard THEN cold is closeFast, hot is closeSlow
Rule-4 IF temp is good and flow is soft THEN cold is openSlow, hot is openSlow
Rule-5 IF temp is good and flow is good THEN cold is steady, hot is steady
Rule-6 IF temp is good and flow is hard THEN cold is closeSlow, hot is closeSlow
Rule-7 IF temp is hot and flow is soft THEN cold is openFast, hot is openSlow
Rule-8 IF temp is hot and flow is good THEN cold is openSlow, hot is coseSlow
Rule-9 IF temp is hot and flow is hard THEN cold is closeSlow, hot is closeFast

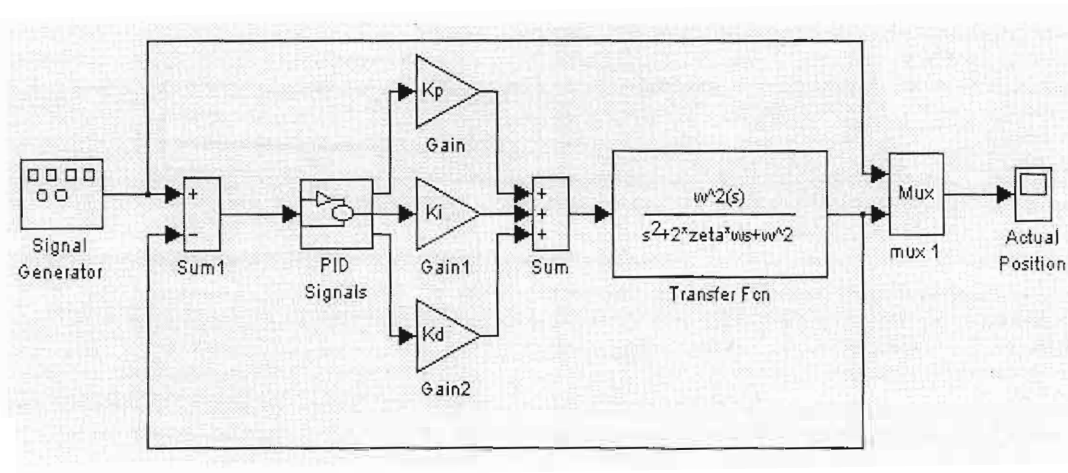


Fig.4: SIMULINK Block Diagram of Cart System with PID Controller

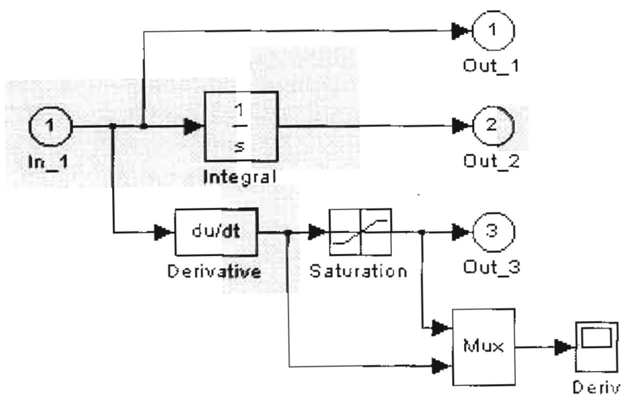


Fig.5: PID Signals Subsystem

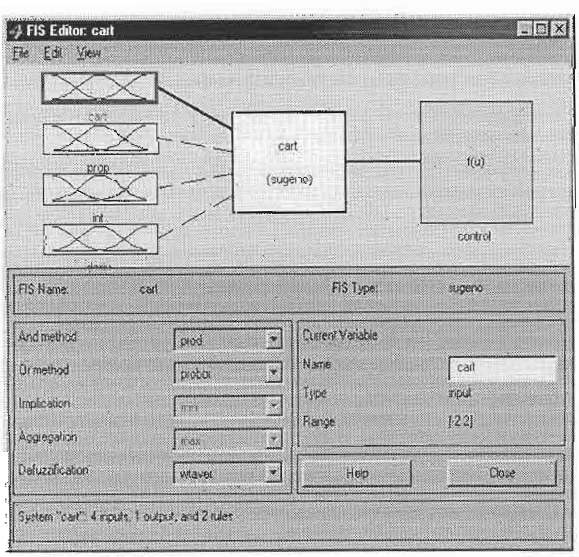


Fig.6: Fuzzy Inference Editor in the Fuzzy Logic Toolbox

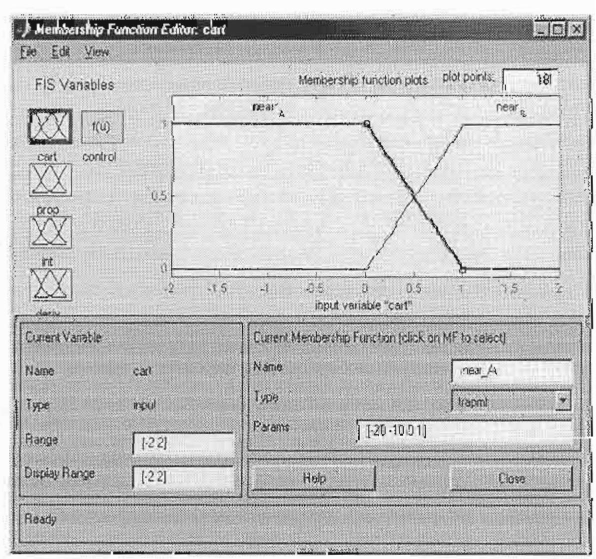


Fig.7: Membership Function for the Cart System

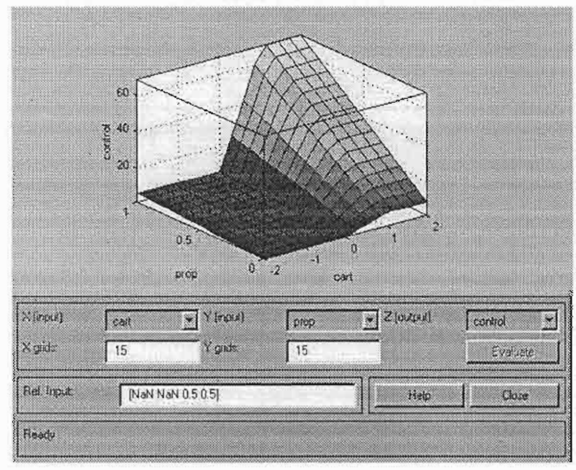


Fig.8: Surface View of Fuzzy Controlled Cart System

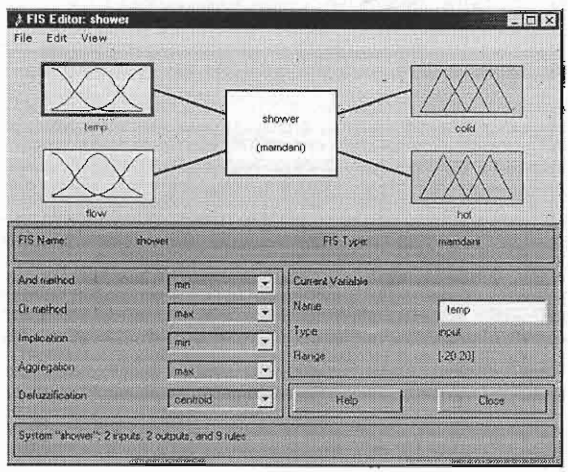
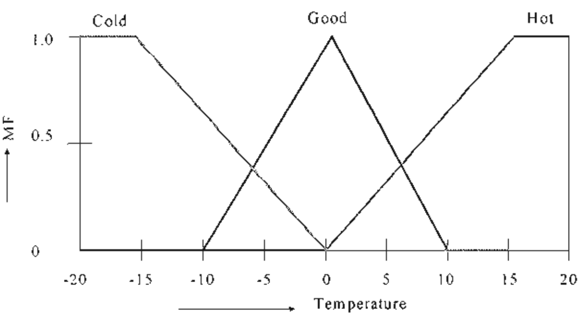
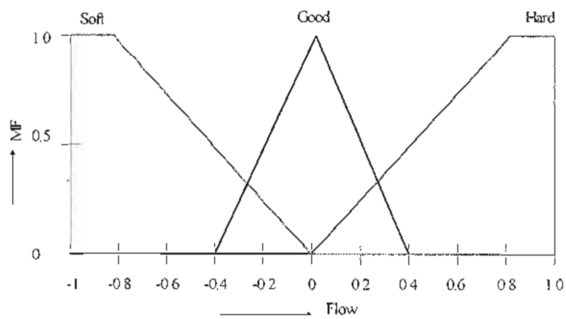


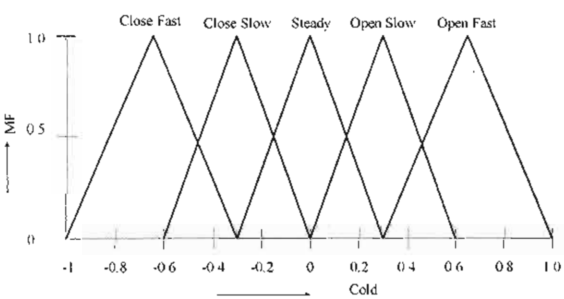
Fig.9: FIS for Shower



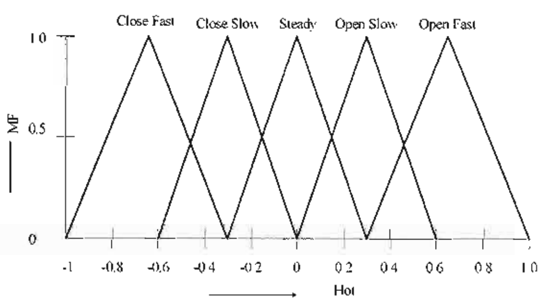
(a) MF of the Temperature Controller



(b) MF of the Flow Controller



(c) MF of the Cold Controller



(d) MF of the Hot Controller

Fig.10 (A-D): MF of the Input and Output Controllers

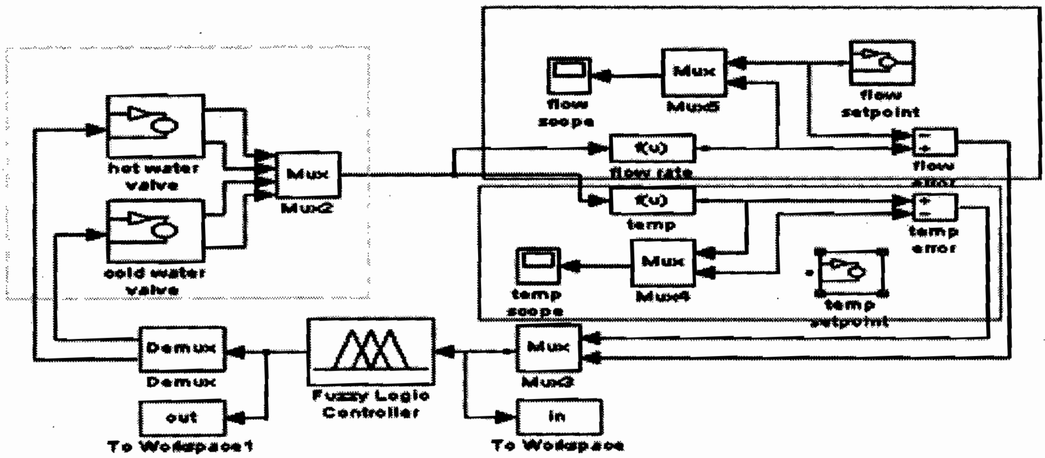


Fig.11: Block Diagram of the Shower System

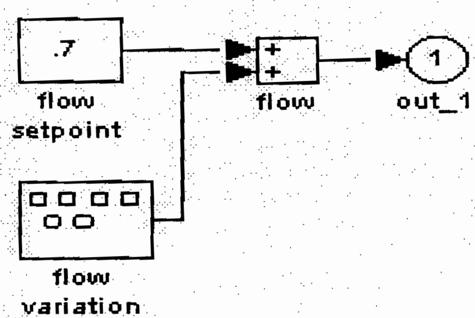


Fig.12: Flow Set-point

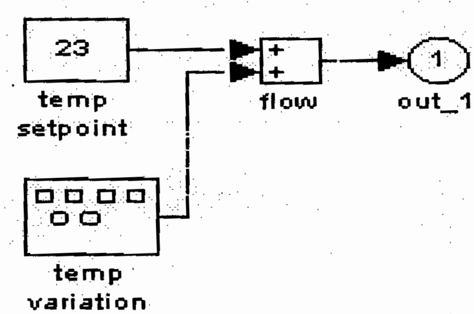


Fig.13: Temp Set-point

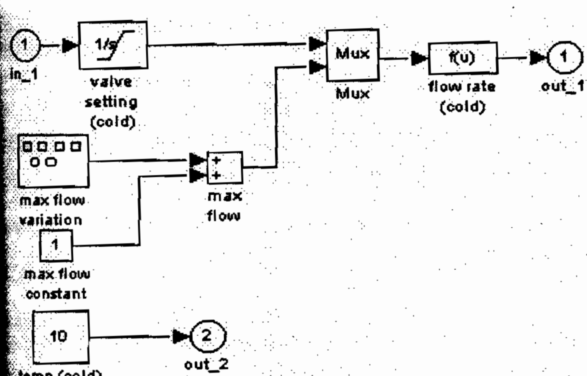


Fig.14: Cold Water Valve Sub-system

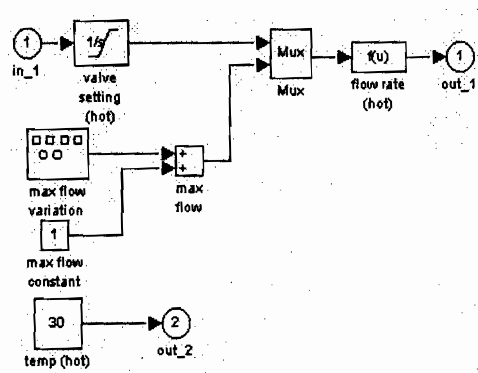


Fig.15: Hot Water Valve Sub-system

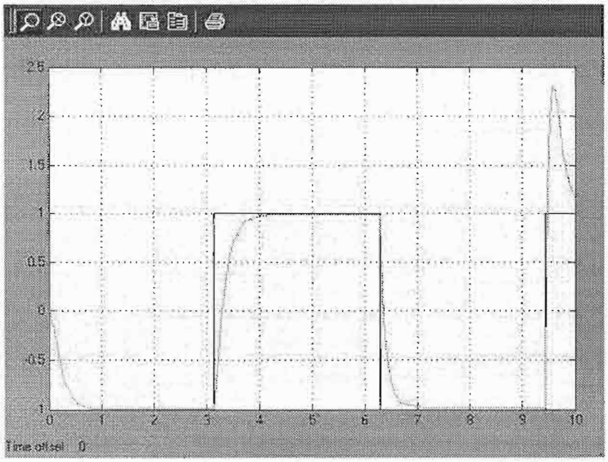


Fig.16: Closed-Loop Step Response for the PID Tight Controller

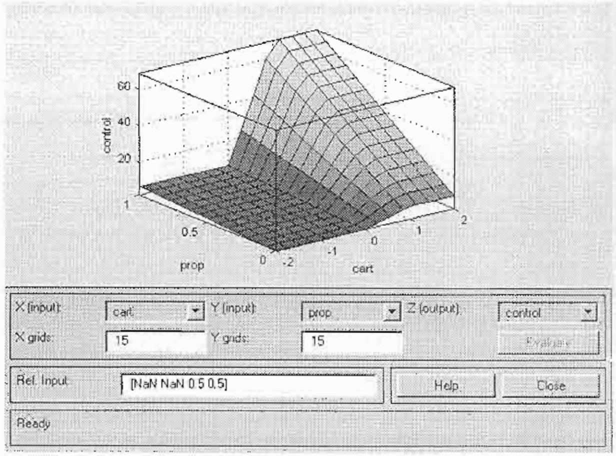


Fig.19: Surface View of Fuzzy Controlled Cart System

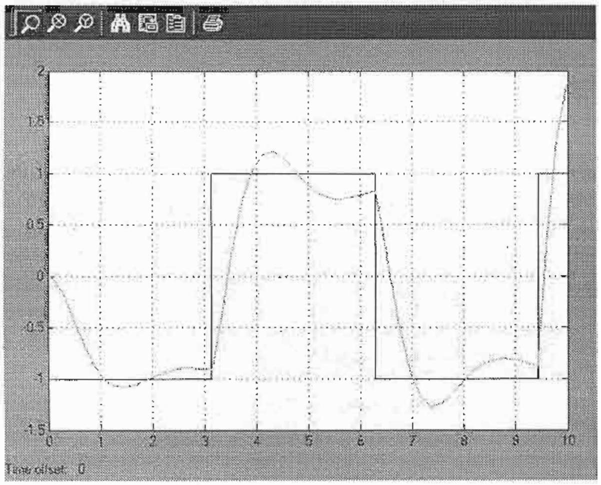


Fig 17: Closed-Loop Step Response For The PID Loose Controller

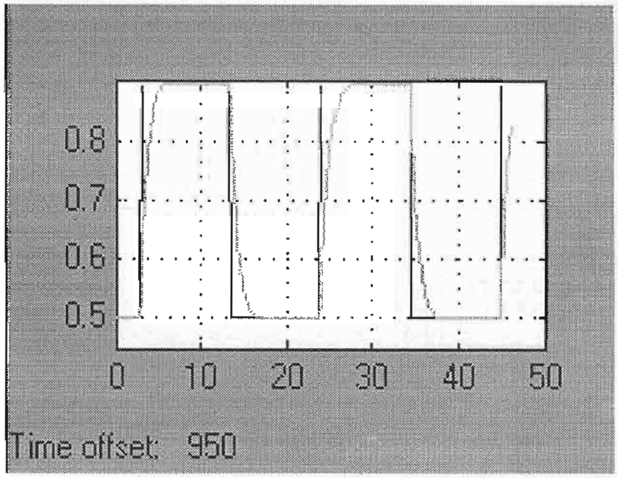


Fig.20: Step Response for the Flow Rate Controller

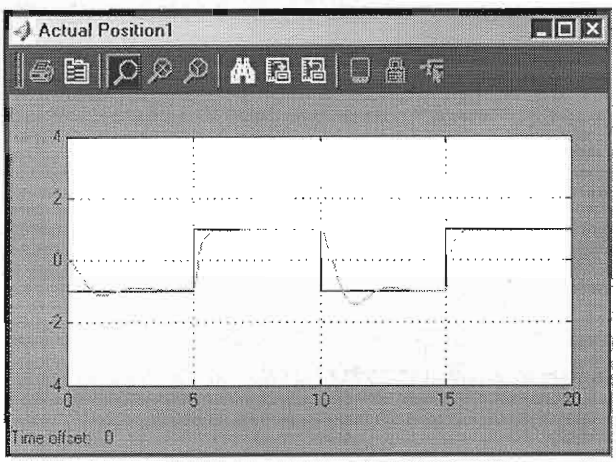


Fig.18: Closed-Loop Step Response with Gain-Scheduling Fuzzy Controller

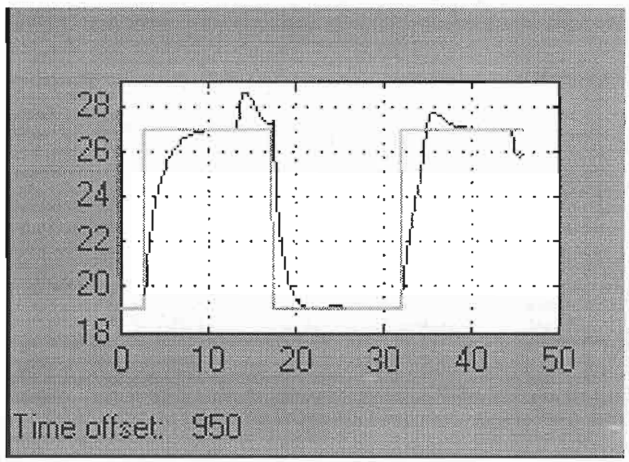


Fig.21: Step Response for the Temperature Controller

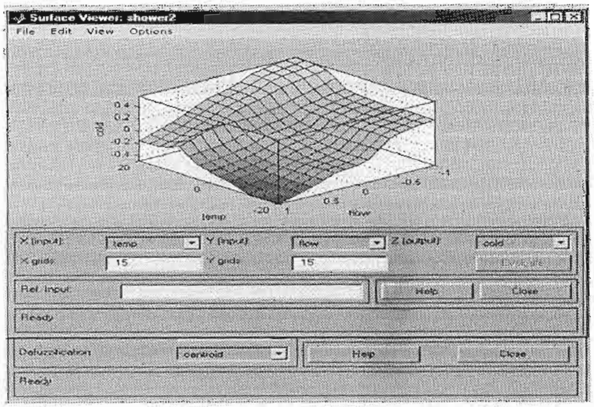


Fig.22: Surface view of fuzzy controlled shower

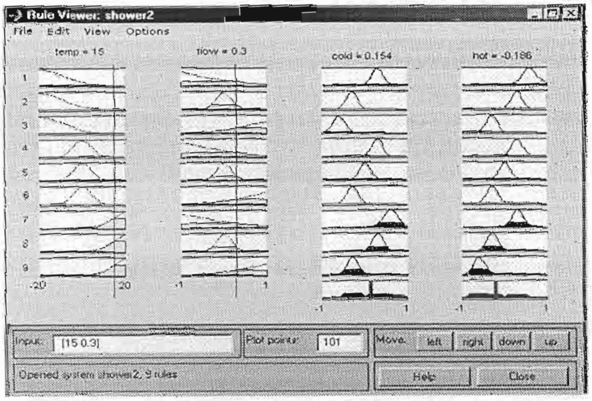


Fig.23: Rule viewer of the FLC for the shower system

The SIMULINK block diagram of the shower system is shown in Fig.11. There are four sub-systems in this model, such as flow set point, temp set point, cold water valve and hot water valve. The different sub-Systems are shown in Fig.12 to 15.

The flow set-point sub-system consists of signal generator that generates the flow rate variation. The input signal supplied by the signal generator is square wave type with amplitude of 0.2 and natural frequency of 0.3 rad/sec. The temp set-point sub-system consists of signal generator that generates the temperature variation. The input signal supplied by the signal generator is a square wave with amplitude 4 and natural frequency 0.2143rad/sec. The cold water valve system and the hot water valve system receive signals from the Fuzzy Logic Controller (FLC).

Results and Discussion

A. Cart System: The main design constraint to be guaranteed with the tight control is zero overshoot near set point B. This is where the difference between the PID controller and fuzzy controller becomes obvious. The closed-loop step response for the PID tight controller shown in Fig.16 has an overshoot. Since one of the design goals is to have zero overshoot, this controller is inadequate. However, despite the overshoot, the PID controller gives a rather tight control over the cart.

The main consideration for the loose controller is minimizing the control effort (while providing a small degree of damping). The closed-loop step response for the PID loose controller is shown in Fig.17. It is seen from Fig.17, that the closed-loop step response does not follow the input square wave tightly, indicating that the controller minimizes its control effort on the cart. The plot in Fig.18 shows the simulation of the proposed fuzzy controller for a square wave.

Fig.19 shows the variation of the controller's output signal as a function of the cart's position and the proportional signal. The mountainous portion of the 3-D graph shows that the control power required is higher and, corresponds to the region where the cart position is near point B. At point A (cart=-2), the control power required is less. In conclusion, this surface represents a map of the required control for the cart system. This kind of visualization can be extremely valuable to a control designer to design and model a system and to ensure the stability of the system.

The step response of the flow rate and temperature controls of the shower system are shown in Fig.20and 21.It is seen from the figures that the step response of the shower system is considerably efficient with minimum overshoot, fast rise time and zero steady state error. The surface view of the fuzzy controlled shower system is shown in Fig.22 and 23 shows the rule viewer for the following input:

Input temp = 15, and flow rate = 0.3

From \Fig.23, it is seen that for the given input, the outputs are cold = 0.154 and hot = -0.186

Conclusion

The Fuzzy Logic Controller has been successfully implemented in two process control systems (cart system and shower system). The tight control using the PID controller gives out satisfactory output but there is some overshoot. It is seen that the tight control using the fuzzy controlled system gives out better and precise output with minimum overshoot. For loose control, both the conventional PID controller and the FLC controller give relaxed control when the cart is near A. Further, it is seen that the Sugeno fuzzy approach gives better performance with gain scheduling for the tight and loose controllers. The flow control and temperature control of the shower system give good step response with the fuzzy logic controller. It is also seen that, the fuzzy controller has combined the flow and temperature controllers into one controller.

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