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A Two-Layered Fuzzy Logic Controller for Systems with Deadzones

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Abstract

Existing fuzzy control methods do not perform well when applied to systems containing nonlinearities arising from unknown deadzones. We propose a novel two-layered fuzzy logic controller for controlling systems with deadzones. The two-layered control structure consists of a fuzzy logic-based precompensator followed by a conventional fuzzy logic controller. Our proposed controller exhibits superior transient and steady-state performance compared to conventional fuzzy controllers. We illustrate the effectiveness of our scheme using computer simulation examples.

I Introduction

Many physical components in control systems contain nonsmooth nonlinearities, such as saturation, relays, hysteresis, and deadzones. Such nonlinearities are especially common in actuators used in practice, such as hydraulic servovalves. Furthermore, the nonlinearities in such systems are often unknown and vary with time. In this paper, we consider only deadzone nonlinearities.

Several classical methods exist for controlling systems with nonsmooth nonlinearities, including sliding mode control [1], and dithering [2]. Motivated by limitations in these methods, such as chattering in sliding mode control, Recker et al. [3] and Tao et al.[4] proposed an adaptive control scheme for controlling systems with deadzones. In practice, however, the transient performance of the adaptive control schemes above is limited.

Fuzzy logic-based controllers have received considerable interest in recent years (see for example [5], [6], [7]). Direct application of conventional fuzzy controllers to a system with deadzones results in poor transient and steady-state behavior, in particular, a steady-state error occurs when using a conventional fuzzy controller to a system with deadzones. To eliminate the steady-state error, we may attempt to use a fuzzy controller that also incorporates the "integral" of the output error as an input to the controller.

In this paper we propose a fuzzy logic-based scheme which does not suffer from the deficiencies mentioned above of conventional fuzzy controllers applied to systems with deadzones. The idea underlying our approach is based on analyzing the source of the steady-state error resulting in using a conventional fuzzy controller. Our control scheme consists of two "layers": a fuzzy precompensator, and a conventional fuzzy controller. We demonstrate that our controller has good transient as well as steady-state performance, and is robust to variations in deadzone nonlinearities.

II Characteristics of Conventional FLC

In this section we describe a conventional fuzzy logic controller (FLC), and study the behavior of the FLC applied to a system with a deadzone.

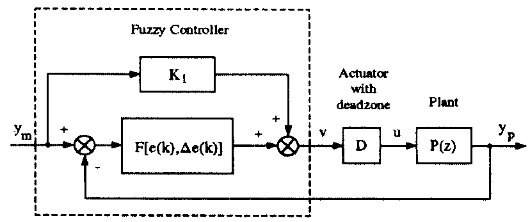

Figure 1: Conventional FLC system with deadzone

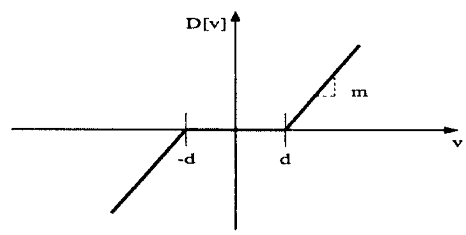

Figure 2: Characteristics of Actuator with deadzone

II.1 Basic Control Structure

We consider the (discrete-time) system shown in Figure 1, which is a conventional FLC control system [7]. The transfer function $P(z)$ represents the plant, D represents an actuator with deadzone, $F[e(k), \Delta e(k)]$ represents a FLC control law, K_1 is the feedforward gain, $v(k)$ is the output of the controller, $u(k)$ is the output of the actuator, $y_m(k)$ is the reference input (command signal to be followed), and $y_p(k)$ is the output of the plant. The characteristics of the actuator with deadzone D is described by the function

$$D[v] = \begin{cases} m(v-d), & \text{if } v > d \\ 0, & \text{if } -d \le v \le d \\ m(v+d), & \text{if } v < -d \end{cases}$$

where $d, m > 0$. Figure 2 illustrates the characteristics of the actuator with deadzone. The parameter $2d$ specifies the width of the deadzone, while m represents the slope of the response outside the deadzone.

II.2 Fuzzy Logic Controller

We describe the FLC control law $F[e(k), \Delta e(k)]$ as follows. We think of $e(k)$ and $\Delta e(k)$ as inputs to the controller, and $F[e(k), \Delta e(k)]$ as the output. As we shall see later, $e(k)$ is the output error $y_m(k) - y_p(k)$, and $\Delta e(k)$ is the change in output error $e(k) - e(k-1)$. Associated with the fuzzy control law is a collection of *linguistic values*

$$L = \{NB, NM, NS, ZO, PS, PM, PB\}$$

Figure 3 shows a plot of the membership functions of linguistic values. The "meaning" of each linguistic value should be clear from its mnemonic.

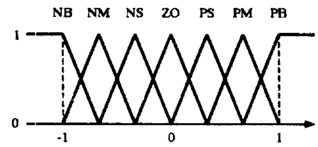

Figure 3: Membership Functions

	$e(k)$							
		NB	NM	NS	ZO	PS	PM	PB
	NB				NB	NS		
	NM				NM	NS		
	NS				NS	ZO		PM
$\Delta e(k)$	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS			
	PM				PM			
	PB			PM	PB			

Table 1: Fuzzy logic rules for conventional FLC

The fuzzy control law consists of three stages: fuzzification, decision making fuzzy logic, and defuzzification. We used a single-tone fuzzification method and the center of area method as defuzzification method. For this conventional FLC, the rules are given in Table 1. This set of rules is fairly standard and well known. Using the mamdani's resoning method [5], we can compute the output $F[e(k), \Delta e(k)]$.

II.3 Analysis of Steady-State System Behavior

We now study the steady-state behavior of the system controlled by the conventional FLC described in the previous section. We will show that in the presense of a deadzone, a steady-state error occurs.

The dynamics of overall system is described by the following equations:

$$\begin{aligned} e(k) &= y_m(k) - y_p(k) \\ \Delta e(k) &= e(k) - e(k-1) \\ v(k) &= K_1 y_m(k) + F[e(k), \Delta e(k)] \\ u(k) &= D[v(k)] \\ y_p(k) &= P(z)[u(k)] \end{aligned}$$

Note that the equation $y_p(k) = P(z)[u(k)]$ involves a slight abuse of notation; however, its meaning should be obvious. It turns out that $F[0,0] = 0$, and therefore if we fix the reference input $y_m(k) = y_m$, the steady-state actuator input is $K_1 y_m$.

Consider the case where there is no deadzone, i.e., $d = 0$, and $m = 1$. In this case the plant output can be written as

$$y_p(k) = P(z)[K_1 y_m(k) + F[e(k), \Delta e(k)]]$$

Since $e(k) = y_m(k) - y_p(k)$, then the plant output can also be written as

$$y_p(k) = y_m(k) - e(k)$$

We now fix $y_m(k) = y_m$, and study the behavior of the system in steady-state. In this case, we can set $\Delta e(k) = 0$ to get

$$y_p(k) = K_s[K_1 y_m + F[e(k), 0]] = y_m - e(k) \qquad (1)$$

where K_s is the steady-state gain of $P(z)$ (assumed stable), given by $K_s = \lim_{z \to 1}(1 - z^{-1})P(z)$. The steady-state error e_{ss} is then the solution to equation (1), that is,

$$K_s[K_1 y_m + F[e_{ss}, 0]] = y_m - e_{ss} \qquad (2)$$

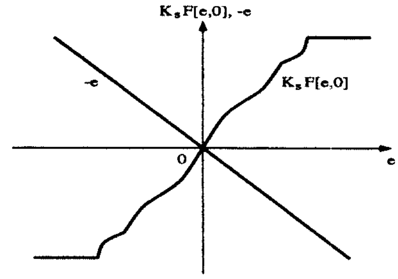

Figure 4: Graph of $K_s F[e,0]$ and $-e$

We assume that the controller is "well-tuned", so that $K_1 = K_s^{-1}$. Equation (2) then becomes

$$K_s F[e_{ss}, 0] = -e_{ss} \qquad (3)$$

We do not have a closed form expression for the function $F[\cdot, 0]$. Nevertheless, it is easy to see from the description of the FLC in the previous section that $F[\cdot, 0]$ is an increasing odd function, as illustrated in Figure 4. The graph of $K_s F[\cdot, 0]$ in Figure 4 was obtained by direct calculation via computer. We can solve equation (3) graphically—we simply plot the left and right hand sides of equation (1) on the same graph, and find the point where they intersect. As can be seen in Figure 4, the solution is $e_{ss} = 0$. Therefore, the steady-state error for a system without a deadzone is exactly zero.

We now consider the case where a deadzone is present, i.e., $d \neq 0$, and $m > 0$ is arbitrary. In this case, the steady-state output of the plant can be written as

$$y_p(k) = K_s D[K_1 y_m + F[e(k), 0]] = y_m - e(k)$$

Therefore, the steady-state error is the solution to the equation

$$K_s D[K_1 y_m + F[e(k), 0]] - y_m = -e_{ss} \qquad (4)$$

The first term in the left hand side of (4) is illustrated in Figure 5(a). Once again we use a graphical approach to solve (4); see Figure 5(b). As we can see, the solution e_{ss} is no longer zero, but some nonzero number (with the same sign as y_m; in Figure 5(b) we have assumed a positive y_m). It is clear that the nonzero steady-state error is a direct result of the presence of the deadzone in the actuator. In the next section we illustrate this behavior via an example.

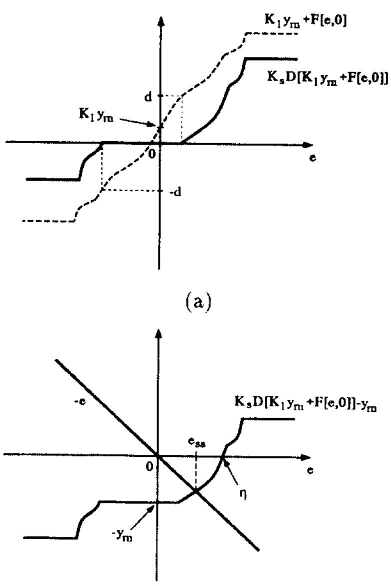

Figure 5: Graphs of: (a) $K_s D[K_1 y_m + F[e,0]]$; (b) $K_s D[K_1 y_m + F[e,0]] - y_m$ and $-e$

II.4 An Example

Consider a (continuous time) plant with transfer function

$$\frac{10}{s^2+s+1}$$

We apply the conventional FLC described before to the above plant, using the standard sample-and-hold approach, with a sampling time of 0.025 seconds. In this example, we set $y_m = 1$. Figure 6 shows output responses of the plant for three values of d: 0.0, 0.5, 1.0. In all cases we used $m = 1$. It is clear from Figure 6 that there is a relatively large steady-state error and overshoot when a deadzone is present. The steady-state error and overshoot increases with the the deadzone width.

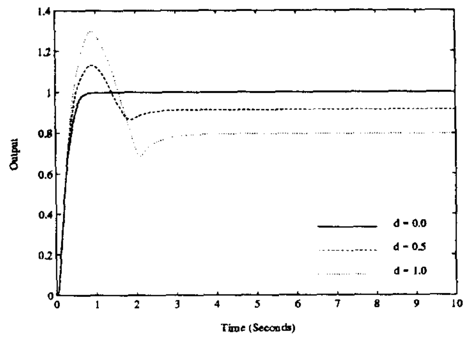

Figure 6: Output responses of plant with conventional FLC

III Two-Layered Fuzzy Logic Controller

In this section we describe a novel two-layered fuzzy logic controller. Our aim is to eliminate the steady-state error and improve the performance of the output response for FLC systems with deadzones. As we shall see, our proposed scheme is indeed insensitive to deadzones, and exhibits good transient and steady-state behavior.

III.1 Basic Control Structure

We use a graphical approach to describe the idea underlying our proposed controller. Consider Figure 5(b), which illustrates the source of the steady-state error for the conventional FLC system. Suppose we shift the graph of $K_sD[K_1y_m+F[e,0]]-y_m$ to the left by an amount equal to η (the intersection point of the graph with the e-axis). Then, it is clear that the steady-state error (the point of intersection of the two graphs in Figure 5(b)) becomes zero. Shifting the graph of $K_sD[K_1y_m+F[e,0]]-y_m$ to the left by an amount η is equivalent to adding η to e. In other words, the graph of $K_sD[K_1y_m+F[e+\eta,0]]-y_m$ intersects the graph of $-e$ at the origin. The key idea underlying our proposed controller is to shift the curve of $K_sD[K_1y_m+F[e+\eta,0]]-y_m$ as described above so that the steady-state error is zero. Note that instead of adding η to e to shift the curve, we can achieve a similar effect by adding some other constant μ to the reference input y_m. In our controller we use fuzzy logic rules to calculate the appropriate value of μ to be added to the reference input.

We now proceed to describe our proposed controller. First, we define the variables $y'_m(k)$ and $e'(k)$ as follows:

$$\begin{aligned} y'_m(k) &= y_m(k)+\mu(k) \\ e'(k) &= e(k)+\mu(k) \end{aligned}$$

where $\mu(k)$ is a compensating term which is generated using a fuzzy logic scheme, which we will describe below. The proposed control scheme is shown in Figure 7. As we can see, the controller consists of two "layers": a fuzzy precompensator, and a conventional FLC. Hence we refer to our scheme as a *two-layered fuzzy logic controller.* The error $e(k)$, change of error $\Delta e(k)$, and $\mu(k-1)$ (previous compensating term) are inputs to the precompensator. The output of the precompensator is $\mu(k)$. The dynamics of overall system is then described by the following equations:

$$\begin{aligned} e(k) &= y_m(k)-y_p(k) \\ \Delta e(k) &= e(k)-e(k-1) \\ \mu(k) &= G[e(k),\Delta e(k),\mu(k-1)] \\ y'_m(k) &= y_m(k)+\mu(k) \\ e'(k) &= y'_m(k)-y_p(k) \\ \Delta e'(k) &= e'(k)-e'(k-1) \\ v(k) &= K_1y'_m(k)+F[e'(k),\Delta e'(k)] \\ u(k) &= D[v(k)] \\ y_p(k) &= P(z)[u(k)] \end{aligned}$$

In the next two sections we describe in detail the two layers of our proposed controller structure.

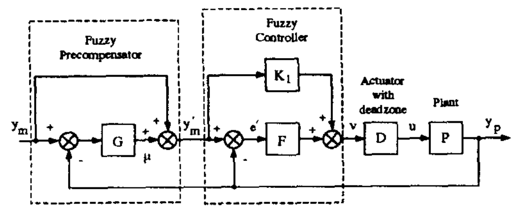

Figure 7: Proposed Two-Layered Fuzzy Logic Controller

III.2 First Layer: Fuzzy Precompensator

We now describe the first layer in our two-layered controller structure, which consists of the fuzzy logic-based precompensator. As before, our fuzzy precompensator makes use of a set of linguistic values. the precompensator uses a new set of linguistic values $L' = NE, ZE, PO$. The mnemonic NE stands for "negative", ZE stands for "zero", and PO stands for "positive". Figure 8 shows a plot of the membership functions. The linguistic values in L' are used for the "input" variables of the precompensator, while the linguistic values in L are used for the "output".

As before, the fuzzy precompensator consists of three steps: fuzzification, decision making fuzzy logic, and defuzzification. The fuzzification and defuzzification method and resoning method are same as section II.

Associated with the decision making fuzzy logic stage of the precompensator are twenty-seven rules $\{R'_1,\ldots,R'_{27}\}$, as shown in Table 2.

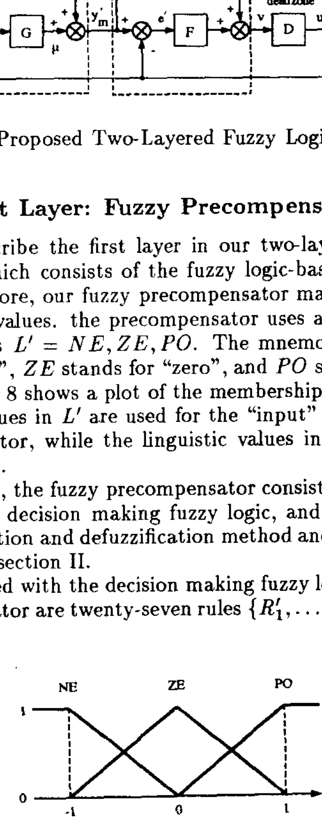

Figure 8: Membership Functions

III.3 Second Layer: Conventional FLC

The second layer of our controller structure consists of a conventional FLC, which is essentially identical to that described in Section II.2. The only difference in this case is that instead of using $e(k)$ and $\Delta e(k)$ as inputs to the FLC, we use $e'(k)$ and $\Delta e'(k)$, where $e'(k) = e(k)+\mu(k)$, $\Delta e'(k) = e'(k)-e'(k-1)$, and $\mu(k) = G[e(k),\Delta e(k),\mu(k-1)]$ is the output of the precompensator. In particular, as indicated by the dynamics equations previously, the output of the FLC is given by

$$v(k) = K_1y'_m(k)+F[e'(k),\Delta e'(k)]$$

where $y'_m(k) = y_m(k)+\mu(k)$.

IF			THEN
$e(k)$	$\Delta e(k)$	$\mu(k-1)$	$\mu(k)$
		NE	NS
	NE	ZE	ZO
		PO	ZO
		NE	PS
NE	ZE	ZE	ZO
		PO	NS
		NE	PM
	PO	ZE	PS
		PO	ZO
		NE	ZO
	NE	ZE	NS
		PO	NS
		NE	ZO
ZE	ZE	ZE	ZO
		PO	ZE
		NE	PS
	PO	ZE	PS
		PO	ZO
		NE	PM
	NE	ZE	PS
		PO	ZO
		NE	PM
PO	ZE	ZE	PS
		PO	ZO
		NE	PB
	PO	ZE	PS
		PO	ZO

Table 2: Rules for the Fuzzy Precompensator

III.4 Example

We consider again the plant of Section II.4. We now apply the proposed two-layered fuzzy logic controller to the plant; as before we use a sampling time of 0.025 seconds and $y_m = 1$.

Figure 9(a) shows output responses of the plant for $m = 1$ and three values of d (as before): 0.0, 0.5, 1.0. The output responses in Figure 9(a) show considerable improvement over those of Figure 6. Not only is the steady-state error reduced to virtually zero, but the transient response is also improved. In Figure 9(a), the "internal variables" (e.g., scale factors, membership functions) used were "tuned" for a deadzone width of $d = 0$ and a slope of $m = 1$. Nevertheless, as we can see, the controller also performs well for deadzone widths of $d = 0.5$ and 1.0. Therefore, we conclude that our controller is robust to variations in the deadzone width.

Figure 9(b) shows output responses of the plant for $d = 0.5$ and three values of m: 2.0, 3.0, 6.0. As we can see, the controller performs well in all three cases. Hence we conclude that the controller is also robust to variations in slope.

IV Conclusions

In this paper, we proposed a two-layered fuzzy logic controller for systems with deadzones. Our controller consists of a fuzzy precompensator and a conventional FLC. The proposed controller has superior steady-state and transient performance, compared to a conventional FLC. An advantage of our present approach is that an existing conventional FLC can be easily modified into our control structure by adding a fuzzy precompensator. In addition, the two-layered control structure is robust to variations in the deadzone nonlinearities (width and slope).

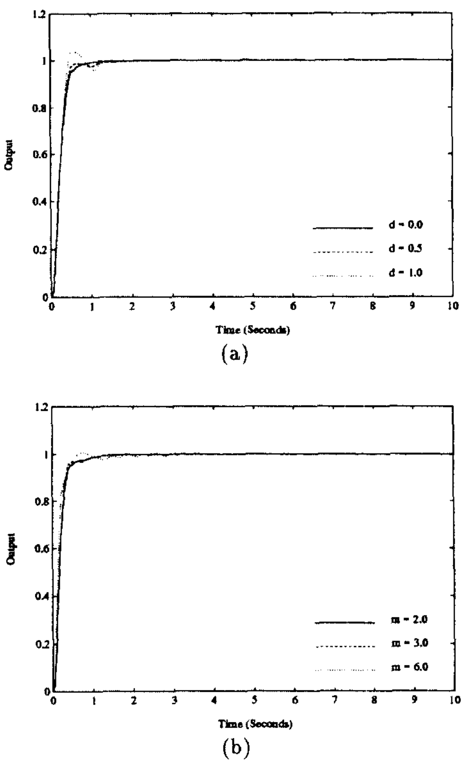

Figure 9: Output responses of plant with proposed FLC

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