A NEW METHODOLOGY FOR DESIGNING A FUZZY LOGIC CONTROLLER

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ABSTRACT

In this study, a fuzzy logic controller is developed using a new methodology for designing its rule-base. This controller consists of two rule-base blocks and a logical switch in between. The rule-base blocks admit two inputs one of which is newly devised and called "normalized acceleration" and the other one is the classical "error". The newly devised input gives a relative value about the "fastness" or "slowness" of the system response. The robustness and effectiveness of the new fuzzy logic controller over the typical MacVicar-Whelan controller has also been illustrated by simulations done on a system under various disturbances and time delays.

I. INTRODUCTION

Fuzzy logic control has been widely used in many successful industrial applications and has demonstrated significant achievements [1-4]. The first fuzzy logic control algorithm implemented by Mamdani [5, 6] was constructed to synthesize the linguistic control protocol of a skilled human operator. Although, this type of fuzzy logic controller (FLC) application was successful compared to classical controllers, the design procedure is dependent on the experience and knowledge of the operator and it is limited by the elucidation of the heuristic rules of control. In order to avoid the major difficulty or drawback of depending on the control experience of the operator, Mac Vicar-Whelan [7] firstly proposed some general rules for the structure of fuzzy controllers. This common or typical fuzzy controller derives its decisions from the input error signal (e) and the change of error (de). Thus, it is structurally similar to a classical proportional plus derivative (PD) controller. In fact, the equivalence of this type of fuzzy logic controllers and conventional PD controllers has been established [8].

In this study, a new methodology is proposed for generating a rule-base for a FLC. This FLC consists of two rule-base blocks and a logical switch in between while each one of the rule-base blocks have been designed so that they admit two inputs; namely the "error"(e) and a newly devised input named as "normalized acceleration" (s). This new input is derived using the first and the second order derivatives of the error and it gives a relative value about the "fastness" or "slowness" of the system response. If this new input variable is used with the error input, we claim that one can easily devise an effective and reliable rule-base that can handle a large variety or class of systems. The robustness and effectiveness of the new FLC over the typical MacVicar-Whelan controller has also been illustrated by simulations done on a marginally stable system under various disturbances and time delays.

II. THE NEW FUZZY LOGIC CONTROLLER

2.1. Basic elements and principles of the new controller

Let us consider a discrete-time set point controller where the error at step k is defined as

$$e(k)=r(k)-y(k) \tag{1}$$

where r(k) is the set-point and y(k) is the system output. The incremental change in error is given by

$$de(k)=e(k)-e(k-1) \tag{2}$$

and the acceleration in error is given by

$$dde(k)=de(k)-de(k-1) \tag{3}$$

The new fuzzy logic controller that we propose in this study will use these three variables as shown in Figure 1.

As it is seen from this figure, the new fuzzy logic controller consists of two rule-base blocks Fuzzy Approach Block (FAB) and Fuzzy Drift-apart Block (FDB) and a logical switch block (LSB) between them. Each one of the rule-base blocks have been designed by making use of two input variables; namely, error e(k) and a newly devised input variable s(k) that is defined as

$$s(k)=\frac{de(k)-de(k-1)}{de(.)}=\frac{dde(k)}{de(.)} \tag{4}$$

where de(.) is chosen as follows

$$de(.) = \begin{cases} de(k) & \text{if} \quad |de(k)| \geq |de(k-1)| \\ de(k-1) & \text{if} \quad |de(k)| < |de(k-1)| \end{cases} \tag{5}$$

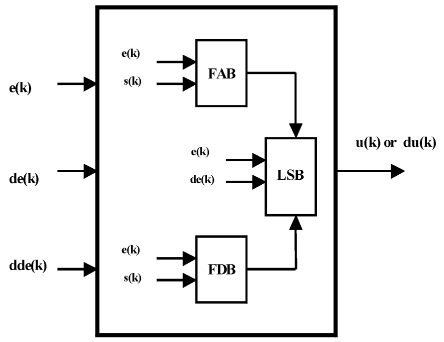


Figure 1. Internal structure of the new fuzzy logic controller

The input variable s(k) is named "normalized acceleration" .When the system response demonstrates a smooth and steady increase or decrease, then the product $de(k).de(k-1)$ is positive and "fastness" and "slowness" of the response can be deduced by using this new input variable s(k). This situation has been illustrated in Figure 2. When the product $de(k).de(k-1)$ is negative then the system response makes a ripple or changes its direction. In this case, it is not possible to make any judgement about the rate of the response.

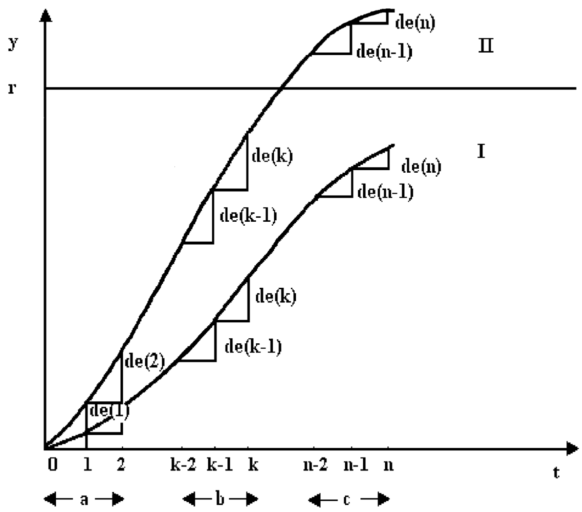


Figure 2. Illustration of the relative rates of the system responses to a step input

As it can be seen from Figure 2, if the absolute value of the change in error $|de(k)|$ is greater than the previous value $|de(k-1)|$ then the system response increases or decreases in a "fast" nature. Contrary to this case, if the absolute value of the change in error $|de(k)|$ is less than the previous value $|de(k-1)|$ then the system response increases or decreases in a "slow" nature. When (3) is taken into consideration with the signs of de(.) then Table I is obtained. Table 1 shows that "fastness" or "slowness" of a system response depends on the signs of both dde(k) and de(.). Thus, (4) has been devised in order to normalize the acceleration term dde(k) while reserving the information about the "fastness" or "slowness" of the system response.

Table 1.Relationship between de(.) , dde(k) and the nature of the system response

de(k-1) or de(k)	**dde(k)**	**System response**
Positive	Positive	Fast
Positive	Negative	Slow
Negative	Positive	Slow
Negative	Negative	Fast

Let us consider (5) and the "fast" rows of Table 1 for the limiting cases; that is, $|de(k)| >> |de(k-1)|$, we obtain

$$s(k) = \frac{de(k) - de(k-1)}{de(k)} = 1 - \frac{de(k-1)}{de(k)} \to 1 \tag{6}$$

When we consider (5) and the "slow" rows of Table 1 again for the limiting case; that is, $|de(k-1)| >> |de(k)|$, we get

$$s(k) = \frac{de(k) - de(k-1)}{de(k-1)} = \frac{de(k)}{de(k-1)} - 1 \to -1 \tag{7}$$

In the case $|de(k)| = |de(k-1)|$ that corresponds to the region b of Figure 2, the normalized acceleration s(k) approaches to zero. This means that the system response increases or decreases with a constant rate and it can be considered as a "medium" rate between "fast" and "slow". Thus, s(k) given in (4) yields us a relative rate information about the system response within a range of [-1,1]. Furthermore, since this variable is in the range of [-1,1] it does not require any normalization procedure when it is used as a fuzzy input.

A typical time response of a closed-loop system has been shown in Figure 3. As it can easily be seen from the figure, the system response "approaches" towards the reference in the regions A_1 and A_3; whereas, the system response "drifts apart" from the reference in the regions A_2 and A_4. The product "e(k).de(k)" is negative in the regions A_1 and A_3 while the product is positive in the regions A_2 and A_4. Since "approach" and "drift apart" behaviors of the system can be distinguished by these two positive and negative crisp values, these two regions can be separated from each other by a logical switch block [9, 10]. That is, when $e(k).de(k) \leq 0$ then the Fuzzy Approach Block (FAB) should become active and its output will be passed to the system; when $e(k).de(k) > 0$ then the Fuzzy Drift-apart Block (FDB) should become active and its output will be passed to the system. In this manner, only half of the overall fuzzy rule-base will be active in every control sequence. This, in return, will reduce the calculation burden and it will fasten the controller.

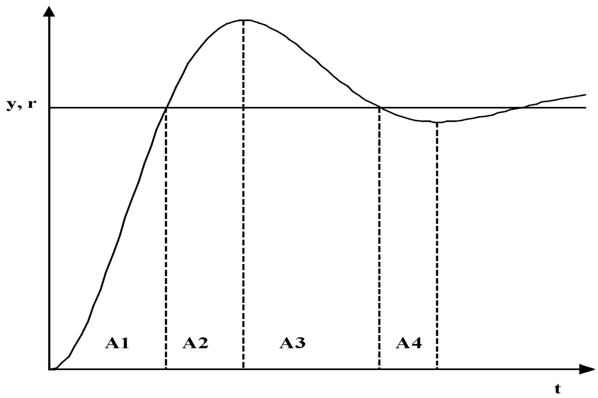


Figure 3. Typical time-response of a closed-loop system

2.2. Rule-base of the fuzzy logic controller blocks

The metarules for the fuzzy logic controller blocks; namely, Fuzzy Approach Block (FAB) and Fuzzy Drift-apart Block (FDB) are given as follows:

***A**- FAB (Fuzzy Approach Block)*

1-If the error e is "large" and the system response is "fast" or "slow" then the control effort u should be "large" or at least "medium" with an appropriate sign.

2-a) If the error is "medium" and the system response is "fast" then the control effort u should be "small" or at most "medium" with an appropriate sign.

b) If the error is "medium" and the system response is "slow" then the control effort u should be at least "medium" with an appropriate sign.

3-a) If the error is "small" and the system response is "fast" then the control effort u should be at most "small" with an appropriate sign.

b) If the error is "small" and the system response is "slow" then the control effort u should be at least "small" with an appropriate sign.

***B**-FDB (Fuzzy Drift-apart Block)*

1-If the error e is "large" or "medium" and the system response is "fast" or "slow" then the control effort u should be "large" or at least "medium" with an appropriate sign.

2-a) If the error is "small" and the system response is "fast" then the control effort u should be at least "medium" with an appropriate sign.

b) If the error is "small" and the system response is "slow" then the control effort u should be at most "medium" with an appropriate sign.

The fuzzy logic controller presented above proposes new metarules that are derived from the general dynamic behavior of a given process. In that respect, this controller is similar to MacVicar-Whelan controller and in fact, it can be seen as an alternative to that controller.

Using the metarules given above, tentative decision tables for FAB and FDB can be formed as shown in Table 2 and Table 3, respectively. The input controller variable e and output control u (or du) are quantized into fuzzy sets of eight levels; whereas, the input variable s is quantized into four levels. The levels are defined as follows:

PL= positive large; NL= negative large;
PM= positive medium; NM= negative medium;
PS= positive small; NS= negative small;
PZ= positive zero; NZ= negative zero

Moreover, standard, uniformly distributed triangular membership functions are used for both input and output fuzzification procedure.

Table 2.A tentative decision table for "FAB"

e\s	**PL**	**PS**	**NS**	**NL**
PL	PM	PL	PL	PL
PM	PS	PM	PL	PL
PS	PZ	PS	PM	PL
PZ	NZ	PZ	PS	PM
NZ	PZ	NZ	NS	NM
NS	NZ	NS	NM	NL
NM	NS	NM	NL	NL
NL	NM	NL	NL	NL

Table 3.A tentative decision table for "FDB"

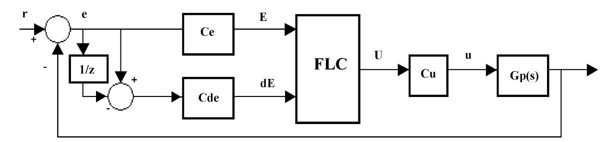
e\s	**PL**	**PS**	**NS**	**NL**
PL	PL	PL	PL	PL
PM	PL	PL	PL	PM
PS	PL	PL	PM	PS
PZ	PL	PM	PS	PZ
NZ	NL	NM	NS	NZ
NS	NL	NL	NM	NS
NM	NL	NL	NL	NM
NL	NL	NL	NL	NL

III. APPLICATIONS

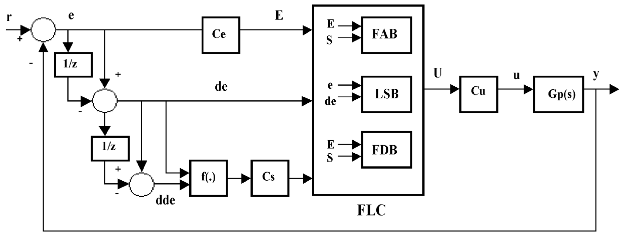
In this part, all of the simulations have been done on a closed loop system as shown in Figure 4. The system that has to be controlled is chosen as the marginally stable system that has a transfer function given by

$$G_p(s) = \frac{5}{s(s+5)} \tag{8}$$

Moreover, there exits a saturation limiter of [-1.5 1.5] at the controller output. It is a known fact that the conventional controllers (PI, PD, or PID) cannot show good performance for this kind of systems. Even Ziegler-Nichols tuned PID controllers may fail to provide a satisfactory performance for such systems due to large overshoots. For this reason, the simulation results are only given related to MacVicar-Whelan PD-type controller and our alternative fuzzy logic controller.

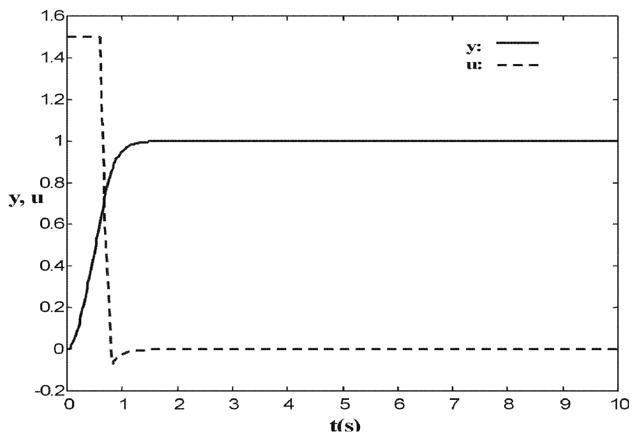


(a)

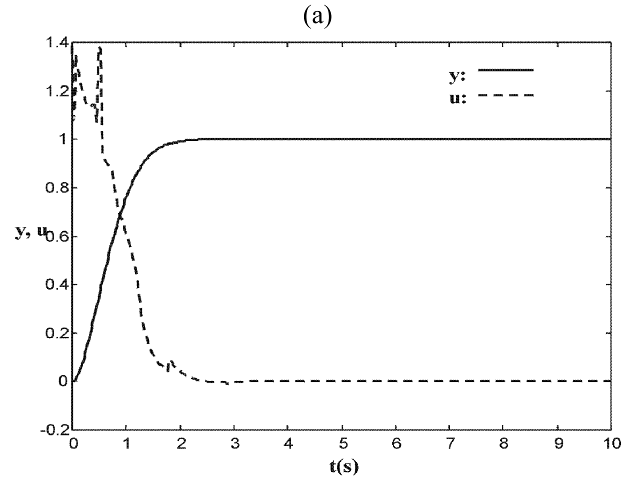


(b)

Figure 4. The closed-loop control structure for a)the typical FLC, b) the new FLC.



(a)

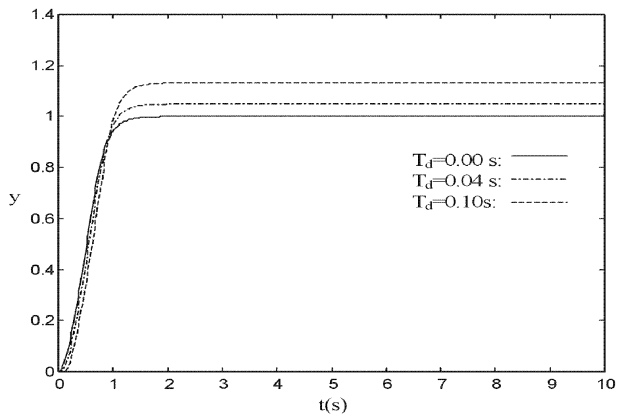


(b)

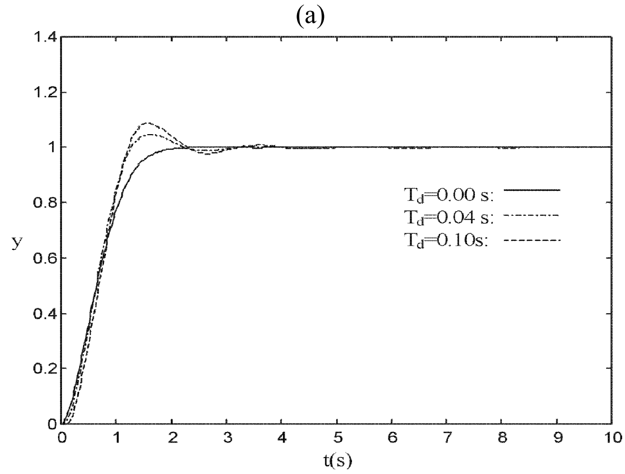
Figure 5. Step response and control output of the system with a)the typical FLC b)the new FLC

Figure 5 shows that output response with typical FLC is faster and the control effort is smoother compared to the new FLC application. However, it should also be noted that the control effort with typical FLC forces the saturation limits; whereas, the control effort in the new FLC stays within the saturation limits. Moreover, one has to make crucial and fine adjustments on the input/output scaling factors of the typical FLC [11,12];whereas, no such need arises in the new FLC application.

A comparison between the performance of MacVicar-Whelan FLC with a typical rule base and the new FLC is tried to be made when a transport delay occurs on the marginally stable system given in (8). Figure 6 shows the step responses of the closed loop system with and without a transport delay using the typical and the new FLC with the nominal I/O SFs. The transport delays (T_d) are chosen to be 0.04 and 0.1 seconds.



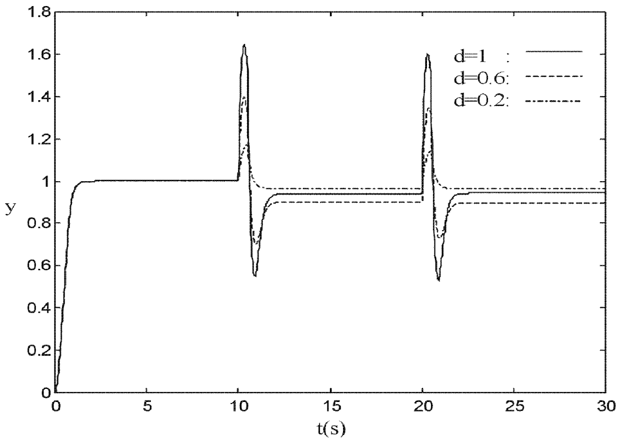
(a)



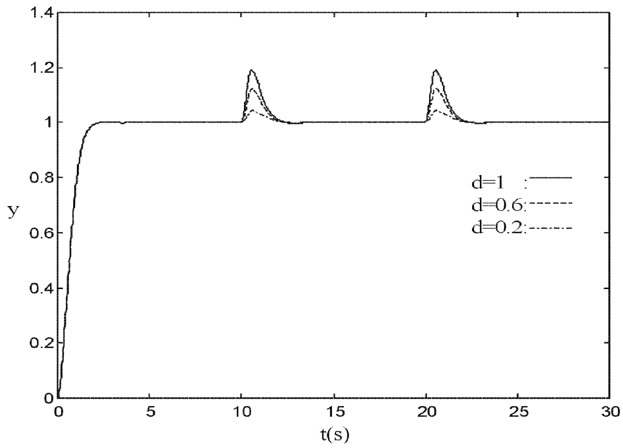
(b)

Figure 6. Step responses of the system with a)the typical FLC b)the new FLC due to various transport

Transport delay causes a steady-state error in the typical FLC application as expected. This steady-state error increases as the delay time increases; however, the form of the output response does not change. Even though, no steady-state error is observed in the new FLC application, the output response becomes oscillatory as the time delay increases. Next, robustness of the new fuzzy logic controller over MacVicar-Whelan fuzzy logic controller is illustrated by applying various disturbances to the same system. Figure 7 shows the output responses of the closed loop system with two different FLCs when disturbances of amplitudes d=0.2,d=0.6 and d=1 with a duration of 0.5 s are applied.



(a)



(b)

Figure 7. Responses of the system with a)the typical FLC b)the new FLC due to various load disturbances

When a load disturbance is applied to the system with the typical FLC, steady-state error is observed even for small amplitude values of disturbances. Moreover, new and different steady-state values are reached at each application of the same disturbance. High oscillatory behavior is observed in reaching every steady state value for the closed loop system with the typical FLC. No steady-state error is observed in the new FLC application, and the response has a smooth nature with very small peak values.

IV. CONCLUSION

In this study, a new input variable is devised and problem independent way of composing a rule-base is proposed. In fact, designing a rule-base using the metarules given in this study is very straightforward and easy since metarules are derived simply using the physical meanings of the process variables. The main superiority of the new FLC over the typical FLC is observed at the static period. If the open loop transfer function of the overall system is not of type zero, no steady-state error occurs in the new FLC application irrespective of I/O SFs; whereas, steady-state error is very common for the typical FLC applications and I/O SF adjustments are needed to overcome to this problem. When a transport delay is introduced to the system, a steady state error is observed in the typical FLC application, while no steady state error occurs in the new FLC application. It is also seen that the new FLC is very robust to the load disturbances; whereas, the typical FLC demonstrates a very poor response in both static and dynamic respects for any load disturbance.

Thus, the new methodology for designing a fuzzy logic controller seems to be a remedy for the major drawbacks of classical fuzzy logic controller design.

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