SOME PRACTICAL CONSIDERATIONS IN IMPLEMENTING A PULSE-CONTROL FUZZY CONTROLLER

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ABSTRACT

A new type of fuzzy controller that is based on a pulse-control technique was proposed in [1]. Unlike the more conventional type of fuzzy controller in which the control and measurement actions are essentially carried out concurrently, this controller separates the control phase from the measurement phase. The proposed fuzzy controller has been found to be able to deal with a range of unstable and unintuitive systems. Some practical issues in implementing such a fuzzy controller are described in this paper.

1. INTRODUCTION

The classical fuzzy controller is typically nonlinear, static, and time-invariant, namely, its output is a nonlinear algebraic function of its inputs, and its characteristics do not vary with time. This type of fuzzy controller has been shown to produce good results in many practical systems. However, the classical static and time-invariant fuzzy controller has been shown [1] to be incapable of stabilizing the class of plant which is not strongly stabilizable [2]. In the linear-control literature, a *not-strongly-stabilizable* plant refers to an unstable linear plant for which any linear-time-invariant (LTI) controller that is capable of stabilizing it is itself unstable. This type of plant is typically non-minimum phase, that is, its transfer function is characterized by one or more right-half-plane zeros in the s-plane. An example of such a plant can be derived from the well-known inverted pendulum system (see [1]).

A new type of heuristically-motivated fuzzy controller, one which is time-variant, was described in [1], and this new arrangement was shown to be able to deal with not-strongly-stabilizable plants. This type of fuzzy controller differs from the more conventional fuzzy controller in several ways: In a usual fuzzy control system, the output conditions of the plant under control are observed and used as inputs to a fuzzy controller in which a control action is inferred. This inferred action is then applied to the plant, and the whole process is repeated. In the conventional type of fuzzy controller, observations, (that is, measurements) of the output conditions are carried out while the plant is being controlled. It has been shown in [1] that this usual concurrent arrangement of the observation and control actions has difficulties when dealing with the not-strongly-stabilizable plants. A heuristically-derived modifications to the observation and control arrangement (the so-called 'blind-man strategy' [1]) has been proposed, in which the observation and control actions occur in separate phases. During the observation phase, the control action is zero; during the control phase, no observation is undertaken, rather the control action is inferred from the previous observation. A block diagram of the scheme is shown in Figure 1.

Although computer simulations of an idealized model of this new scheme have been reported earlier, the present paper demonstrates practical aspects of the new scheme using an analog model of a plant that is controlled by a PC-based fuzzy controller. This more realistic setting allows some practical aspects of the scheme to be identified and addressed.

Section 2 discusses the major features of this new type of fuzzy controller. Section 3 describes a not-strongly-stabilizable plant that the fuzzy controller is challenged to stabilize, along with its analog model. Section 4 examines the experimental setup and results obtained. Conclusions are provided in Section 5.

2. A PULSE-CONTROL FUZZY CONTROLLER

The separation of the control and observation phases described earlier can be implemented in a quite straightforward fashion. Diagrammatically, the pulse-control fuzzy controller, as depicted in Figure 1, differs from the conventional fuzzy controller in that the output of the former is modulated by a pulse signal. At least two types of modulation are possible, namely, pulse-amplitude modulation (PAM) (as shown in Figure 1), and pulse-width modulation (PWM) (not shown here). In a PAM scheme, the pulse is of fixed width, and the amplitude of the control pulse to the plant is determined by a typical fuzzy inference process. In a PWM scheme the pulse width is determined by the inference process, while the amplitude of the pulse is fixed. This work focuses on the PAM scheme.

During the interval when the modulating pulse has an amplitude of 1, the control signal is passed to the plant. The amplitude of the control during this interval of time is determined by the fuzzy inference process, and is based on observations of the output of the plant in the previous interval in which the control to the plant is reduced to zero by the modulating pulse.

The pulse-control fuzzy controller provides the necessary framework for the implementation of the so-called 'blind-man strategy [1]' which is capable of stabilizing not-strongly-stabilizable plants. The stabilization strategy requires the

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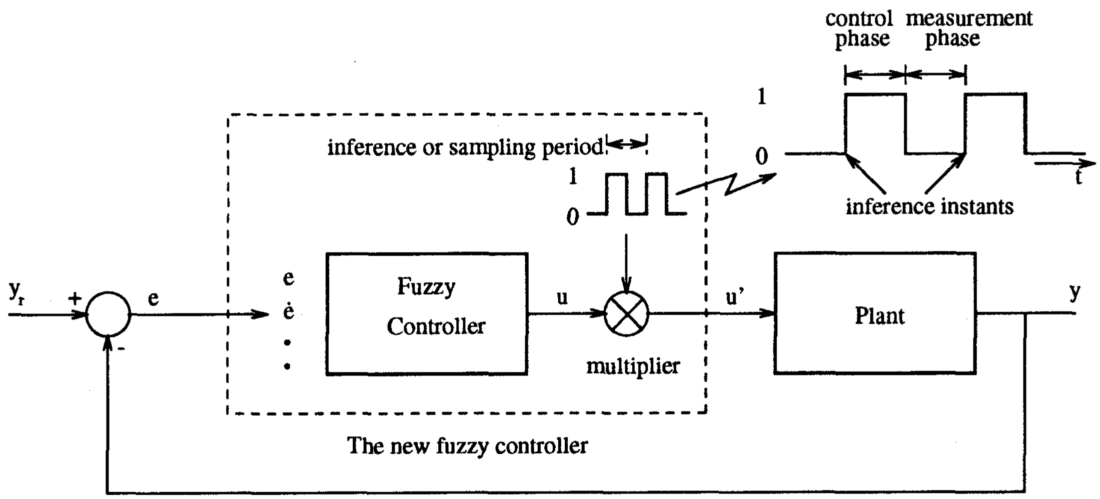


Figure 1. A modified fuzzy-control system using the pulse-amplitude-modulation scheme. (Both the control phase and the measurement phase are of fixed durations.)

separation of the observation and control actions, and in addition, the stabilization of higher order derivatives of the output before attempting to stabilize the output.

3. A NOT-STRONGLY-STABILIZABLE PLANT

In this Section, a linear not-strongly-stabilizable plant (which is unstable and non-minimum phase) is used to demonstrate the workings of the pulse-control fuzzy controller implementing the 'blind-man strategy'. It must be stressed that the plant to be used is well-defined and is linear, and to emphasize that there exist conventional control techniques [3-4] that can stabilize it. The purpose of this paper is *not* to compare the advantages and disadvantages of fuzzy versus conventional techniques, but rather to show how a heuristically-based pulse-control fuzzy controller can stabilize such a plant (though a classical fuzzy controller cannot).

A particular not-strongly-stabilizable linear plant, in state-space form, is given below:

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 2 \end{bmatrix} x + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \tag{1a}$$

$$y = [-1 \;\; 1]\, x \tag{1b}$$

where $x = [x_1 \, x_2]'$ is the internal state of the system, $y(t)$ is the output of the plant, and $u(t)$ is the input to the plant. The corresponding transfer function is

$$\frac{Y(s)}{U(s)} = \frac{s-1}{s(s-2)} \tag{2}$$

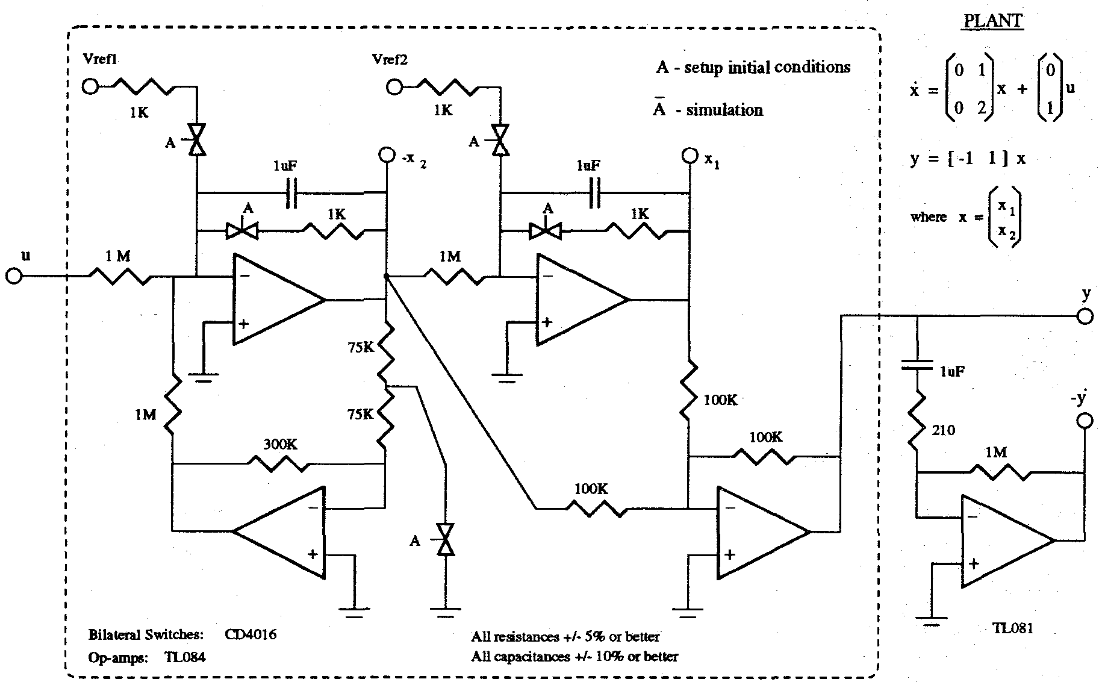
where $Y(s)$ and $U(s)$ are the Laplace-transformed variables of $y(t)$ and $u(t)$, respectively. This plant has a pole-zero interlaced property which is such that to be stabilized by a linear time-invariant (LTI) controller, the controller must itself be unstable [2]. A much simplified way of looking at the difficulties in stabilizing this plant is to note that the output, y, is formed by the difference of two exponentially increasing quantities (one of which is the derivative of the other). So, it is possible that while y may seem small over a certain interval of time, its constituent components can actually be expanding. Thus a decision based on direct observation can easily be wrong.

Correspondingly, it has been shown in [1] that a typical static and time-invariant fuzzy controller which bases its inferred control action directly on the conditions of the output y and its derivatives, is incapable of stabilizing such a plant. To deal with the difficulties, the so-called 'blind-man strategy' as discussed in Section 2 was introduced; there, computer simulation results showed that this plant can be stabilized by such an approach.

To examine the fuzzy-control approach in a more realistic manner, an analog model of the plant described by Equation (1), and shown in Figure 2, was built for experimental stabilization by a PC-based fuzzy controller. A differentiator circuit that was used to obtain the first derivative of the output is also shown in Figure 2. A more detailed description of the experimental setup is provided in Section 4.

4. AN EXPERIMENTAL INVESTIGATION OF THE PULSE-CONTROL FUZZY-CONTROL SYSTEM

A PC-based fuzzy controller which implemented the pulse-control scheme described in Section 2 was used to stabilized the analog model introduced in Section 3. The fuzzy



An analog model of the plant described by Equation (1).

Differentiator

Figure 2. Analog model of the plant including the output differentiator.

controller consisted of a PC that was equipped with an analog-to-digital (A/D) and digital-to-analog (D/A) card for interfacing with the analog model. The A/D-D/A card had 12-bit resolution, and could support up to 16 analog inputs and two analog outputs. All measured waveforms shown later in this Section were obtained using the Tektronix TDS 520 Digitizing Oscilloscope.

The analog model of the plant shown in Figure 2 allowed the initial state to be set-up from the PC through the use of V_{ref1} and V_{ref2}. After initialization, the stabilization strategy (following the blind-man strategy) was to try to stabilize $\dot{y}$ first, and then when $\dot{y}$ was almost stabilized, to stabilize y. The corresponding rules and the accompanying input and output membership functions were essentially the same as those described in [1], and are reproduced here in Table 1 and Figure 3 for convenience.

Differentiator design

The design of a differentiator depends on the speed of the signal on which the differentiator is intended to operate. While the fastest time-constant of the plant was 0.5 sec, the sampling period (or inference period) was set to 10 ms, and the length of the control phase was set to 5 ms (a small fraction of 0.5 sec). The differentiator shown in Figure 2 was actually a high-pass filter with the corner frequency at about 750 Hz; this was done to minimize the effects of high-frequency noise. This corner frequency was much higher than the expected major frequency components of the output signal, which in the present system were due to the pulse-control scheme, having a fundamental frequency of $\frac{1}{10\text{ms}}$, or, 100 Hz. Correspondingly, the pulse frequency of the pulse control technique was the dominating factor in the differentiator design.

$\dot{y}$	y	u
PL	-	NL
PS	-	NS
NS	-	PS
NL	-	PL
ZE	PL	PS
ZE	PS	PVS
ZE	ZE	ZE
ZE	NS	NVS
ZE	NL	NS

Table 1. Rulebase for stabilizing the plant described by Equation (1). In the table, the abbreviated labels have the following meanings: Positive Large (PL) Positive Small (PS), Positive Very Small (PVS), Zero (ZE), Negative Very Small (NVS), Negative Small (NS), and Negative Large (NL).

Choice of pulse shape

The simplest choice of possible pulse shape is rectangular as shown conceptually in Figure 1; however, rectangular pulses imply abrupt changes in the control signal, which could excite high-frequency dynamics of the system. An example of this effect is shown in the output derivative waveform, $\dot{y}$, depicted in Figure 4. In that Figure, damped high-frequency oscillations in $\dot{y}$ can be seen associated with both the rising and trailing edges of the input pulse. In a physical system, the high-frequency dynamics are typically due to some unmodeled higher-order effects in the system. In the present analog model, the higher-order effects are due to op-amp dynamics, the high-pass filter (which was used instead of the differentiator), and other parasitic effects which had not been explicitly taken into account. These unmodeled high-order effects are often not of direct interest, but, in general, can interfere with the normal operation of the system if not handled properly.

As shown in Figure 4, in order to obtain stable measurements during the observation phase, the observation phase should be long enough to let the high-frequency effects die away. Alternatively, the input signal can be modified in such a way as to avoid exciting the high-frequency dynamics of the system. This can be achieved by shaping the control pulses from the fuzzy controller to reduce the high-frequency components before applying the pulse train to the plant. A simple pulse-shaping technique that was actually employed was to low-pass filter the pulses as shown in Figure 5. The low-pass filter used had a time constant of 0.33 ms, and effectively, as shown in Figure 6, removed the damped oscillations in $\dot{y}$.

Experimental results

The fuzzy controller employed the rules shown in Table 1. The parameters for the input and output membership functions shown in Figure 3, which are given in Table 2, were based on those obtained by the Simulated Annealing (SA) optimization procedure [1]. The initial condition of the analog model was set to y=$-2V$, and $\dot{y}$=$-1V$. The stabilization results for y, as well as the corresponding waveforms for $\dot{y}$ and u'' are shown in Figure 7.

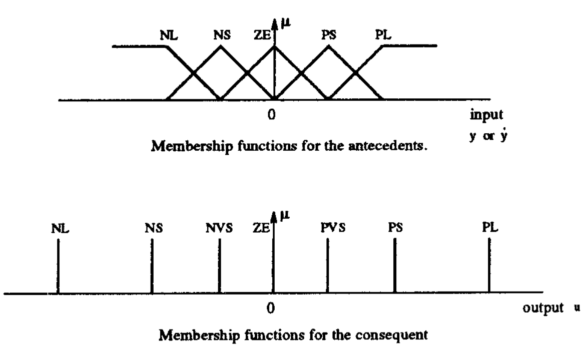


Figure 3. Membership functions.

Apex	PL = -NL	PS = -NS	PVS = -NVS	ZE
$\dot{y}$	1.7	0.2	–	0
y	4.8	0.2	–	0
u	5.15	3.75	0.2	0

Table 2. Locations of the apex points of the membership functions shown in Figure 3.

5. CONCLUSIONS

An experimental examination of the pulse-control fuzzy controller and the associated 'blind-man strategy' introduced earlier [1] has been reported. The results confirm the viability of the scheme, and show that :

(i) the requirements on the differentiator are determined by the pulse frequency used in the pulse-control scheme, which is typically much higher than the highest-frequency component of the plant,

(ii) the pulse shape should be chosen to avoid exciting high-frequency dynamics of the plant which are not of particular interest, and are often not identified explicitly.

To ensure a successful design, both points should be taken into consideration when using this pulse-control strategy.

6. REFERENCES

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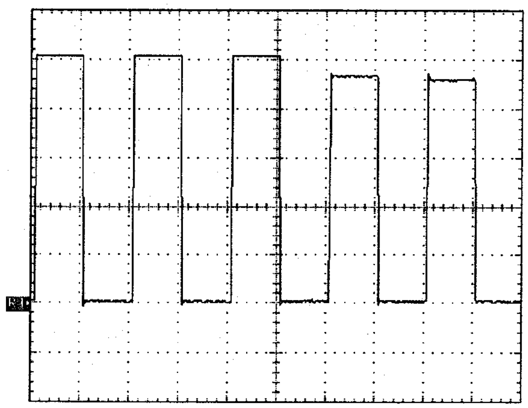

Figure 4a. u' (see Figure 1) versus t.
Vertical scale : 1 V/division, zero reference at R1.
Horizontal scale : 5 ms/division.

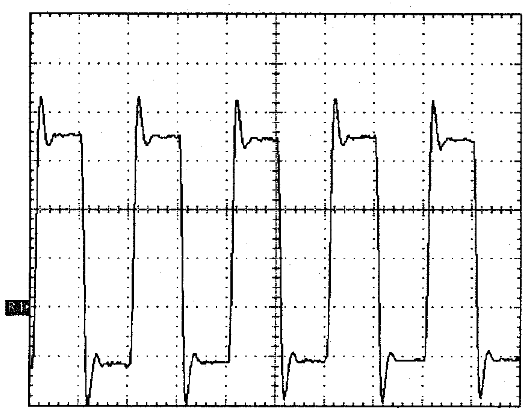

Figure 4b. The corresponding waveform for $\dot{y}$.
Note the damped oscillations in the waveform.
Vertical scale : 1 V/division, zero reference at R1.
Horizontal scale : 5 ms/division.

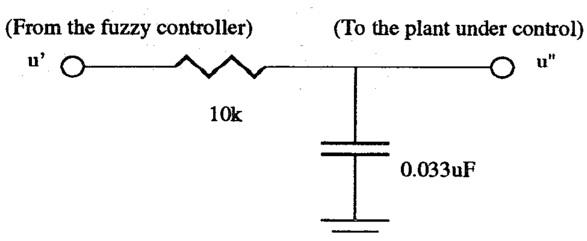

Figure 5. A low-pass filter for pulse shaping.

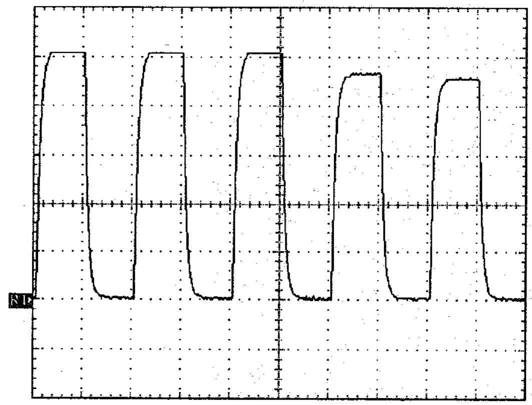

Figure 6a. The waveform of u'' (a low-pass version of u' in Figure 4a, see also Figure 5).
Vertical scale : 1 V/division, zero reference at R1.
Horizontal scale : 5 ms/division.

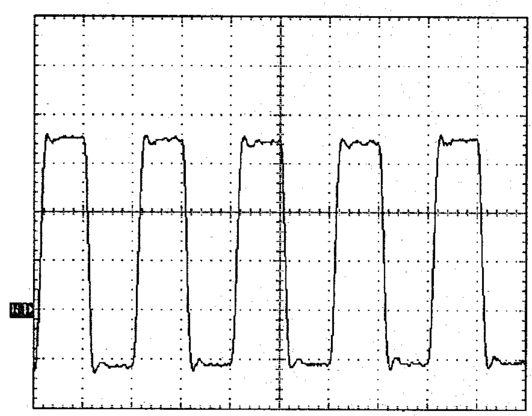

Figure 6b. The corresponding waveform for $\dot{y}$.
Note that damped oscillations are very much reduced.
Vertical scale : 1 V/division, zero reference at R1.
Horizontal scale : 5 ms/division.

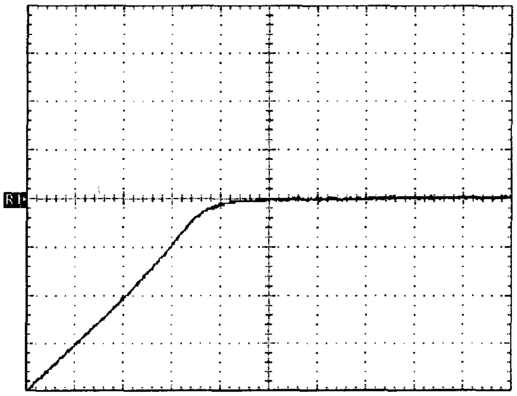

Figure 7a. y versus t.
Vertical resolution: 0.5 V/division, zero reference at R1
Horizontal resolution: 400 ms/division.

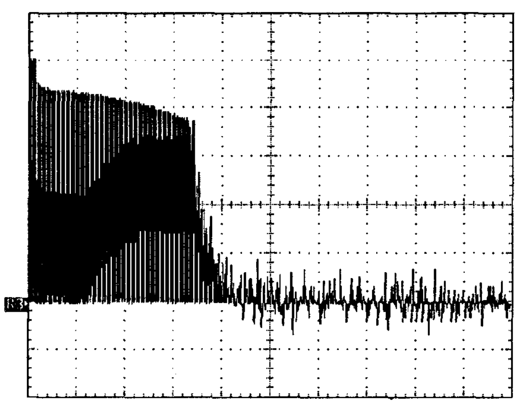

Figure 7b. u'' versus t.
Vertical resolution: 1 V/division, zero reference at R3
Horizontal resolution: 400 ms/division.

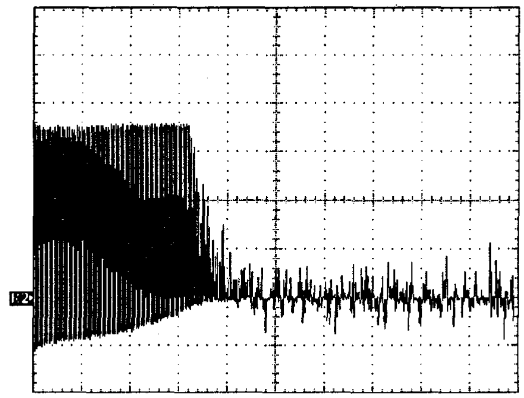

Figure 7c. $\dot{y}$ versus t.
Vertical resolution: 1 V/division, zero reference at R2
Horizontal resolution: 400 ms/division.

Figure 7. The measured waveforms of y, $\dot{y}$, and u'' versus t.
The apparent shaded areas in $\dot{y}$ and u'' were due to the effect of the control pulses. Expanded views which show the finer details of the initial portions of $\dot{y}$ and u'' are given previously in Figure 6. The switching actions that occur in $\dot{y}$ and u'' after y has been stabilized arised because of the noise in the plant.