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# FUZZY LOGIC CONTROLLER FOR NETWORKED CONTROL SYSTEMS WITH PACKET LOSSES

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## ABSTRACT

Networks and their applications have been evolving substantially in the last two decades. Networked Control Systems (NCS) are one of the hottest topics in network-based applications. By networked control system we mean controlling the system through the network. Such systems offer advantages such as lower installation costs, increased flexibility, reliability, also reduced maintenance costs. The change of communication architecture from point-to-point to this common bus approach, however, introduces different forms of loss of packets in the closed-loop system dynamics. These packets loss comes from node failures or message collisions. Packet losse in a control application can degrade a system's performance and even cause system instability. In this paper, optimal design of fuzzy logic PI and PID controllers have are developed to compensate the network-induced packet losses. Simulink model of a distributed DC servo system using CAN network has been built. Different simulation examples are given to explore the simplicity and effectiveness of the proposed controllers in compensation of the packet losses compared with other different techniques.

## KEYWORDS

Networked Control Systems, Packet Loss, Fuzzy logic, Distributed Control, PI, PID and CAN Network.

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## INTRODUCTION

Data networking technologies give several benefits for linking data among different data sources of distributed control systems. Networks enable remote data transfers and data exchanges among subsystems, reduce the complexity in wiring connections, enable easy in maintenance, and a lower installation cost Networked Control Systems (NCSs) are one type of distributed control systems where sensors, actuators, and controllers are interconnected by communication networks [1].

Fig.1. shows a standard networked control system. NCSs offer a number of advantages over their traditional predecessors, including low cost of installation, ease of maintenance, higher flexibility and rapid installation and diagnostics.

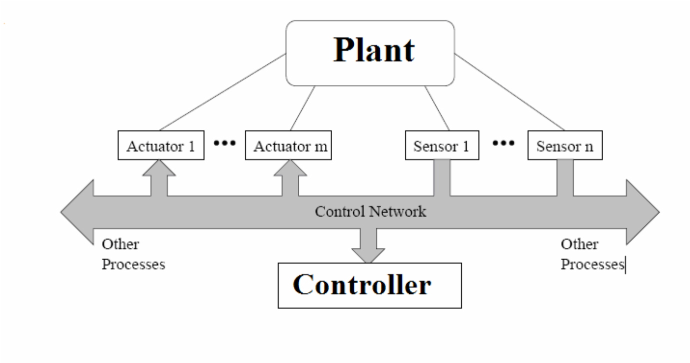



Fig.1. A standard networked control system

Dropping network packets occasionally happens on an NCS when there are node failures or message collisions. Although most network protocols are equipped with transmission-retry mechanisms, they can only re-transmit for a limited time. After this time has expired, the packets are dropped. Furthermore, for real-time feedback control data such as sensor measurements and calculated control signals, it may be advantageous to discard the old, untransmitted message and transmit a new packet if it becomes available, in this way; the controller always receives fresh data for control calculations.

As the number of devices in a system grows and the functions of a system need to be more intelligent, these devices need to exchange a large amount of data among them. When there is overcrowding in the communication network, some packets are dropped to either reduce the queue size in the path or to inform the senders to reduce their transmission rates. In real time systems, particularly control systems, delays or dropped packets may cause performance degradation and system destabilization [2-4]. Normally, feedback-controlled plants can tolerate a certain amount of data loss, but it is valuable to determine whether the system is stable when only transmitting the packets at a certain rate, and to compute acceptable lower bounds on the packet transmission rate [5-8].

In order to consider the uncertainty of communication packet losses, intelligent computational approaches such as fuzzy logic [9-11] can be used. In this work, an optimal design of Fuzzy Logic PI and PID controllers are carried out for distributed control of a DC servo system. The parameters in Fuzzy Controller are optimized to adapt the nonlinearity of the controlled systems due to packet losses. The dynamic performance of Networked Control System is improved with this method compared with classical digital PID controller. Several simulation examples are applied using CAN network to clarify the efficiency of the proposed methods.

## COMPENSATION OF PACKET LOSS EFFECTS

From a reliability point of view, it would be desired that an NCS can endure more packet dropping without violating stability of the system. For an NCS, a comparatively large packet dropping margin indicates that the system is less sensitive to packet dropping effect. However, it is difficult to design a controller $G_c$ to achieve a large packet dropping margin, at the same time and keep the system stable. In [12] a necessary and sufficient condition for stability of NCSs in the mean square sense is derived to determine the robustness of the system with respect to packet dropping. The pole assignment approach to design has been used to make the system less sensitive to packet dropping effect. However, this method is applied only for a linear time variant systems that satisfy the margin of the condition of the system stability. In [13] the uncertainty threshold principle has been used to show that under certain conditions there is a rate for dropped packets for which an undisturbed networked control system is mean square stable. These conditions are verified such that the parameters of the non-networked control system and the packet dropping rate in the network are given.

In general, fuzzy logic control is used for the control of plants where the plant modeling is difficult and conventional control methods have shown limited success [14,15]. The controller design should take into consideration, the plant of NCS and the network that connects the system components. The modeling of the network part of the plant is quite difficult to handle because it is difficult to find a differential or a difference equation to describe it. The state transition of the network in NCS occurs at discrete time instants. Due to these reasons, fuzzy logic control becomes a very attractive method for controller design for NCS.

## MODELING NCSS WITH DATA PACKET DROPOUT

The NCS model considering an NCS setup with the possibility of dropping data packets is shown in Fig.2. The model consists of a continuous plant:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= C(t) \end{aligned} \tag{1}$$

and a discrete controller:

$$u(kh) = -Kx(kh) \qquad \mathrm{k} = 0,1,2,\ldots \tag{2}$$

where, $x \in R^n, u \in R^m, y \in R^p,$ and A, B ,C ,K are of compatible dimensions.
with constant sampling period h,

$$\Phi = \mathrm{e}^{\mathrm{Ah}} \tag{3}$$

$$\Gamma = \int_0^h e^{As} ds B \tag{4}$$

The network can be modeled as a switch that closes at a certain rate r. When the switch is closed (position $S_1$), the network packet containing x (kh) is transmitted, whereas when it is open (position $S_2$), the output of the switch is held at the previous value and the packet is lost. Thus, the dynamics of the switch (state $\hat{\mathrm{x}}$) can be modeled as

$$S_1 : \hat{x}(kh) = x(kh),$$
$$S_2 : \hat{x}(kh) = \hat{x}((k-1)h). \tag{5}$$

Define the transmission indicator function s(kh) as

$$s(kh) = \begin{cases} 1, & sample\ is\ transmitted, \\ 2, & sample\ is\ not\ transmitted, \end{cases} \tag{6}$$

Let $\omega(kh) = [x^T(kh),\ \hat{x}^T(kh)]^T$ be the augmented state vector, the closed-loop system with the network packet dropout effect is represented by

$$\omega((k+1)h) = \tilde{\Phi}_s(kh)\,\omega(kh) \tag{7}$$

When the switch is in position $S_1$, *S(kh) =1* and

$$\tilde{\Phi}_1 = \begin{bmatrix} \Phi & -\Gamma\mathrm{K} \\ \Phi & -\Gamma\mathrm{K} \end{bmatrix} \tag{8}$$

When the switch is in position $S_2$, *S(kh) =2* and

$$\tilde{\Phi}_2 = \begin{bmatrix} \Phi & -\Gamma\mathrm{K} \\ 0 & 1 \end{bmatrix} \tag{9}$$

Normally, an NCS can tolerate a certain amount of feedback data loss.

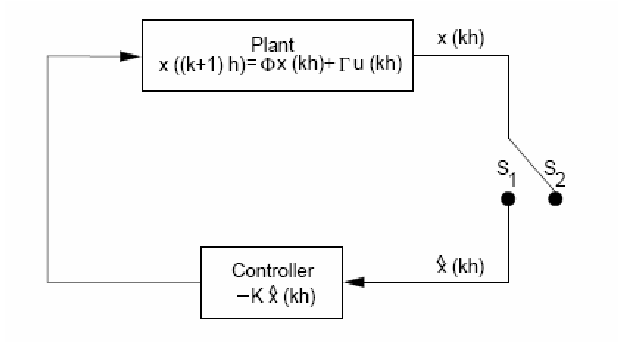



Fig.2. NCS with data packet dropout.

## DESIGN OF FUZZY LOGIC CONTROLLERS

There are several methods to design a fuzzy logic controller:

- Modellization of the experience of the control engineer or human operator
- Fuzzy modellization of the controlled plant

There is no systematic methodology to design the fuzzy controller. The most used approach is to define membership functions of the inputs and outputs, and rule data base. Fuzzy controller is nonlinear and it is very difficult to examine the influence of certain parameters. Inputs variables or process states in the fuzzy controller are:

- The error e(k).
- The change in error Δe(k).
- The integral of the error e(k).

Fig.3. shows the structure of a fuzzy logic controller for a single-input-single-output plant. In the figure, controller and plant are connected via a CAN, and control input and plant output are transmitted through the CAN. Due to the use of the CAN, control input and plant output inevitably contain the network-induced delay. The fuzzy inputs of FLC are error, e(t) and change of error, Δe(t), while its output is change of control input.

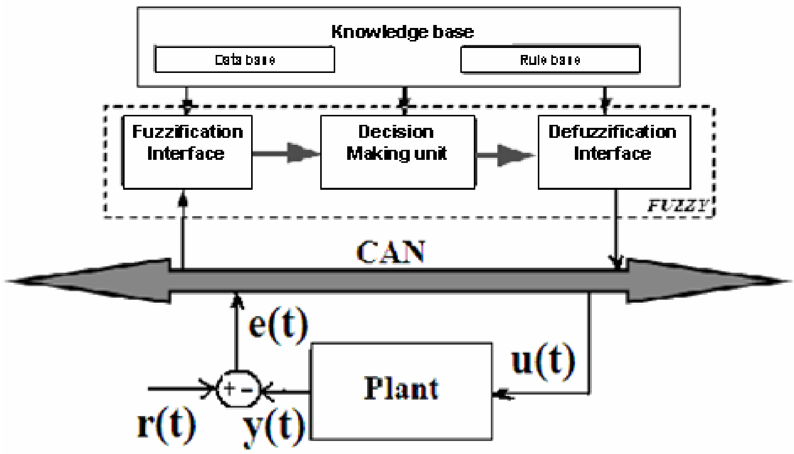



Fig.3. Structure of FLC in NCS

The rule-base for computing the output u is given in Table 1, where, PB is positive big, PM is positive medium, PS is positive small, NB is negative big, NM is negative medium, NS is negative small and ZE is zero. The control rules in Table 1 are built based on the characteristics of the step response as shown in Fig. 3. In this figure feature points are classified into four groups i.e. $a_1$, $b_1$, $c_1$ and $d_1$ and fuzzy control rules can be formulated by examining these feature points. As an example, at the first point a1,e is positive and Δe is 0. Hence, the plant output should be increased in order to decrease error between the reference input and the plant output and Δe should be positive. For this reason, when e varies, fuzzy control rules required for a1 are as follows:

If e is PB and Δe is ZE then Δe is PB
If e is PM and Δe is ZE then Δe is PM
If e is PS and Δe is ZE then Δe is PS
If e is ZE and Δe is ZE then Δe is ZE

By similar measuring, we can formulate the control rules for b1,c1 and d1, resulting in a primary fuzzy control rule base that consists of the control rules shown in Table 1.

Table 1. Fuzzy rules computation of Δ u

| e(k)/ **Δ**e(k) | NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NB | NM | NS | NS | ZE |
| NM | NB | NM | NM | NM | NS | ZE | PS |
| NS | NB | NM | NS | NS | ZE | PS | PM |
| ZE | NB | NM | NS | ZE | PS | PM | PB |
| PS | NM | NS | ZE | PS | PS | PM | PB |
| PM | NS | ZE | PS | PM | PM | PM | PB |
| PB | ZE | PS | PS | PM | PB | PB | PB |

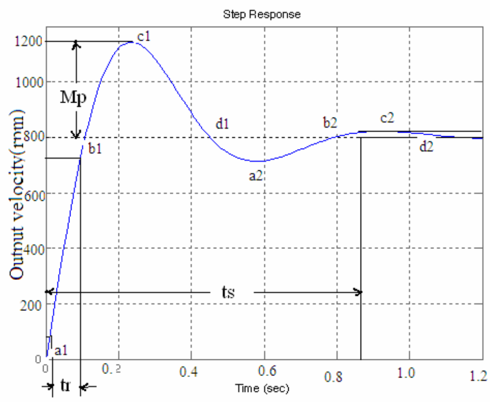



Fig.4. Step Response

The evaluation performance measures are overshoot, settling time and rising time, as shown in Fig.4.

**Design of PI fuzzy controller**

The Simulink of the PI fuzzy controller is shown in Fig.5., where the input at node 1 represents the error between the output and the reference input. The input membership functions for the error and integral of the error are shown in Fig.6. The output membership function is shown in Fig.7. The surface viewer of the inference rule is shown in Fig.8.

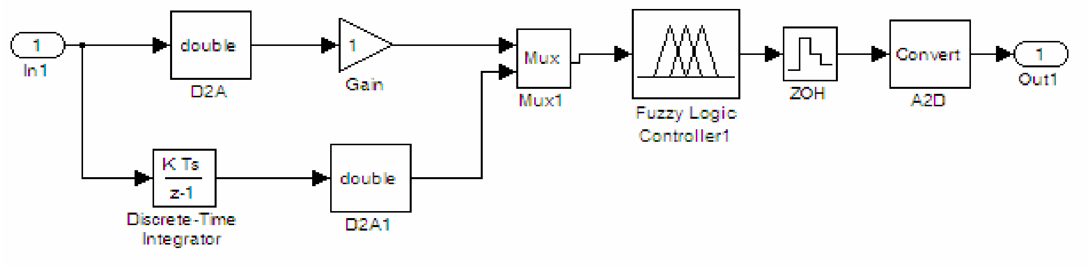
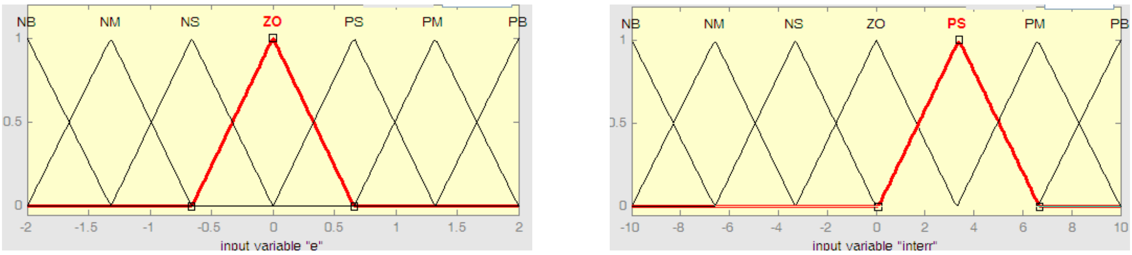



Fig.5. The Simulink of the PI fuzzy controller




**(a)** **(b)**

Fig.6. The input membership functions for (a) the error and (b) the integral of the error

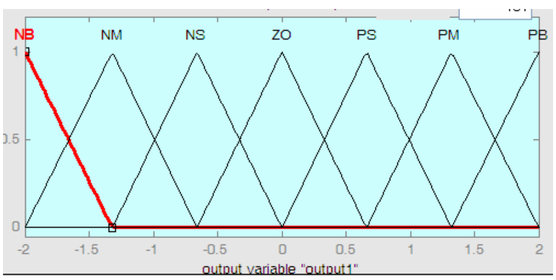



Fig.7. Output Membership function

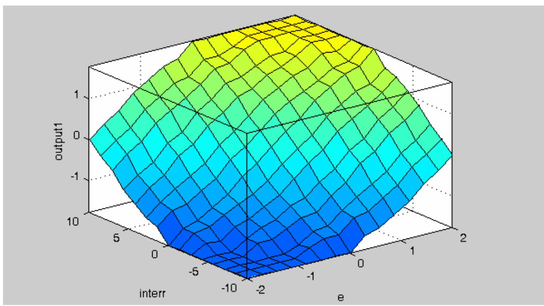



Fig.8. Surface viewer of PI Fuzzy Controller

## Design of PD fuzzy controller

The Simulink of the PD fuzzy controller is shown in Fig.8. the input at the node 1 represents the error between the output and the reference input. The input membership functions for the error and derivative of the error are shown in Fig.9. The output membership function is shown in Fig.10. The surface viewer of the inference rule is shown in Fig.11.

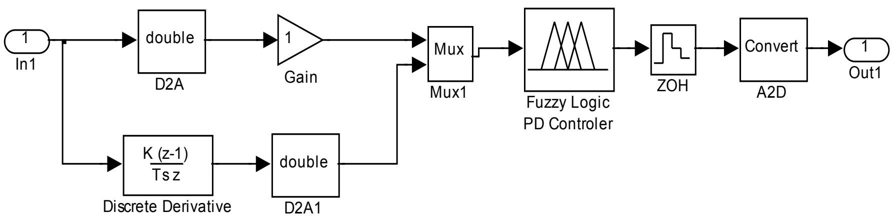
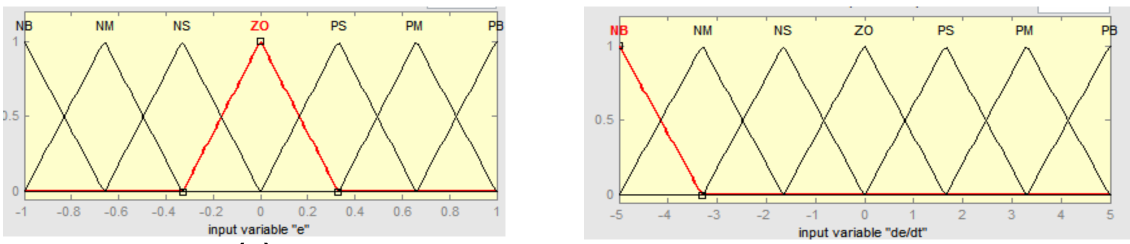



Fig.9. The Simulink of the PD fuzzy controller




**(a)** **(b)**

Fig.10. The input membership functions for (a) the error and (b) the error derivative

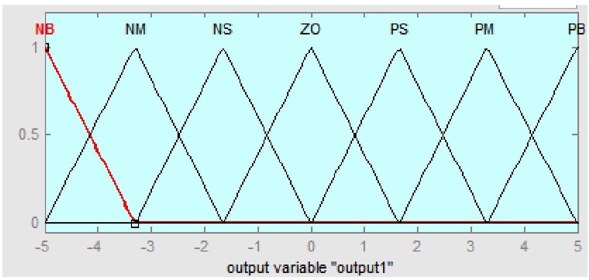



Fig.11. The output membership function

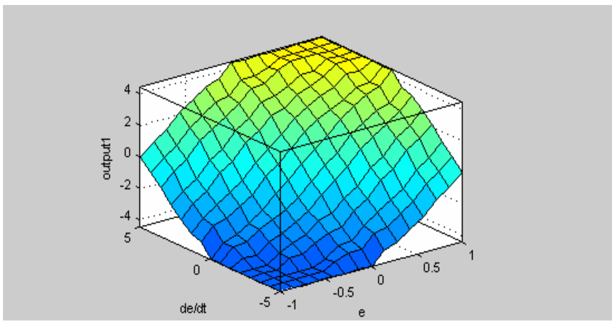



Fig.12. The surface viewer of the inference rule

**Design of PID fuzzy controller**

The PI fuzzy Controller and the PD controller are combined to form a modified PID controller as shown in Fig.13.

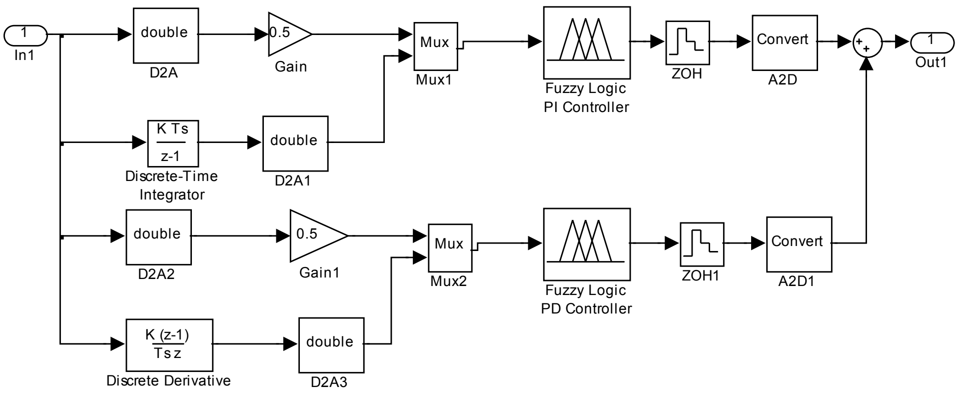



Fig.13. The Simulink of the PID fuzzy controller

**SIMULATION RESULTS**

Consider the SIMULINK model NCS of distributed DC servo system shown in Fig.14. The system contains four computer nodes connected by one network block. The time-driven sensor node contains a periodic task, which at each invocation samples the process and transmits the sample package to the controller node. The controller node contains an event-driven task that is triggered each time a sample arrives over the network from the sensor node. Upon receiving a sample, the controller computes a control signal, which is then sent to the event-driven actuator node, where it is actuated. The model also contains an interference node with a periodic task generating random interfering traffic over the network. We assume a CAN network where transmission of simultaneous messages is decided based on package priorities.

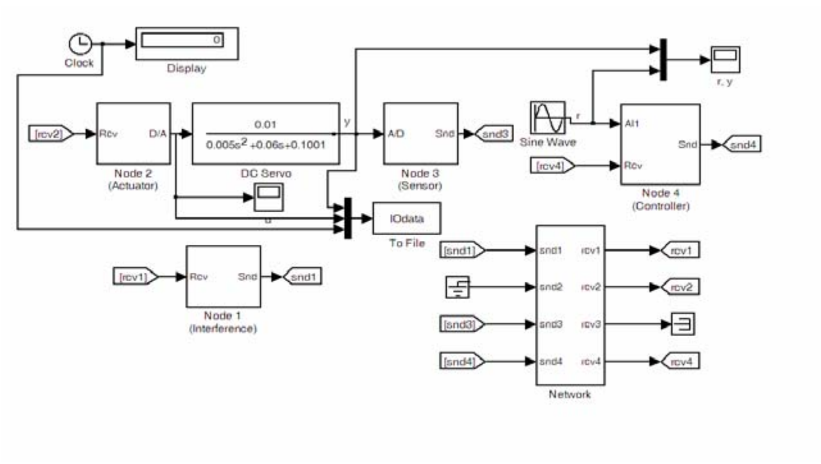



Fig.14. SIMULINK model NCS of distributed DC servo system

The step response of the NCS DC servo system using three different controllers PI fuzzy and PID fuzzy compared with digital PID, controller using CAN network for different percentage of packet dropout losses (0,10%,20%, 30%, and 40%) and 0.12 sec sampling interval are shown in Fig.15. and Fig.16. respectively.

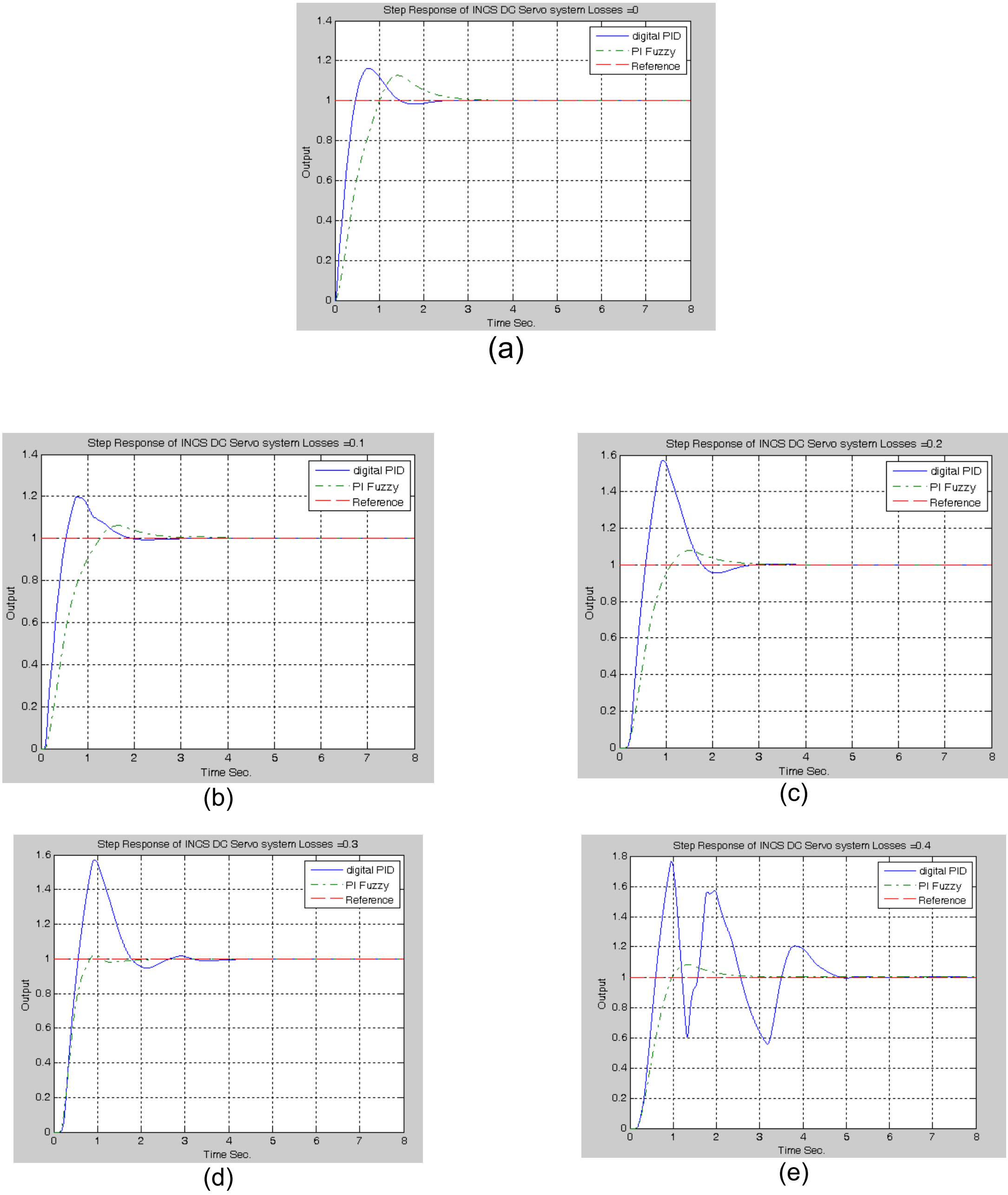



Fig.15. The step response of the NCS DC servo system using three different controllers PI fuzzy compared with digital PID controller for different percentage of packet dropout losses (0,10%,20%, 30%, and 40%)

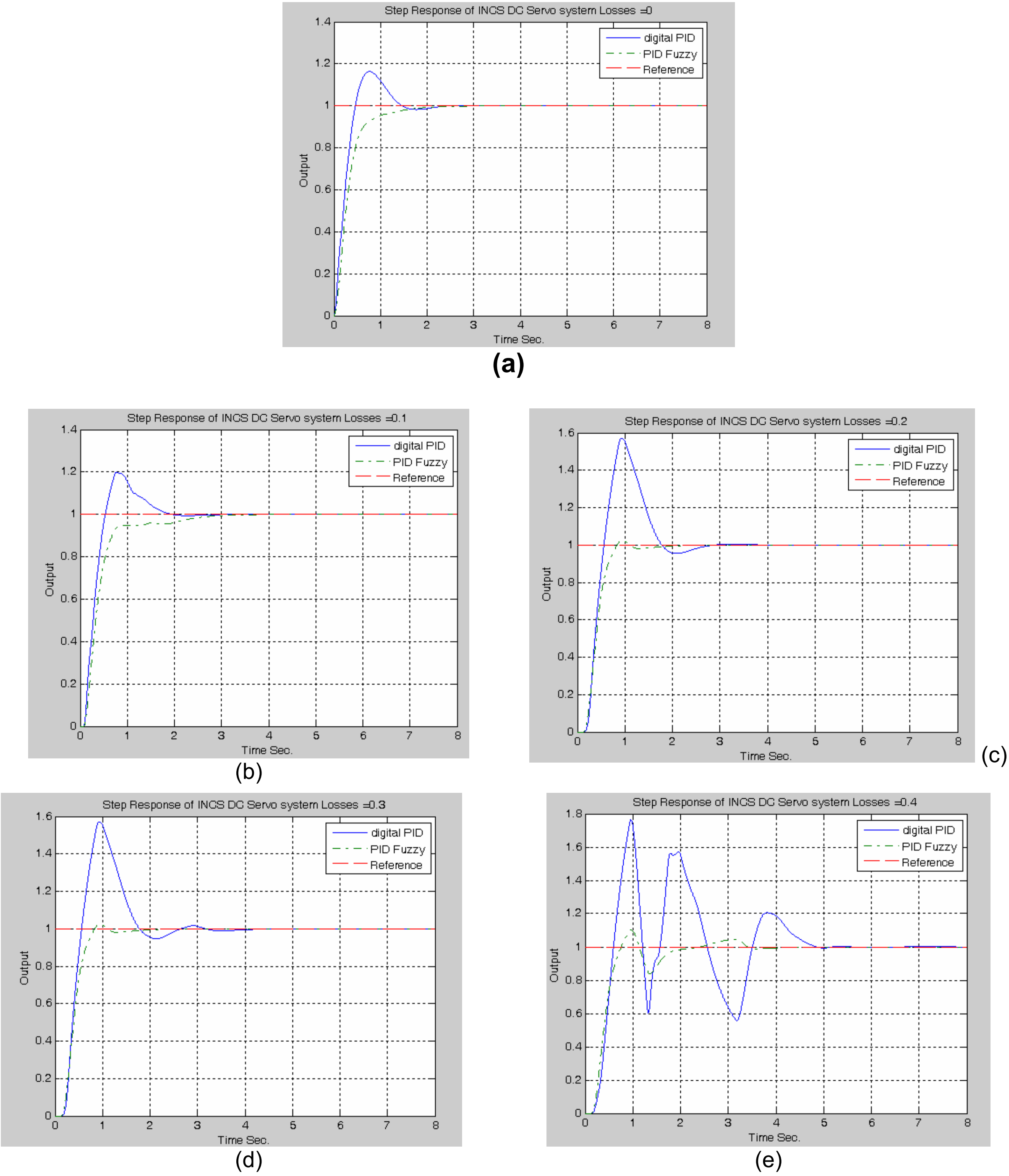



Fig.16 The step response of the NCS DC servo system using three different controllers PID fuzzy compared with digital PID controller for different percentage of packet dropout losses (0,10%,20%, 30%, and 40%)

From Fig.15. and Fig.16., it is clear that as packet dropout increases i.e.0.1,0.2 , 0.43 and 0.4 the digital PID controller cannot efficiently tolerate these effects, while the PI fuzzy and PID fuzzy controllers efficiently minimize these effects.

From these results, fuzzy logic control for NCS is a very appropriate choice due to its robustness in terms of system parameters. This type of controllers does not require plant models and measurement of network. Therefore, once a fuzzy logic controller is tuned for the plant, it may be used for NCS with little modifications on the membership function

## CONCLUSION

The introduction of networked control systems addresses many of the demanding issues of modern industrial and commercial systems. The change of communication architecture from point-to-point connection to the common-bus approach, however, introduces different forms of packet dropout in closed-loop system dynamics. Packet dropout is coming from node failure or data collision. The packet dropout, in a control application can degrade a system's performance and even cause system instability. In this paper an optimal design of the Fuzzy Logic PI and PID controllers are built. The parameters in Fuzzy Controllers are optimized to adapt the nonlinearity of the controlled systems due the packet losses. The dynamic performance of networked control system is improved with this method compared with classical digital PID controller. The proposed controllers are applied on distributed DC servo system. The network is built using the Simulink - MATLAB toolbox. Several simulation examples are applied using CAN network to demonstrate the efficiency of the proposed methods. From these results, fuzzy logic control for NCS is a very appropriate choice due to its robustness in terms of system parameters.

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