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Fuzzy PID Gain Scheduling Controller for Networked Control System

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Abstract:
The use of a communication network in the closed loop control systems has many advantages such as remotely controlling equipment, low cost, easy to maintenance, efficient information transmission, etc. However, the Networked Control System (NCS) has many drawbacks, such as network-induce end-to-end time delay and packet loss, which lead to significant degradation in controller performance and may result in instability. Aiming at solving performance degradation in NCS, this paper propose to take the advantages and strength of the conventional Proportional-Integral-Derivative (PID), Fuzzy Logic (FL), and Gain Scheduling (GS) fundamentals to design a Fuzzy-PID like-Gain Scheduling (F-PID-GS) control technique, which has been proved to be effective in obtaining better performance. The True Time toolbox is used to establish the simulation model of the NCS. Ethernet as a communication network is simulated for different load conditions and random packet loss. The design approach is tested on a second order stepper motor. The results obtained show the effectiveness of the proposed approach in improving the overall system performance.

Keywords: Fuzzy logic, Gain scheduling, NCS, PID controller, True Time toolbox.

Introduction:

The traditional control system architecture is point-to-point control architecture, where the controller device is directly connected with the controlled system (plant). This control system scheme is no longer suitable to meet new requirements, such as modularity, decentralization of control, integrated diagnostics, quick and easy maintenance and low cost[1]. Networked Control System (NCS) is one type of distributed control system where the control loops are closed over a communication network [2]). NCS is closed loop control systems in which different devices (sensor, actuator, and controller) are connected by means of a shared communication network. NCS has become more and more common as the hardware devices for networks and network nodes have become cheaper. For many years now, general data networks are successfully applied in many industrial and military control applications [3]. The main reasons for using data networks for transmissions of control system signals (instead of using special control networks) are ease of installation, less system complexity by reducing system wiring, ease of system diagnosis and maintenance, and increased system agility [4].

NCS introduces the so-called “communication constraints” to the conventional control system, which includes the network-induced delay, packet dropout, and the synchronization issue. The delayed packets in NCS may be more harmful to system stability than packet loss [5,6]. Besides the effect of the imperfect communication channel, which resulted in delayed control packets and degradation in the performance of overall control system, many other challenges must maintain a tradeoff between two important aspects for NCS: Quality of Service (QoS) of network and Quality of Performance (QoP) of control.

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The well-known Proportional Integral Derivative (PID) controller is the most common way of using a feedback control system. PID controllers are commonly used, over 95% of the controllers in industrial applications are PID controller [7].

The Gain Scheduling (GS) concept can make the delay-independent controller, such as a PID controller, to be a delay-dependent controller by adjusting the controller parameters continuously based on the current time delay. When using GS, the time delay (the scheduling variable) values are first measured or estimated with different NCS conditions and discrete operating points, the time delay values arranged by partitioning it into certain groups, and then obtain the controller tunable gains for each group. The controller gains will be constant within each region or group.

The work in [8] proposes the use of Fuzzy Logic (FL) methodology within NCS instead of using the conventional control methodologies. The basic idea of using FL in control of systems is to use a machine on the fuzzy model for system control instead of a person, it is a computer numerical control method based on fuzzy set theory, fuzzy language variables and fuzzy reasoning. FL control belongs to a non-linear control and intelligent control, it is especially useful when the mathematical models of the controlled object are unknown or quite complex [9]. The FL rules are established based on knowledge and human's experience.

The contributions of this paper are listed below:

- A new Fuzzy PID-like Gain Scheduling (F-PID-GS) controller is designed.
- The random variable delay is predicted to control signal.
- F-PID-GS controller has the capability to withstand against packet loss up to 20%.

NCS Platform

In order to test the designed F-PID-GS controller algorithm over a communication network, a complete NCS model should be designed. The effect of different communication network parameters and computation parameters on the control system performance could be further studied and analyzed. The used NCS platform is taken from our recent paper [10], which is built on using MATLAB and TrueTime toolbox [11]. Figure-1 shows the designed NCS model. As described in [10], the local side consists of a time-based sensor and an event-based actuator. Both sensor and actuator assumed to have a shared local memory and clock, and both connected with the plant directly by A/D and D/A input and output ports.

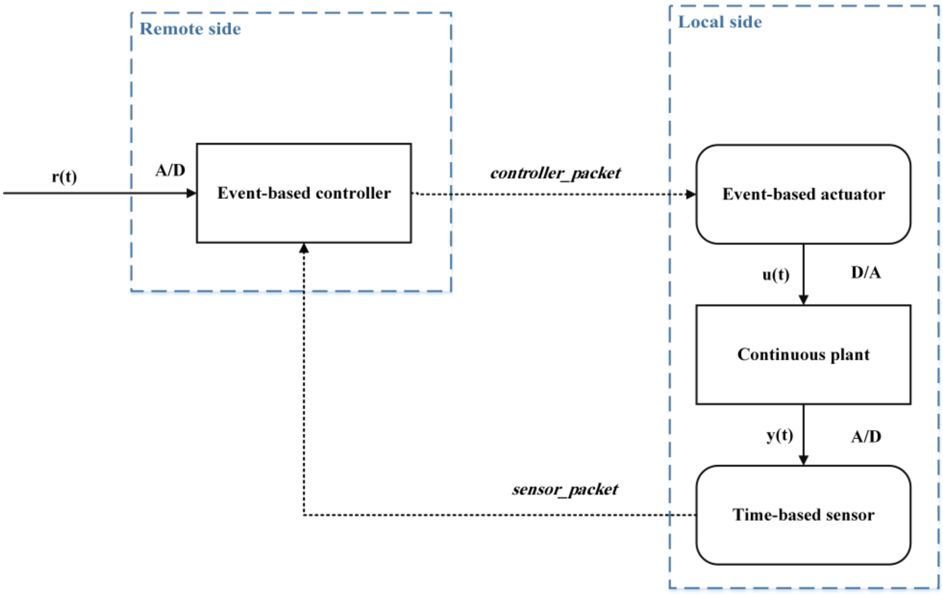


Figure 1-The designed NCS model.

The remote side consists of an event-based controller connected with reference input via A/D input port and will be used to implement the designed controller algorithms. In this structure, there is no need for clock synchronization between controller and sensor nodes, which relief the network from additional packets needed for synchronization and that lead to better QoS of the network. Sensor and actuator are responsible for calculating the RTT value and send it to the controller node within the sensor packet.

The algorithm of F-PID-GS Controller

The proposed F-PID-GS controller consists of two main parts. The first part is used for adjusting or manipulating the inputs and outputs of the second part by using scaling factors as multiplying gains.

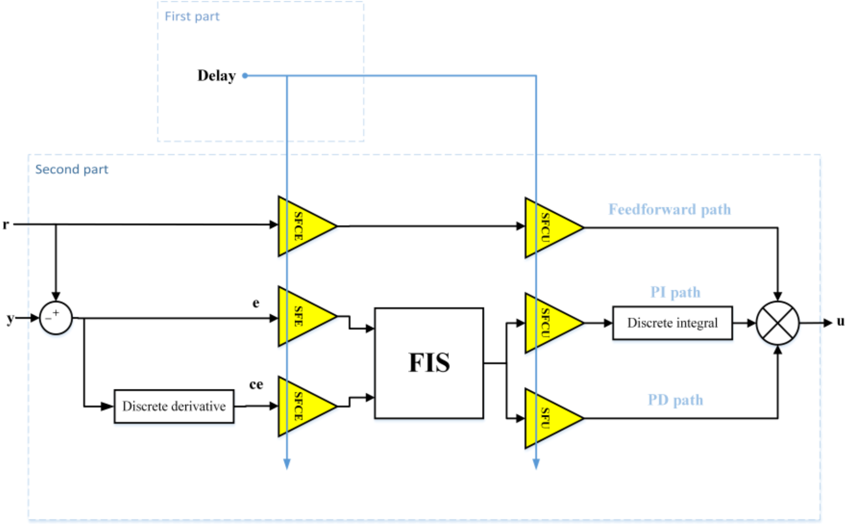


Figure 2-Structure of the F-PID-GS controllers

F-PID-GS controller is shown in Figure-2, the first upper part will choose the appropriate scaling factors based on the time delay (RTT), and these scaling factors will be used in the second part. The second part of the proposed controller is divided into three paths:

Feed forward, fuzzy PI control, and fuzzy PD control. The scaling factors are used for mapping the inputs and the outputs values of the second part, this mapping means moving values between different sets but within their Universe of Discourse (UoD). The used scaling factors are: scaling factor of error (SFE), scaling factor of change of error (SFCE), scaling factor of the control signal (SFU), and scaling factor of change of control signal (SFCU). The second part is a Fuzzy-PID like (F-PID) controller. The final F-PID is a nonlinear 2-Degree-of-Freedom (2-DoF) controller.

The important procedure is how to determine the FL gains (or the scaling factors): SFE, SFCE, SFU, and SFCU. They are obtained from the conventional PID controller parameters (K_p,K_i, and K_d). By comparing the expressions of PID and F-PID controllers, it is found that they are related by:

$$K_p = (\mathrm{SFCU} \times \mathrm{SFCE}) + (\mathrm{SFU} \times \mathrm{SFE}) \quad (1)$$

$$K_i = \mathrm{SFCU} \times \mathrm{SFE} \quad (2)$$

$$K_d = \mathrm{SFU} \times \mathrm{SFCE} \quad (3)$$

The designation of a fuzzy inference system consists of [12] input variables with triangular membership functions as shown in Figures –(3 and 4), and output variable with a singleton membership function as shown in Figure-5. Fuzzy control rule table, as in Table-1, shows the controller rule base.

F-PID-GS Controller evaluation

Ethernet network with 500 connected nodes and 10 Mbps data rate is used as the communication medium for the NCS. By applying different network traffic scenarios, as described in our recent paper [10]. A stepper motor is chosen here as a plant case study, with the following transfer function:

$$G(s) = \frac{1000}{s^2+3s} \quad (4)$$

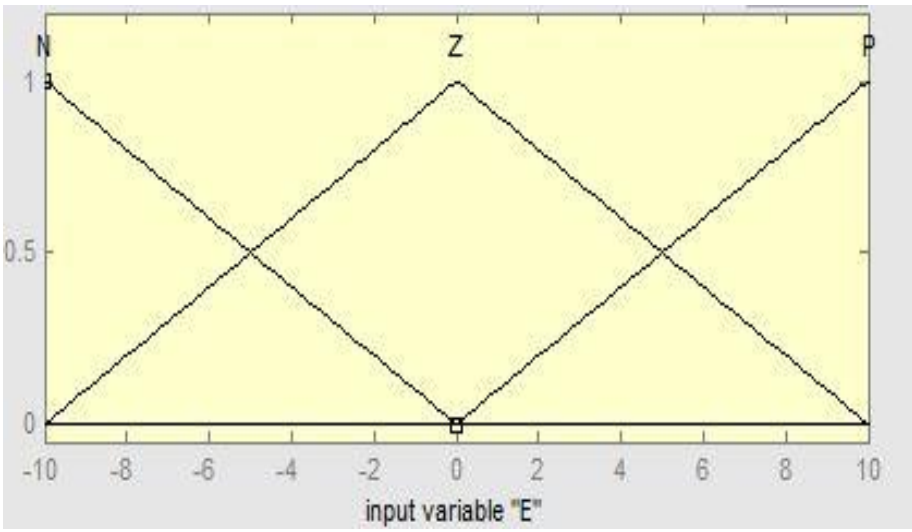
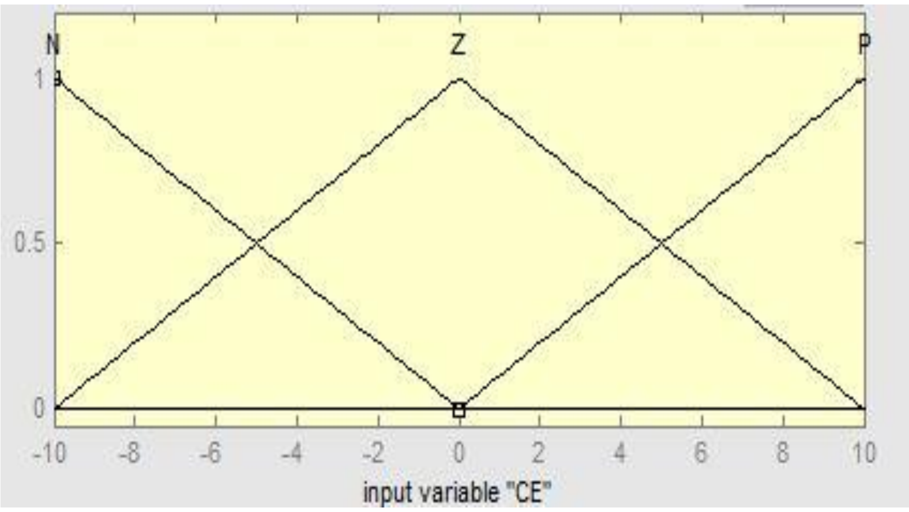


Figure 3-The input membership function of error E



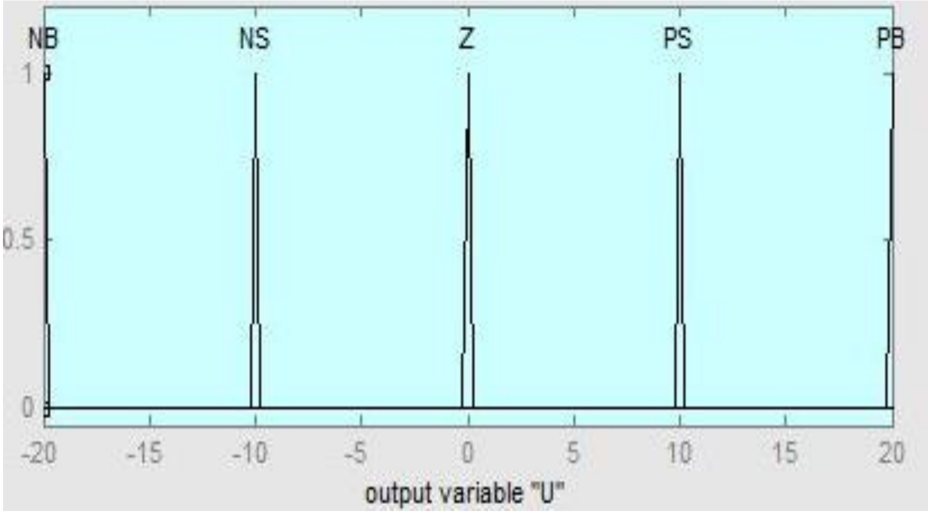


Figure 4-The input membership function of change of error E

Figure 5-Output membership function of output control signal U

Table 1-Controller Fuzzy Rules

CE \ E	N	Z	P
N	**NB**	**NS**	**Z**
Z	**NS**	**Z**	**PS**
P	**Z**	**PS**	**PB**

The sampling time for the sensor T_s is taken to be 0.05 sec. It is chosen to be convenient for both QoS of the network and QoP of the controller. Throughout the simulation, it is found that the minimum and maximum round trip time RTT are equal to 5.615 ms, and 1 sec respectively.

Because the sensor and actuator are responsible for the RTT calculation, the controller node will receive an old value of RTT within the received sensor packet. Therefore, a time series Moving Average (MA) forecasting technique will be used to give a predication of the next RTT value, or a Forecasted RTT (FRTT). The technique of using an MA is described in our paper [10.

The FRTT values were divided equally into six groups:

1. Group one: (0.005 $\leq$ FRTT $<$ (0.1
2. Group two: (0.1 $\leq$ FRTT $<$ (0.2
3. Group three: (0.2 $\leq$ FRTT $<$ (0.3
4. Group four: (0.3 $\leq$ FRTT $<$ (0.4
5. Group five: (0.4 $\leq$ FRTT $<$ (0.5
6. Group six: (0.5 $\leq$ FRTT $<$ 0.6 and more)

To obtain the scaling factors values for each group, the PID gains are calculated first. The *pidtune* MATLAB function is used to give K_p,K_i, and K_d values for the median value for each FRTT group. By fixing SFE at 10 because the maximum error is equal to one (assumes a square wave input with amplitude equal to one).

Table 2**.** shows the obtained PID gains and the corresponding scaling factor values. This table is stored as a lookup table within the local memory of controthe the ller node. The working procedure of F-PID-GS controller is as follow: when a sensor packet is received, the RTT value is examined and MA technique is applied to obtain the FRTT, the lookup table is searched to find for which group this FRTT value belongs, then scaling factors for the corresponding group is retrieved. The second part of the controller (F-PID) is then implemented.

Table 2-PID gains and corresponding scaling factors

Parameter \ FRTT	K_p	K_i	K_d	SFE	SFCE	SFU	SFCU
0.05	**19.62**$\times 10^{-3}$	**9.406**$\times 10^{-4}$	**5.172**$\times 10^{-3}$	**10**	**2.669**	**0.002**	**9.406** $\times 10^{-5}$
0.15	**5.712**$\times 10^{-3}$	**9.739**$\times 10^{-5}$	**1.514**$\times 10^{-3}$	**10**	**2.664**	**5.686** $\times 10^{-4}$	**9.739** $\times 10^{-6}$
0.25	**4.585**$\times 10^{-3}$	**6.048**$\times 10^{-5}$	**1.218**$\times 10^{-3}$	**10**	**2.666**	**4.569** $\times 10^{-4}$	**6.048** $\times 10^{-6}$
0.35	**3.768**$\times 10^{-3}$	**4.045**$\times 10^{-5}$	**1.068**$\times 10^{-3}$	**10**	**2.844**	**3.757** $\times 10^{-4}$	**4.046** $\times 10^{-6}$
0.45	**3.145**$\times 10^{-3}$	**2.858**$\times 10^{-5}$	**9.800**$\times 10^{-4}$	**10**	**3.124**	**3.137**	**2.858**

						$\times 10^{-4}$	$\times 10^{-8}$
0.55	**2.746**$\times 10^{-3}$	**2.203**$\times 10^{-3}$	**9.605**$\times 10^{-4}$	**10**	**3.506**	**2.739** $\times 10^{-4}$	**2.203** $\times 10^{-8}$

Where f is the fuzzy input-output mapping. The response of the NCS with the F-PID-GS controller for 450 sec simulation run is examined, along with control signal for unloaded Ethernet network from 0 to 150 sec, medium loaded Ethernet network from 150 to 300 sec and high loaded Ethernet network from 300 to 450 sec. In order to check the robust stability and performance of the designed F-PID-GS controller, 10% random packet loss is applied to the communication network with the same previously obtained controller parameters. The NCS responses for these tests are shown in Figure-6.

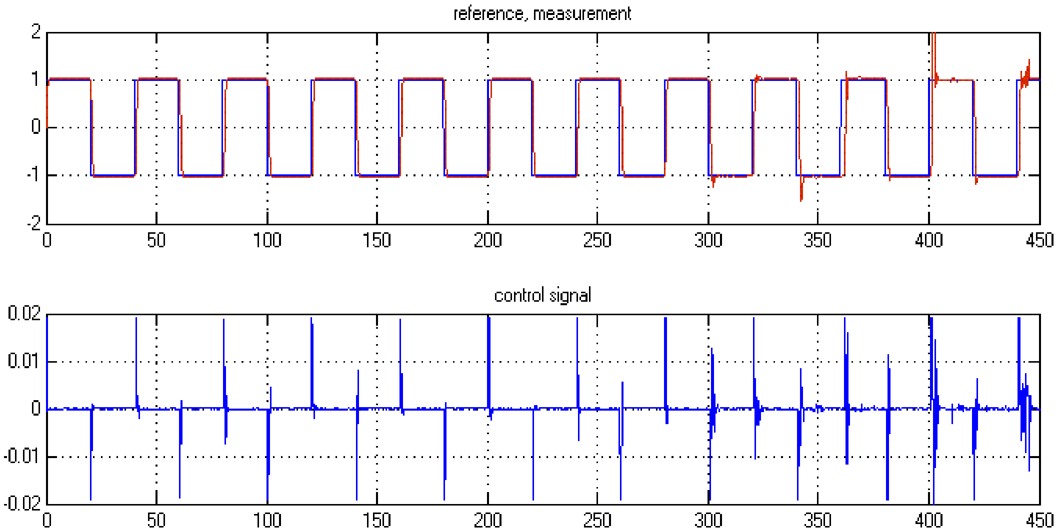


Figure 6-The NCS response along with the control signal for different Ethernet network traffic and 10% packet loss probability using the F-PID-GS controller.

The final control signal of the F-PID-GS controller will be in the form:

$$U = [SFCE \times SFCU \times r(t)] + \left[\sum_{t_k} SFCU \times f(SFE \times E, SFCE \times CE) \times T_s\right] + [SFU \times f(SFE \times E, SFCE \times CE)] \quad (5)$$

Conclusion

The time delay as the main issue of NCS is studied and analyzed for a DC motor system. The time delay was varied by changing the network traffic load. According to the estimated delay and the calculated actual network delay at each sample, the equivalent fuzzy control was developed based on the delay class and the best PID tuned parameters at each class. The feasibility and effectiveness of the F-PID-GS control scheme had been proved. F-PID-GS controller shows a good capability to withstand against packet loss up to 20%. The developed strategy outperforms the PID controller designed by previous work (10).

Using the same NCS model, an appropriate solution when a packet is lost will be our future work, as well as implement an F-PID-GS controller for a large-scale network.

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