Design Of Fuzzy Adaptive Proportional Integral Derivative Controller For Networked Control System Using Switched Ethernet Network

Mberede Pearl Obianuju*, Chidiebele C. Udeze, Akpeghagha Oghenevwaire
Department of Electronic Engineering, University of Nigeria
Email: mberedealexxy@gmail.com; chidiebele.udeze@unn.edu.ng
akpeghagha.oghenevwaire.pg02690@unn.edu.ng

Abstract: One of the major concerns in networked control system is networked-induced delay. The real-time industrial network, often referred to as fieldbus, is an important element for building automated manufacturing systems. Thus, in order to satisfy the real-time requirements fieldbus protocols were developed. These fieldbus protocols have an important advantage over the widely used Ethernet in terms of their deterministic behavior. However, the application of fieldbuses has been limited because of the high cost of hardware and the difficulty in interfacing them with multivendor products, as a result led to further improvement of Ethernet to switched Ethernet. The use of the 100M Switched Ethernet technology is more efficient when the real-time process shares the same medium with other applications due to its large bandwidth. This research work is focused on delay compensation in 100M switched Ethernet using a fuzzy adaptive Proportional Integral Derivative (PID) controller for Networked control system, with the aim of making it more deterministic. The result obtained from this simulation of fuzzy adaptive PID controller was compared to PID and Fuzzy_PID controllers. MATLAB/Simulink was employed in the system implementation of the model. The result however, showed that the signal of Fuzzy adaptive PID had no overshoot and lesser settling time, which indicates more stability.

Keywords: *NCS- Networked Control System, PID Controller, Fuzzy, 100M Switched Ethernet, MATLAB/Simulink*

I. INTRODUCTION

A Networked Control Systems (NCS) is a system that contains a large number of interconnected control devices that exchange data through communication networks; examples of application areas include industrial and building automation, office and home automation, intelligent vehicle and transportation systems, and advanced aircraft and spacecraft, among other automate d systems. NCS provide several advantages such as modular and flexible system design (e.g., distributed processing and interoperability), simple and fast implementation (e.g., small volume of wiring and powerful easy-to-use configuration tools), and powerful system diagnosis and maintenance utilities. However, the combination of sensors, controllers, and actuators with communication networks also makes the analysis and design of NCS a complex task, because it requires the integration and good understanding of several disciplines including control systems, communications systems, and real-time systems (Gupta & Chow, 2010).

Computer networks and communication systems present rich and sophisticated models of varying degrees of complexity, also the problem of stabilizing queue lengths, for example, is of secondary importance. Integrating computer networks into control systems to replace the traditional point-to-point wiring has enormous advantages, including lower cost, reduced weight and power, simpler installation and maintenance, and higher reliability, within stochastic and deterministic settings, and of various underlying physical communication media (Fuertes & Fohler, 2005).

Basically, majority of computer networks described in the primary challenge on the exchange of data between nodes is that the respective channels are exclusive. This means that the attempt of more than one node to transmit data at a given time will result in data loss, i.e., a collision. Collisions can be prevented by arbitration of network access through the use of scheduling protocols that decide which node(s) can transmit and at what time.

II. RELATED WORKS

Several works have been done in the research area of networked control system. However, one of the major concerns in networked control system is networked-induced delay and packet dropout, which is frequently the main concern for the decline of system performance and potential system instability. The network can introduce unreliable/non-deterministic levels of service in terms of delays, jitter, and losses(B. Singh & Mishra, 2015). Author in (Gupta & Chow, 2010) stated in time- sensitive NCSs, if the delay time exceeds the specified tolerable time limit, the plant or the device can either be damaged or have a degraded performance. Time-sensitive applications can be either hard real time or soft real time. Author in (Grimholt & Skogestad, 2018) specified that time delays are found in most industrial processes.

Authors in (K. Sato, H. Nakada, 1988) explored some techniques for network delay analysis which was based on the fact that, in the network, the information can be efficiently integrated and transported by maximizing the use of the busty information flow, store and forward process at the transport nodes. Later, Wu et al (J. Wu, F.-Q. Deng, 2005), modelled and analysed the stability of NCSs with long random delay.

In (H. Ye, 2004), the influence of networked-induced delay on conventional observer based fault detection systems was first investigated. However, the method could not meet the requirements for effective residual information. To solve this problem, Zhang et al (W. Zhang, M. S. Branicky, 2001), presented that if the unknown network-induced delay is less than the sampling period, an NCS with disturbance and fault can be regarded as the NCS without delay.

Consequently, for the random network-induced delay, two main research methods are adopted in NCS design, the deterministic method and the stochastic method. The deterministic method is to convert the random delay to fixed delay by introducing data buffer, then use the existing method to design the controller(Z. X. Yu, H. T. Chen, 2002). However, this approach artificially extends the random delay of the controller, and lowers the system control performance. Bauer uses Smith predictor to compensate time delay in the networked control system, the control structure is simple, but it is necessary to know the exact value of the network delay in advance(P. H. Bauer, M. Sichitiu, 2001). Since the Smith compensator is based on the accurate mathematical model of controlled object and network delay, random network-induced delay and disturbances makes the model with Smith compensator mismatches with controlled object. Following the reasons stated above, it is difficult to get better effect to compensate network delay only utilizing smith compensator. In order to overcome the impacts of those factors, it is necessary to introduce effective means of control. Some researchers have presented many improved methods including two aspects of structural improvement(Watanabe, 1981) and parameter tuning(J. J. Liu, W. M. Ni, 1999). PID networked control system based on TrueTime is designed by combining the fuzzy control rules and PID controller. Take the typical second-order inertia plant in the process of industrial production as an example, and through the simulation study of changing parameters and transmission rates, increasing network delay, the feasibility and effectiveness of the control scheme had been proved.(Peng et al., 2014)

Author in (M. Singh, 2017) proposed fuzzy adaptive PID shows the best dynamic performance but didn't solve the problem like time delay, however stated it solve the problem of time delay.

C. Grimholt et al, presented the assumption of a smith predicator been better in terms of processes with large time delays when compared with PI and PID controller was mere myth and the narrative changed. The author proved that, for a given robustness level in terms of the peak sensitivity (Ms), performance improvement with the Smith predictor is small even for a pure time delay process. For other first-order processes a PID controller is generally better for a given robustness level. In addition, the Smith Predictor is much more sensitive to time delay errors than pi and PID controllers(Grimholt & Skogestad, 2018).

Scheduling method was also proposed in other to solve the problem of delay in networked control system. Kim et al. (D. S. Kim, D. H. Choi, 2009) proposed obtaining a maximum allowable delay bound for the scheduling of networked discrete control systems. Also Lian et al. (F. L. Lian, J.Moyne, 2002) who studied the key components of time delay to provide guidelines for obtaining the optimal working range of sampling times. Walsh et al. (G.C.Walsh, H.Ye, 2002) introduced a novel control network protocol, try-once-discard (TOD), for multiple-input-multiple-output NCSs. But these works did not consider the use of switched Ethernet in an NCS. According to Li. Ming sin (Li, 2014a), stated the feasibility and superiority of a NCS based on 100M switched Ethernet which was proved in (Li, 2014a), concluded that this class of the NCSs can be widely used in the fields of industrial automation

III. DELAY IN 10M, 100M SWITCHED ETHERNET AND CAN NETWORK.

Delay caused by a networked communication in NCS is called networked induced delay. The delay of a NCS is actually induced in the communication process when the data are transmitted from one node to other nodes. The delay induced by control networks may be constant, time-variant, or random. Following the comparative analysis done in (Asif, 2015) which describe performance of the control systems under different network environments, 10M switched Ethernet, CAN fieldbus, and non-network environment. The result showed that we can find the performance of the NCS based on single-level 100M switched Ethernet very similar to that of the non-networked control system, and their performances are better than those of the NCS based on 10M switched Ethernet and CAN fieldbus.

IV. DESIGN OF MODEL

1. Block diagram of model

In other to demonstrate delay compensation in NCS using 100M switched Ethernet, the model in the Truetime NCSs in-built model is used. Figure 1, shows the block diagram of the model. The speed of the plant is sampled using a sensor and the data is processed and sent to the controller through the network. The controller computes the control amount and sends the resulting signal to the actuator, where it is subsequently implemented. The interference node produces both non- periodic and periodic signals, and this influences the load on the network traffic.

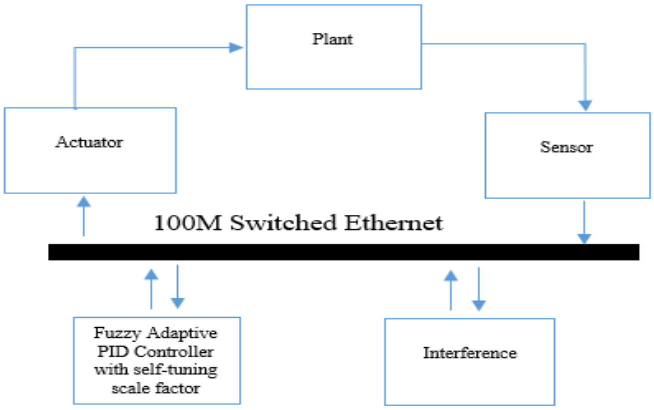

Figure 1: The block diagram of the model

The control system of this model is a co-design controller of fuzzy adaptive PID controller, the adaptive controller is made up of a set of fuzzy rules that attach to the classic PID controller.

2. Model Of Fuzzy Adaptive PID Controller On MATLAB

Figure 2 shows the Fuzzy Adaptive PID Controller built in model by Truetime kernel in the environment of Matlab/ Simulink

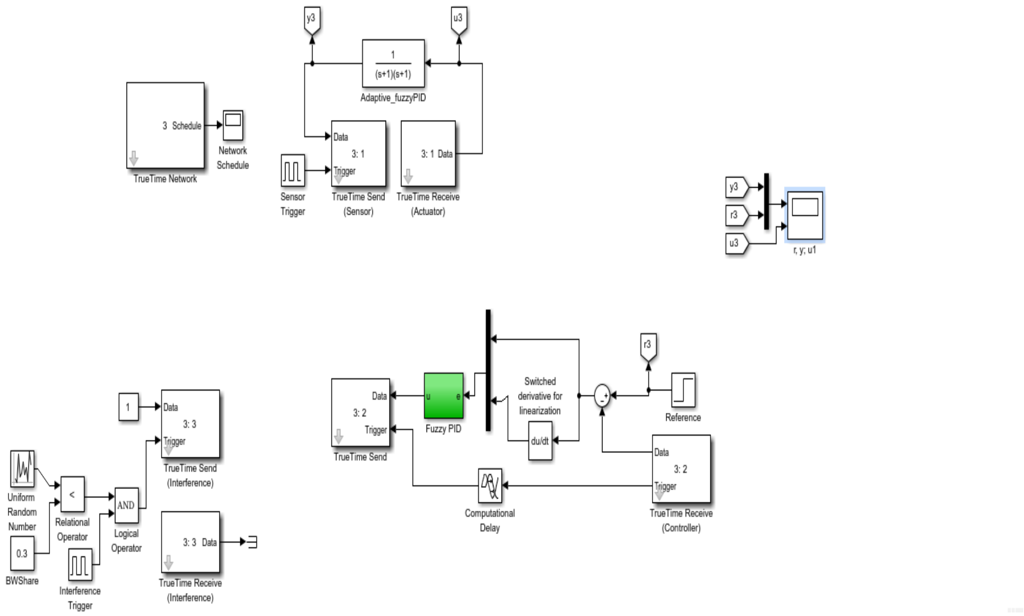

Figure 2: Fuzzy adaptive PID Controller

3. Controller Component

(a) PID (Proportional Integral Derivative)

Proportional integral derivative controller (PID controller) is a control loop feedback mechanism commonly used in industrial control system. The PID controller continuously calculates an error value as a difference between measured process variable and desired set points, the controller attempts to minimize the error over time by adjustment of controlled variable, such as position of control value, a damper or the power supplied to the heating element.(M. Singh, n.d.)

The transfer function for a second order plant was used, which represents a process with second order dynamics with time delay (Pelusi & Mascella, 2013). This is given below:

$$H(s) = \frac{1}{(s+1)(s+1)} \qquad (1)$$

$$G_C[s] = K_p + K_i/s + K_d s \qquad (2)$$

Where the proportional, integral and derivative gains are represented by K_p, K_i, amnd K_d, respectively. The PID transfer function can also be written as:

$$G_C[s] = K_p|1 + 1/|T_i s| + T_d s| \qquad (3)$$

In Eqn. 3.2, the integral and derivative time constants are respectively represented by T_i and T_d. These terms are related as:

$$T_i = \frac{K_p}{K_i} \qquad (4)$$

$$T_d = \frac{K_d}{K_P} \qquad (5)$$

Furthermore, the expression for discrete-time equivalent of a PID control is represented as:

$$u(k) = K_P e(k) + K_i . T_s \sum_{i=1}^{n} |e(i)| + \frac{K_d}{T_s} \Delta e(k) \qquad (6)$$

The control signal is represented with $u(k)$, while the error, which results due to the difference between reference, and the process output is represented by $e(k)$. The controller sampling period is T_s.

The error, which results due to the difference between the reference and the process output, can be approximated as:

$$\Delta e(k) = e(k) - e(k-1) \qquad (7)$$

The measure by which a PID controller samples the error fed from a process is greatly dependent on the manipulation of the parameters K_P, K_i and K_d. Accordingly, establishing optimum values of these parameters is important.

(b) Fuzzy Logic Controller

Fuzzy logic controllers have logical resemblance to a human operator. It operates on the foundations of a knowledge base which in turn rely upon the various if then rules, similar to a human operator. Fuzzy logic controller is simpler as compared to other controller because there is no complex mathematical knowledge required. The FLC requires only a qualitative knowledge of the system thereby making the controller not only easy to use, but also easy to design(Li, 2014)

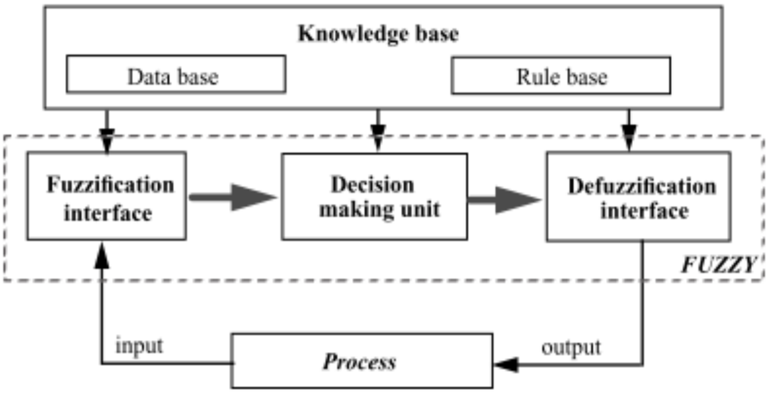

Figure 3: General structure of fuzzy inference system

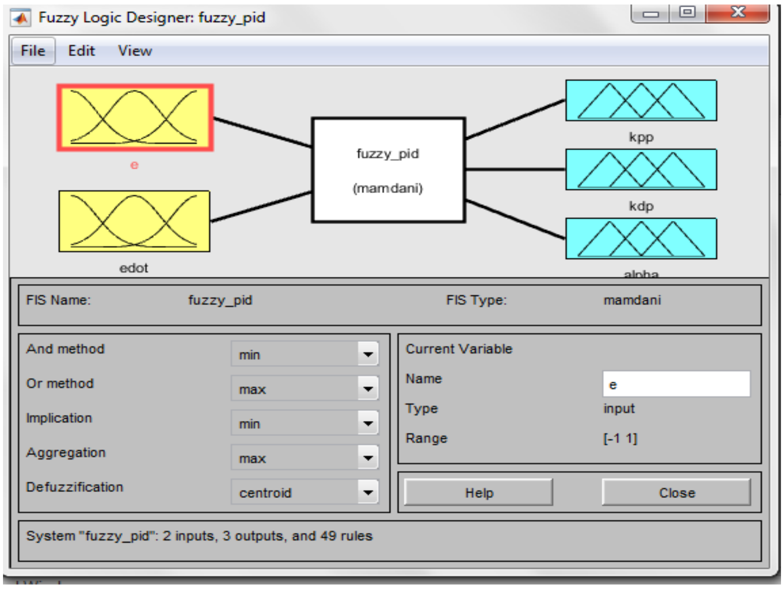

Fig 4: FIS (Fuzzy Inference System)

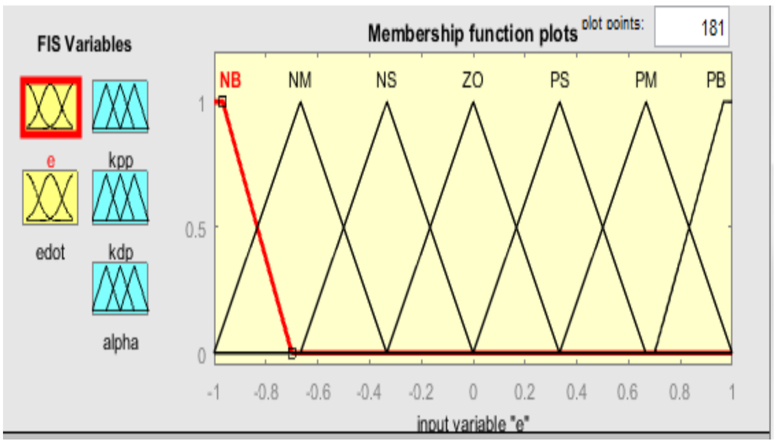

Fig 5: Membership function

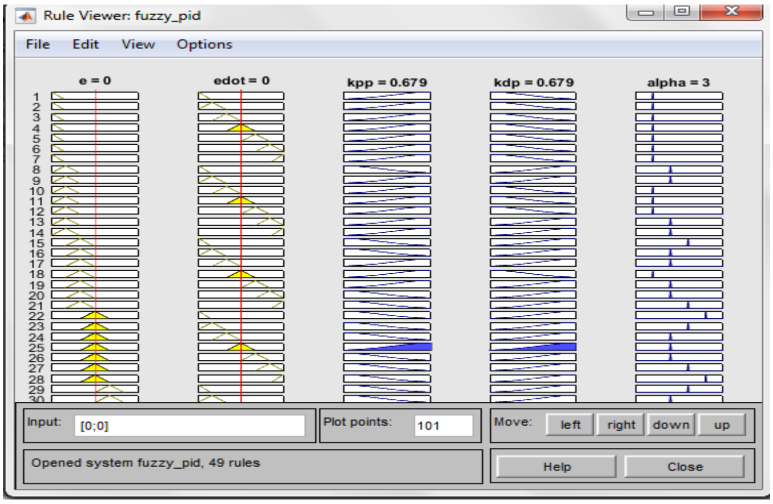

Figure 6: Fuzzy_PID rule

Fuzzy adaptive PID control algorithm, whose inputs are error and error rate, and the output, is the three changing values of PID parameters. This kind of algorithm realize self-adjusting by changing PID parameters on-line according to fuzzy reasoning made by fuzzy control rules, then the modified PID parameters are taken to conventional PID so as to improve control performance of control system.(Peng et al., 2014)

V. MITIIGATING THE DELAY IN 100M-SWITCHED ETHERNET NCS

The authors in (Li, 2014) has shown that the delay introduced by the 100m Switched Ethernet may degrade the performance of the NCS and also carried out a proper analysis on the key factors that affect the upper bound delay of a 100M Switched Ethernet. Although, the author demonstrated the feasibility and superiority of 100M-switched Ethernet based NCSs without modification of the network protocols. Nevertheless, for future application areas of the 100M-switched Ethernet NCS, the need may arise to mitigate the influence of delay on the performance of the system. Several techniques have been employed to mitigate the influence of delay in NCS. We have designed and implement an adaptive fuzzy tuned PID controller with a self-tuning scale factor. An analysis of our result is shown in the following sections.

VII. SIMULATION RESULTS AND ANALYSIS

This simulation wasn't done on an ideal condition; an interference of 30% was introduced to the model indicating the network was shared with other appliance. A sampling period of 0.007 was used. In the simulation the following should be noted:

r= Reference; e= Error; u= Input signal (sampled signals from the initial state of the plant); y=Output Simulation run time= 20 secs; Network block loss probability= 0

Computational delay = 0.002 secs.

1. Result presentation of PID Controller

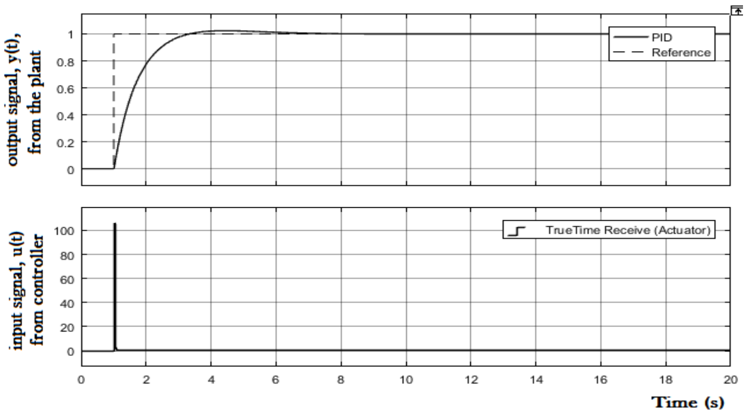

Figure 7: Simulation result for PID controller graph

2. Fuzzy_PID Controller

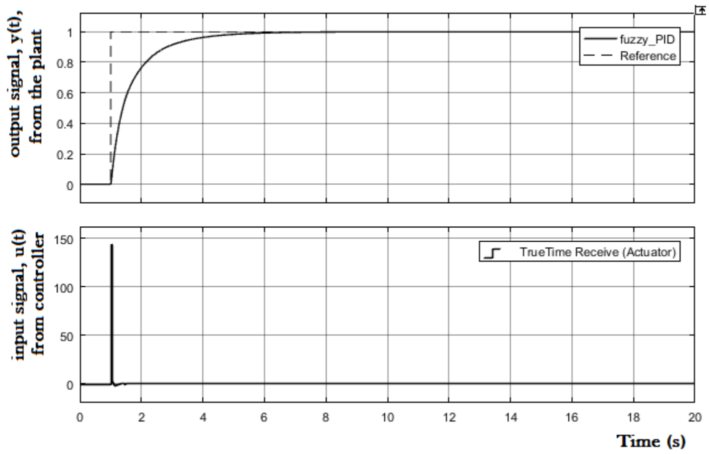

Figure 8: Simulation result for Fuzzy_PID controller

3. Fuzzy adaptive PID with self tuning scale factor

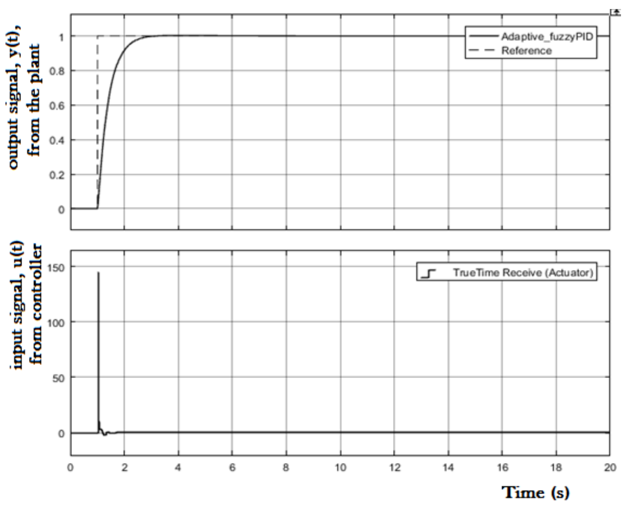

Figure 9 : Simulation result for Fuzzy Adaptive PID controller with self tuning scale factor

4. Result Analysis

PID controller, Fuzzy_PID controller and Fuzzy adaptive PID controller with self-tuning scale factor were simulated with 30% interference and sampling period of 0.007 seconds and a simulation time of 20 seconds. The simulation results for the PID controller, Fuzzy PID controller and the adaptive Fuzzy PID controller is shown in Fig 7 - 9 respectively. For each of the result we attached the output from the controller to the plant, u(t). The three results were combined in a single graph in Fig 11.

From the simulation result shown in Fig 11, we have been able to put the outputs of the different controllers under study together. We thereafter made our comparison based on the peak overshoot, undershoot, settling time and the rise time of the different outputs obtained.

In terms of the peak overshoot, the Fuzzy PID controller and the Adaptive Fuzzy PID controllers performed better than the PID controller as its output signals did not move above the set reference signal. Here, we see a good performance in our proposed controller design as it was more inclined to the reference signal than the other controllers.

The undershoot of the Fuzzy PID controller was more compared to the PID controller and Fuzzy Adaptive PID controller. Considering the undershoot of the different output signals we can clearly see the adaptive Fuzzy PID controller having a better performance as it was more inclined to the reference signal.

5. Parameterization of the 2nd Order Step Response

In order to carry out a proper analysis of our result with respect to the desired step response, we chose a set of meaningful parameters that define the behavior of the response. The most commonly chosen parameters are shown in figure (b) below:

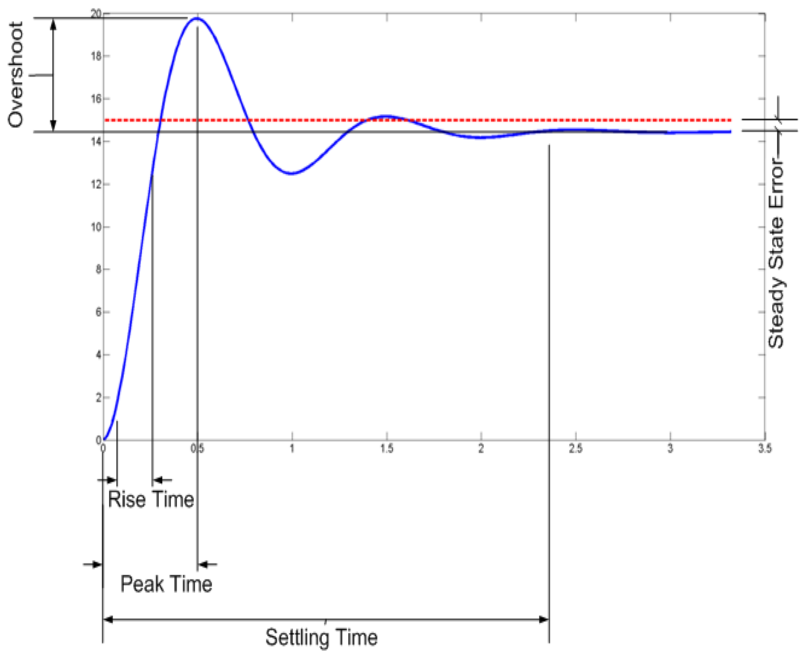

Figure 10: A typical step response for a 2nd order system with complex poles and no finite zeros.

(a) Rise Time (t_r) – The time taken for the output to go from 10% to 90% of the final value.

(b) Peak Time (t_p) – The time taken for the output to reach its maximum value.
(c) Overshoot – (max value – final value)/final value x 100.
(d) Settling Time (t_s) – The time taken for the signal to be bounded to within a tolerance of x% of the steady state value.
(e) Steady State Error e_{ss} – The difference between the input step value (dashed line) and the final value.

6. Comparative graph of The Different Simulation Result

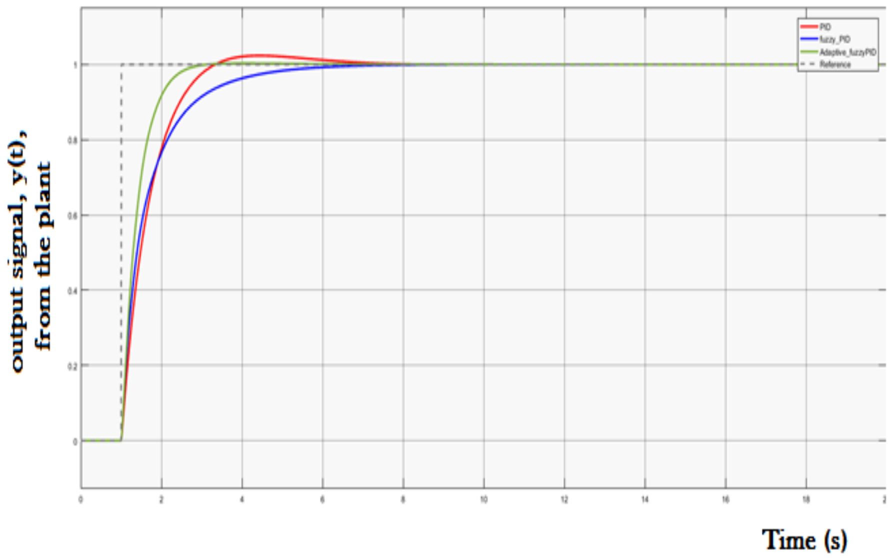

Figure 11: comparative graph of the different simulation results

Table A below gives a proper analysis of the result of the simulation done in this research work, an analysis of the parameters discussed in Figure # is presented and discussed.

Table 1: Result Presntation

Parameters	**PID**	**Fuzzy_PID**	**Fuzzy Adaptive PID**
Rise Time (t_r)	1.368 secs	1.723 secs	862.822 ms
Peak Time (t_p)	3.436 secs	12.71 secs	3.021 secs
Overshoot	2.577%	0.471%	0.505%
Settling Time (t_s)	6.536 secs	6.769 secs	1.997 secs
Steady State Error e_{ss}	0%	15.0 x 10^{-8} % (~0%)	4.0 x 10^{-8} % (~0%)

From Table 1, the various parameter evaluated shows the superiority of the approach presented in this research work. For an optimal control each of the parameter presented must be reduced to the barest minimum. Generally, the fuzzy adaptive PID presented in this work demonstrated good performance except for the area of peak overshoot where the Fuzzy PID outperformed it.

VIII. CONCLUSION

The obtained results obtained, the adaptive fuzzy PID controller is seen to demonstrate a better rise time when compared to the other controllers as it was more inclined to the vertical line of the reference signal, this is a clear indicator of its stability, that is, the adaptive fuzzy PID controller presents more stability compared to PID and Fuzzy_PID controller . An important performance goal, which has received increasing attention in the recent literature, is robustness with respect to time variability of channel capacity of feedback channel. The use of 100m-ethernet technology is more efficient when real-time process shares the same medium with other application due to its large bandwidth.

IX. CONTRIBUTIONS

The implication of this result for the 100M-switched Ethernet follows that great improvement and optimization can be achieved in the performance of 100M-switched Ethernet NCS applications. Also, the research has been able to demonstrate a technique that can be employed across the field of NCS to mitigate the effect of delay introduced by the use of communication network in an NCS architecture even for future applications that may require better Quality of Control.

X. RECOMMENDATION

A research focus should be on enhancing the deterministic nature of switched ethernet, as it provides a robust network.

Scheduling in 100M-switched ethernet: In other to improve the deterministic nature of switched ethernet, priority scheduling should be analyzed and studied.

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