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Delay Compensation Model in 100mbps Switched Ethernet Using Sliding Mode Controller (SMC)

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ABSTRACT: In the realm of networked systems, achieving timely and reliable communication is paramount, particularly in high-speed environments like 100Mbps Switched Ethernet networks. However, inherent delays in communication channels poses significant challenges to maintaining synchronization and real-time data transfer. This paper proposes a novel approach to address communication delay compensation in such networks through the utilization of a Sliding Mode Controller (SMC).

The proposed method leverages the robustness and adaptability of sliding mode control techniques to dynamically adjust transmission parameters and compensate for communication delays. By incorporating the SMC into the network architecture, the system can effectively mitigate the adverse effects of delays, ensuring improved performance in terms of packet delivery, latency reduction, and overall network efficiency.

Through simulation studies and practical implementation, the efficacy of the proposed approach is demonstrated, showing promising results in enhancing the reliability and responsiveness of 100Mbps Switched Ethernet networks. This research contributes to the advancement of communication protocols and control strategies in networked systems, offering a viable solution to address the challenges posed by communication delays in high-speed environments.

KEYWORDS: NCS- Networked Control System, Fuzzy PID Controller, Sliding Mode Controller, 100M Switched Ethernet, MATLAB/Simulink

1. INTRODUCTION

Networked control systems (NCS) are control systems that include a communication network. A NCS is a feedback control system where sensors, controllers and actuators of a discrete controller are separated and arranged on separate computer nodes which are connected by a communication network. At the level of application, NCS aim to overcome the challenges of traditional digital control systems, such as maintenance costs, modifications, vulnerability to electrical noise, and upgrades.

Although this mechanism helps to solve the challenges of traditional digital control systems, it introduces its own problems:

The communication network introduces at times unpredictable delays.

It also brings along the possibility of data or information loss and corruption.

It is still not clear how to separate the algorithms used in the control into parts. Some control systems are not suitable for such separation.

Increasing the delay in the control loop directly results in instability in the control system due to network-induced delays. The loss of data or information is similar in this regard as well. Therefore, research work must be carried out to facilitate the implementation of this type of control implementation.

Network-induced delay and packet dropout are major concerns in networked control systems. These delays and packet dropouts frequently cause system performance to decline and instability to occur.

Real-time industrial network, often referred to as fieldbus are used in NCS for real-time application. 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.

In contemporary networked control systems operating over 100M Switched Ethernet, the pervasive challenge of communication delays has become a critical impediment to system performance.

Therefore, there is need to minimize/reduce the effect of the total delay in the system by compensating for the non-deterministic behaviour of the 100M Switched Ethernet network in other to make it more deterministic by using an optimal controller design.

This research addresses this overarching issue by proposing a novel approach to delay compensation through the application of a sophisticated sliding mode controller.

The current landscape of networked control systems is marred by the deleterious effects of communication delays, leading to suboptimal performance and compromised stability.

2. RELATED WORKS

Networked control systems (NCS) are increasingly prevalent in various applications due to their ability to decentralize control processes and improve system scalability. However, communication delays inherent in networked environments, particularly in Ethernet-based systems, pose significant challenges to maintaining system stability and performance. Also, the integration of control loops within networked control systems can result in delays that may degrade performance and even cause the system to become unstable. Researchers Zhang et al., (2001) have demonstrated that these delays can arise from a multitude of reasons, including data transmission, network congestion, and packet loss. Strong delay compensation strategies are necessary to overcome these issues. Ethernet is a widely used communication protocol in NCS due to its high-speed data transfer capabilities and cost-effectiveness. Nevertheless, the non-deterministic nature of Ethernet introduces variable delays. In their article, Liu and Goldsmith (2004) discuss how delayed signals can have a significant impact on control signal timing and synchronization. The authors emphasize that effective delay management techniques must be utilized in order to address them. Sliding Mode Control (SMC) operates by driving the system states onto a predefined sliding surface and maintaining them on this surface, ensuring desired performance despite the presence of delays. According to Utkin (1992), SMC's robustness makes it effective in dealing with the variable and unpredictable nature of communication delays in Ethernet-based systems. The use of SMC has been investigated in recent studies as a way to compensate for communication delays in NCS. By dynamically adjusting control signals, Gao et al., (2008) demonstrated that SMC effectively counteracted delays in networked environments, thus maintaining system stability and performance. Similarly, Li and Yu (2010) applied SMC to a networked robotic system and reported significant improvements in delay compensation, leading to enhanced system responsiveness and accuracy.

3. METHODOLOGY

Research utilizing Truetime Simulator and MATLAB aims to develop integrated models capable of accurately predicting travel times, traffic flows, A/D and D/A conversion, sending and receiving network messages, setting up timers, changing task attributes and lots more. Truetime Simulator is a robust and versatile tool that can be used in real-time simulation of complex systems.

The Truetime toolbox is a simulation toolbox that is used alongside Matlab/Simulink. It is mostly used to study the influence of communication network delay uncertainty on the performance of control systems and also useful in the simulation of multi-scheduling algorithms. Figure 1 shows the Truetime block library (Cervin, 2016). The Truetime toolbox simulator contains three crucial parts: Truetime kernel (computer, input-output device), Truetime network and a controlled process

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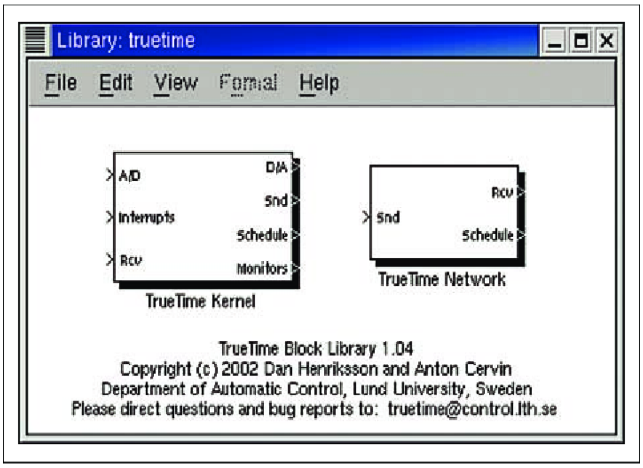

Figure 1: The Truetime Block Library

The blocks are used for the modelling of network-based control systems and can be interfaced in the Matlab/Simulink Environment.

In establishing the behaviour of communication networks, several approaches can be used but two major approaches are the event-based and time-based simulation.

The following steps were used to model in the Truetime Simulator:

i. The init_truetime.m was run to add the necessary Matlab paths and to set the TTKERNEL environment.
ii. Establish real-time networked control system through the Matlab/Simulink and Truetime toolbox.
iii. Configure the Truetime kernel for each node (controller, actuator, etc.).
iv. Set the network parameters such as type of network

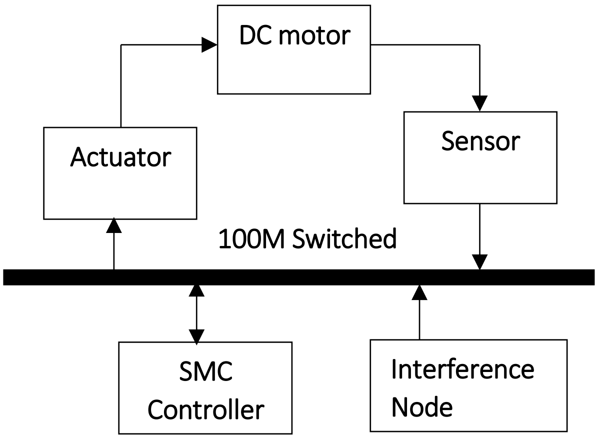

Figure 2: Block Diagram Design for a Standalone NCS

2. Simulation of the Model

Truetime toolbox with Matlab/Simulink 16b using adaptive fuzzy PID controller design, was used for the Simulink design of a NCS model with Fuzzy adaptive PID controller. The diagram below shows the model designed using the TrueTime toolbox with Matlab/Simulink 16b using the proposed sliding mode controller design. Figure 3 show the Integral Sliding Mode Controller implemented in a NCS environment.

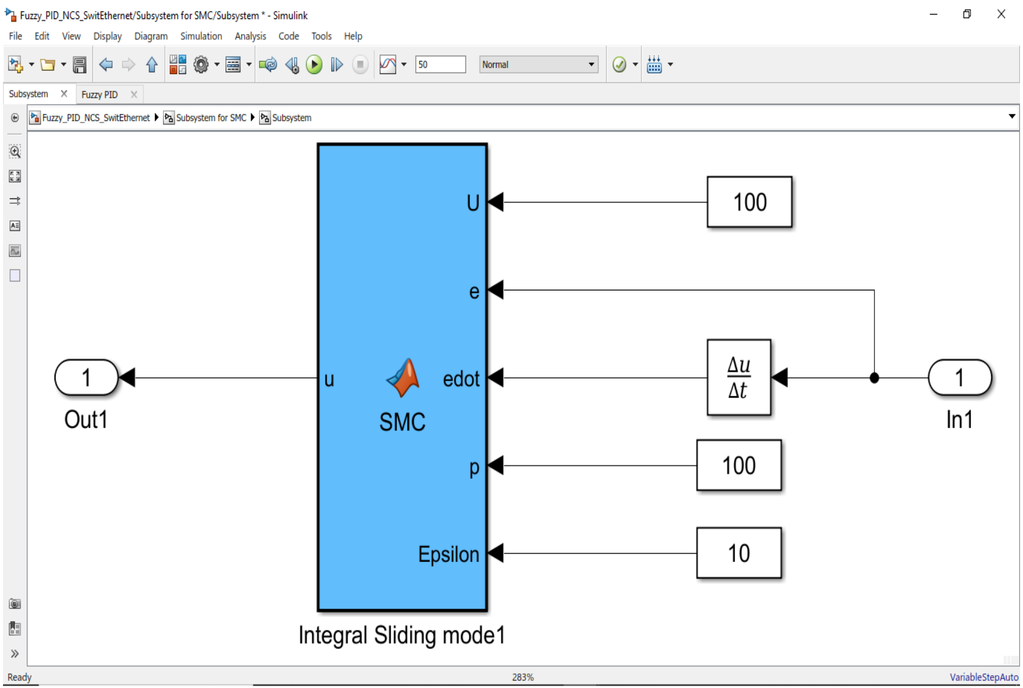

Figure 3: sliding mode controller design

In this model, the sensor nodes samples the plant at periodic intervals configured at the sensor trigger block and sends sampled signals via the network block to the controller node. At the controller node the received signal is conditioned using the SMC controller respectively. The controlled signal is then transmitted back to the actuator node through the network node. The actuator in turn implements this control command to control the plant to the desired reference signal introduced at the controller node. The interference node is used to introduce some amount of traffic in the network to show that the network is used by other applications.

3. Controller Components

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.

A standalone networked control system has been designed in Matlab/Simulink environment with the aid of the Truetime library. The transfer function of two (2) nonlinear plant has been adopted to model and represent the behavioural characteristics of the controlled system. The transfer functions used in this regard are as given below:

$$\text{Plant 1} = \frac{27}{(s+1)(s+3)(s+3)(s+3)} \quad (1)$$

$$\text{Plant 2} = \frac{1}{(s+1)(s+1)} \quad (2)$$

The NCS model was designed using the proposed sliding mode controller for delay compensation and also an equivalent model was also designed for the conventional adaptive fuzzy PID controller for delay compensation. This was done in order to evaluate and validate the performance of the proposed sliding mode controller for delay compensation.

a) PID (Proportional Integral Derivative)

PID control is a widely used control strategy in industrial and engineering applications due to its simplicity and effectiveness in various control scenarios. It combines three distinct control actions: proportional, integral, and derivative, each contributing uniquely to the overall control effort. The PID control consists of proportional, integral, and derivative algorithm, which is based on present, past, and future error, respectively. The proportional (P) control is given by multiplying the error (e) with a constant i.e., proportional gain (K_P).

$$P = K_P * e(t) \quad (3)$$

The proportional control helps reduce the overall error, but may not eliminate it completely, often resulting in a steady-state error. However, the proportional control creates an off-set between the set-point and output, even when the output reaches steady state (i.e., steady state error). To eliminate this off-set, the integral (I) term is added to the algorithm. The integral control is given by multiplying the integral of error after time with a constant i.e., integral gain (K_i).

$$I = K_i * \int e(t)\ dt \quad (4)$$

The integral term eliminates steady-state error but can lead to slow system response and potential overshoot if not properly tuned.

On the other hand, the derivative (D) control is based on rate of change of the error (time derivative of error) i.e., derivative gain (K_d).

$$D = K_d * \frac{det}{dt} \quad (5)$$

Similarly, the derivative term improves system stability and transient response by countering rapid changes in error, thus reducing overshoot and settling time, (Nise, 2015).

As a result, output from integral and derivative control helps the system quickly reach desired set point without large oscillation. Details of PID algorithm and related issues were presented elsewhere, Astrom and Hagglund, (2001); Ang et al., (2005).

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The typical form of representing the overall PID control output is the sum of these three components:

$$u(t) = K_P e(t) + K_i * \int e(t)\ dt + K_d * \frac{det}{dt} \quad (6)$$

Where, u(t) is the control signal, and e(t) is the error at time t.

b) Sliding Mode Controller

A robust control method such as sliding mode control (SMC) is well-suited for maintaining the control of nonlinear or uncertain systems. As a result, it ensures smooth dynamic behavior and robustness against interruptions by driving the system states onto a predefined sliding surface and maintaining them there.

SMC is highly robust against system uncertainties and external disturbances due to its discontinuous control action. Once on the sliding surface, the system is insensitive to matched uncertainties (Slotine & Li, 1991).

Defining the sliding surface is the first step in defining the system's dynamics. When the system states are on this surface, the system exhibits the desired behavior. This can be represented as:

$$s(x) = 0 \quad (7)$$

Where, s(x) is the sliding surface function based on the system states x.

The control law in SMC is designed to drive the system states toward the sliding surface and maintain them on it. This is typically achieved through a discontinuous control action that switches based on the sign of the sliding surface, expressed as:

$$u = u_{eq} + u_n \quad (8)$$

where, u_{eq} is the equivalent control to keep the states on the sliding surface, and u_n is the switching control to drive the states to the surface.

Whereas, the switching control is expressed as:

$$u_n = -K.sgn(s(x)) \quad (9)$$

where K is a positive gain, and sgn(s(x)) is the sign function (Utkin, 1992).

5. SIMULATION RESULTS AND ANALYSIS

The simulation was done under various operating conditions in order to evaluate the performance and efficiency of the proposed controller design.

Three indicators describe the adequacy of the system tuning: rise time, peak time, and overshoot, as shown in figure 4. Rise time (t_r) defines the time taken for the output to go from 10% to 90% of the final value, while Peak Time (tp) refers to the time taken for the output to reach its maximum value. Overshoot quantifies the degree to which the system surpasses the target value

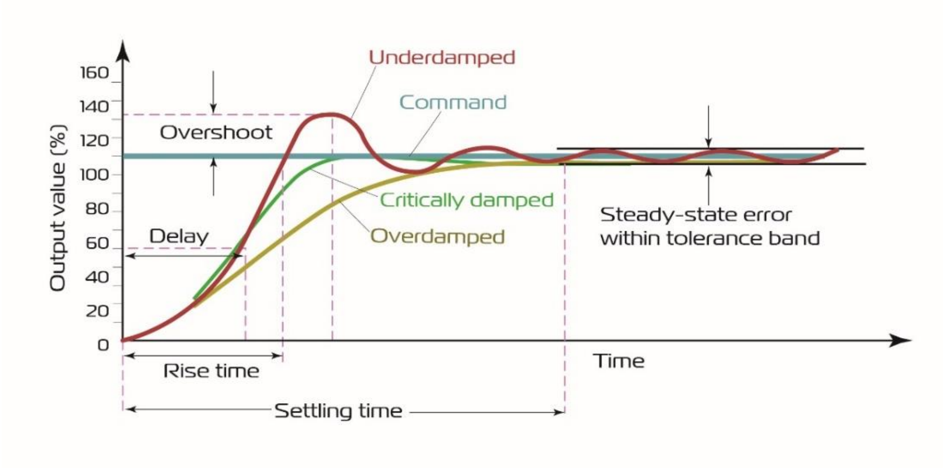

Figure 4. Output Response Specifications and Characterization

No matter the duration of the response or settling process, a system with overshooting or undershooting cannot attain the desired position, velocity, or torque. As a result, the damping ratio provides a measure of how far the system will overshoot or undershoot. Over-damped systems tend to undershoot their targets, creating extended rise times and extended settling times. They ultimately fall short of their target values. The opposite is true for under-damped systems, which tend to overshoot their targets, often resulting in oscillations of protracted rise times and short settling times.

In order to simulate delay performance for the 100M switched Ethernet network, three major parameters are needed, namely (Packet Dropout, Sampling Period, and Network Utility).

1. Result Presentation

According to the output response specifications and characterization shown in Figure 4, the results obtained from the designed model can be readily interpreted and evaluated as shown in figure 5. The simulation was performed to evaluate the effects of network delays and uncertainties on the output signal of three different plant models in order to evaluate how the controller designed would mitigate those effects.

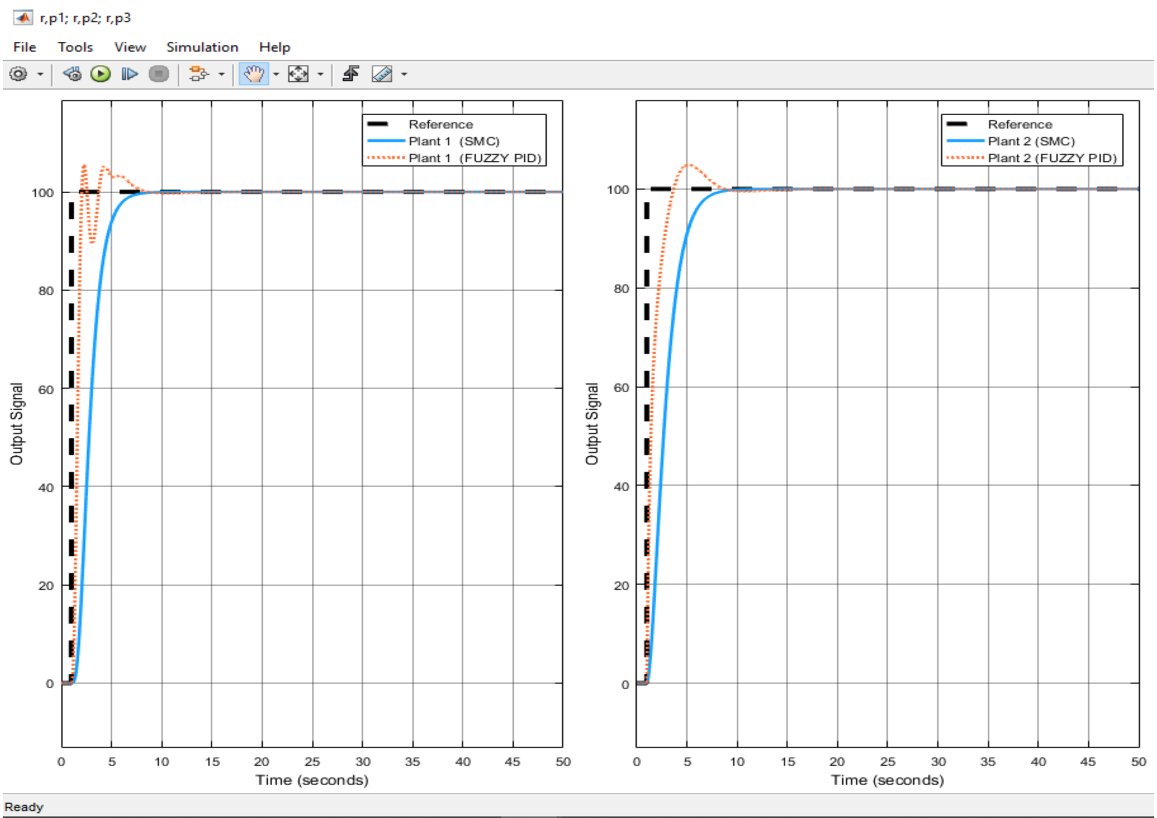

Figure 5: Simulation results for the three plants

6. CONCLUSION

The adaptive fuzzy-PID controller was used as a measure to validate the performance of the proposed sliding mode controller design. It is important to also mention that the adaptive fuzzy-PID controller is a robust controller and makes use of fuzzy logic to tune the parameters of a PID controller, therefore it has the ability to demonstrate optimum control of control systems and has been implemented for several applications. Nevertheless, the sliding mode control designed in this research is more robust and was able to demonstrate stability in all scenarios considered in this research. In overall, SMC could significantly reduce the adverse effects of delays on system performance. The study compared SMC with traditional PID controllers, revealing that SMC outperformed PID in terms of stability and robustness under varying delay conditions.

7. RECOMMENDATION

Future research should be focused on improving the rise time of the Sliding Mode Controller enhancing the deterministic nature of switched ethernet, as it provides a robust and stable characteristic.

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