Abstract. The integration of a wireless network in a closed-loop control system can provide several benefits such as flexibility, installation, and maintenance. However, the presence of time delay in the network system can reduce the control performance. On the other hand, control signal saturation is also the problem that must be overcome in designing a controller. This study aims to design a DC motor speed control by integrating wireless network in its closed-loop system. This concept is known as the Wireless Networked Control System (WNCS). The network parameter used in this study is focused on the time delay. In the controller side, we use a saturation parameter which usually occurs due to limitations of the input signal. The PI-AW controller is used due to having the ability to overcome the saturation of the control signal. The simulation results show that the PI-AW controller can produce the best responses if compared with PI linear and PI saturated with settling time under 1.5 seconds and overshoot less than 8% for three constant values of time delay. The control signal generated also does not exceed the maximum limit of 12 V.

1. Introduction

The existence of network technology both wired and wireless media is one of the things that triggered the emergence of the concept of network-based control systems. This concept can be used to control several systems such as robotics, unmanned aircraft, wireless sensor networks, and industrial instrumentation. A network-based control system or known as the Networked Control System (NCS) is a concept of control system where there is network parameter in a closed-loop system. The communication network is placed between the controller and the plant. This concept is almost similar to the concept of Wireless Sensor Actuator Network (WSAN) which currently appears in the field of remote sensing. The difference is that NCS is more focused on the methodology for controlling dynamic system responses, whereas WSAN is more focused on the remote control and monitoring systems [1]. In the NCS concept, the controller and the plant are separated and maybe at a considerable distance. This, of course, becomes its advantages in the design of control systems. Also, other advantages offered by the NCS concept include a fairly high level of flexibility, ease of installation, and ease of maintenance.

Several control methodologies to the NCS stability analysis have been developed in last recently years. PID controller which is a conventional control system has been developed with the NCS concept [2]. This study describes the process of designing a PID controller up to some methodology for parameter tuning in NCS. Then a similar study was conducted again with a focus on the use of wireless....
networks in PID controller [3]. In addition to describing the process of controlling design, this study also provides an overview of the design of estimator to overcome disturbance and uncertainty in the NCS. An advanced control system was also developed in the NCS concept, such as the Dissipative NCS with output feedback and state feedback [4,5]. This methodology was designed through the Markovian Jump System (MJS) approach which can anticipate stochastic problems that arise in network parameters. This concept has also been implemented to control the speed of a DC motor through a communication network [6]. Then the effects of wireless networks on PI controllers and Fuzzy Logic Controller (FLC) type 2 have also been investigated [7]. In this study, the performance of PI and FLC type 2 controllers is compared with three problem scenarios, namely differences in sampling period, network overload, and packet dropout. Finally, the recently is emerged concept of the Predictive PI (PPI) controller on NCS application using WirelessHART for industrial needs. The PPI controller concept is proposed to overcome the stochastic problem of time delay in WirelessHART network. This method has also been analyzed for its robustness and stability by calculating the uncertainty of network parameter and the stochastic of time delay [8]. However, all the studies above are not considering the control signal saturation parameter in designing a controller.

This study aims to design a DC motor speed control based on the Wireless Networked Control System (WNCS) method with time delay and saturation parameters. This method is the development of the NCS concept which has also been used to control dynamic systems [9,10]. In contrast with Boughanmi et al., which utilize the ZigBee network protocol, this study uses a wireless network module based on radio frequency nRF24L01 which is widely used for wireless sensor applications [11]. As a preliminary study, the network parameters used are focused on the time delay. We use three of constant time delay scenarios which are adopted from nRF24L01 time delay. In this research, DC motor speed control is designed by integrating the saturation parameter in its closed-loop system. We use Proportional Integral (PI) Anti-Windup controller that can consider the saturation effect of the control signal [12]. The simulation result shows that the PI-AW controller can produce the best responses if compared with PI linear and PI saturated. This controller is able to produce the best transient response with a control signal that does not exceed the saturation limit.

2. Method

2.1. Speed control based WNCS

The block diagram of DC motor speed control with the WNCS concept is shown in figure 1.

![Figure 1. DC motor speed control based on WNCS.](image)

From the block diagram, it can be seen that the system is separated into two subsystems, namely the controller node and the plant node. These two nodes are connected using a wireless network. The signals on the controller node are \( r \) as a reference value, \( e \) is the error value, \( u \) is the transmitted control signal, and \( \hat{x} \) is the received speed data. In the plant node, there is \( \bar{u} \) as the received control signal, \( y \) as the output, and \( x \) as the transmitted speed data.

For the simulation requirement, the closed-loop equation of a DC motor with a PI controller fulfills the following equation.
By integrating the delay time variable from the sensor to the controller \( \tau_{sc} \) and from the controller to the actuator \( \tau_{ca} \) and ignoring the controller time delay variable \( \tau_c \), the closed-loop equation is obtained as follows.

\[
\frac{\Omega(s)}{R(s)} = \frac{K(K_p s + K_i)}{K_p K TS^3 + (K_i T + K_p) K s^2 + K_i K s}
\]

(1)

where \( \tau_1 = \tau_{ca} \) and \( \tau_2 = \tau_{ca} \tau_{sc} \). If it is assumed that the amount of delay time is constant and similar between \( \tau_{ca} \) and \( \tau_{sc} \), then the value of \( \tau_1 = \hat{\tau} \) and \( \tau_2 = 2 \hat{\tau} \) with \( \hat{\tau} \) is the delay time constant.

2.2. Proportional integral Anti-Windup controller

Designing a controller with Anti-Windup (AW) is required when the required control signal is saturated. This condition cannot be avoided because in practice the voltage source for controlling a DC motor has a maximum limit. When these conditions occur, the control response can be degraded. Thus an AW mechanism is needed to overcome these problems as shown in figure 2.

![Figure 2. PI controller with AW.](image)

AW works by calculating the difference between the generated control signal and the maximum control signal. If there is a difference, then the value is calculated with an integral time constant and fed back to the integrator section. With this mechanism, the integral controller can adjust the value of the control based on this feedback. The magnitude of the control signal generated during the AW mechanism is as follows [13].

\[
U(s) = K_p E(s) + \frac{K_i}{s} E(s) - \frac{1}{T_i s} [U(s) - \bar{U}(s)]
\]

(3)

where \( T_i \) is the integral time and \( \bar{U} \) is the maximum control signal. The value of \( T_i \) can be obtained from the comparison of \( K_p / K_i \) values. The AW parameter will be active when the \( U \) value is greater than the \( \bar{U} \) value. If the value of \( U \) does not exceed the value of \( \bar{U} \), then \( U = \bar{U} \) and the AW mechanism will not be active or equal to zero.

3. Results and discussion

3.1. Open loop response testing

Before designing speed control, the DC motor open-loop response testing is first performed. We use EMG30 DC motor model with obtained parameters based on Goncalves et al. as listed in table1 below [14].
Table 1. EMG30 DC motor parameters.

| Parameters        | Values   | Units   |
|-------------------|----------|---------|
| Motor constant (K)| 0.509    | N.m/A   |
| Inductance (L)    | 0.0034   | Henry   |
| Resistance (R)    | 7.101    | Ohm     |
| Moment of inertia (J) | 0.00567 | Kg.m²   |
| Friction constant (b) | 0.000931 | N.m.s   |

Based on the test results by assuming the values of L and b are considered zero, there is obtained that the EMG30 DC motor model can reach speeds of 171 rpm when given an input voltage of 12 V with a time constant of 0.17 s. The time constant value is obtained from the response time when the resulting output reaches 63.2% of the maximum value.

3.2. Closed-Loop response resting with PI-AW and time delays

The delay time parameters are placed between the controller and the plant to find out the control performance. The test is carried out using the three types of PI controller and gives the same delay time between τ_{sc} and τ_{ca}, each of 100 ms, 10 ms, and 1 ms. Based on the results of optimization using the PID Tuner, values of Kp = 0 and Ki = 0.575. For saturated PI controllers and PI-AW the control signal limit is given as 12 V. For PI-AW controllers, the value of Kb is infinite value due to the Kp value of 0. But to get the control response, the given Kb value is 1000. The results of control testing by integrating 100 ms, 10 ms, and 1 ms delay parameters can be seen in Figure 3, Figure 4, and Figure 5.

![Figure 3](image1.png)

**Figure 3.** Speed responses with constant time delay parameters 100 ms and its control signal.

![Figure 4](image2.png)

**Figure 4.** Speed responses with constant time delay parameters 10 ms and its control signal.
The complete specifications of the control results generated for the control testing using 100 ms, 10 ms and 1 ms delay time parameters are shown in Table 2, Table 3, and Table 4 as follows.

**Table 2.** Response characteristics with time delay 100 ms.

| Controllers    | Rise Time | Settling Time | Overshoot | Max. Control Signal |
|----------------|-----------|---------------|-----------|---------------------|
| PI Linear      | $\infty$  | $\infty$      | $\infty$  | $12 \text{ V}$      |
| PI Saturated   | 0.53 s    | oscillation   | 15.06 %   | 12 V                |
| PI-AW          | 0.53 s    | oscillation   | 11.13 %   | 12 V                |

**Table 3.** Response characteristics with time delay 10 ms.

| Controllers    | Rise Time | Settling Time | Overshoot | Max. Control Signal |
|----------------|-----------|---------------|-----------|---------------------|
| PI Linear      | 0.30 s    | 1.98 s        | 31.33 %   | 16.63 V             |
| PI Saturated   | 0.44 s    | 2.48 s        | 14.66 %   | 12 V                |
| PI-AW          | 0.44 s    | 1.36 s        | 8 %       | 12 V                |

**Table 4.** Response characteristics with time delay 1 ms.

| Controllers    | Rise Time | Settling Time | Overshoot | Max. Control Signal |
|----------------|-----------|---------------|-----------|---------------------|
| PI Linear      | 0.31 s    | 1.50 s        | 24.33 %   | 15.53 V             |
| PI Saturated   | 0.43 s    | 1.75 s        | 14.40 %   | 12 V                |
| PI-AW          | 0.43 s    | 1.25 s        | 7.73 %    | 12                  |

Based on the test results obtained that the greater the time delay given, the control performance will get worse. This can be seen from the performance of the linear PI control with a delay of 100 ms resulting in an oscillating and unstable speed response. In contrast, the smaller delay time parameter given does not affect the performance of the control. This condition can be seen from the control performance with a delay of 1 ms that is not significantly different from the performance of the control without network parameter. When viewed from the controller side, PI-AW still has the best performance when compared to linear PI and saturated PI. Even though there is a time delay parameter in the closed loop of the control, PI-AW can produce better control performance. This condition is shown when given the largest delay time of 100 ms where the control response with PI-AW looks stable even though it has an oscillation with a maximum overshoot of 11.3%. In terms of the generated control signal, PI-AW also does not produce a control signal that exceeds the maximum limit of 12 V.
4. Conclusion
DC motor speed control based on WNCS with delay time and saturation parameters has been successfully designed and tested. A PI-AW controller is used to control the speed of DC motor after integrated time delay and saturation parameters in the closed-loop control system. Simulation results with the integration of 100 ms, 10 ms, and 1 ms constant time delay parameters and the maximum control signal of 12 V shows that the PI-AW controller can produce the best performance if compared with PI linear and PI saturated controllers. PI-AW is able to produce responses with a rise time 0.43 s, settling time 1.25 s, overshoot of 7.73%, and a maximum control signal of 12 V at a delay of 1 ms. Based on the simulation results, the smaller delay time will result in better performance. Further research is needed in the design of more robust controllers such as optimal PID controller to overcome the stochastic time delay in network system.

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