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Time delay effect reduction on the wireless networked control system using an optimized FOPI-FOPD controller

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ABSTRACT

Wireless networked control system (WNCS) is made up of an actuator, sensor, and controller that communicate through a wireless network rather than typical point-to-point cable connections. Lower maintenance costs, greater flexibility, and increased safety are the main WNCS advantages. So as a result, it has attracted a lot of researchers. Nevertheless, time delays and packet losses in wireless data transmission are classified as complicated problems, which impair WNCS output accuracy and may influence the overall system stability. Integer-order PI-PD (PI-PD) and fractional-order PI-PD (FOPI-FOPD) controllers are suggested to reduce the impact of the control signal transmission's time delay and improve system performance. MATLAB and True-time simulators are utilized to simulate the WNCS, and ZigBee protocol is used to transceiver the control signal between the controller and system sides. rotary inverted pendulum (RIP) acted as the controller's objective. The grey wolf optimization (GWO) method is used to evaluate the best controller parameters. Xbee S2 modules are used to implement the signal transmission process over ZigBee protocol. The FOPI-FOPD controller outperforms the PI-PD in the simulation and experimental results in decreasing the influence of time delay on system stability.

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1. INTRODUCTION

The development of sensor technology has enabled wireless communication techniques to be given not only for office and home usage, but also for industrial uses such as manufacturing, industrial monitoring, and control networks. Sensor nodes in wireless networked control system (WNCS) are linked to a physical mechanism that gathers and wirelessly transmits data to the controller. The controller calculates control commands based on sensor data and transmits them to the actuators of the system [1], [2]. WNCS systems provide several advantages over typical wired network control systems, including extra versatility, a more straightforward setup, and reduced total costs. It is also conceivable to employ WNCS when vibrations or chemicals influence the equipment [3]. However, wireless medium properties influence WNCS execution. The stability of the system may be harmed when time delay increases, resulting in unreliable WNCS. As a result, a robust control system should be presented to ensure dependable and achieve a high quality of service real-time performance [4], [5].

Many searches have been focused on minimizing the influence of time delay on system stability during signal transmission over wireless networks. A state predictor-based output feedback controller was presented to adjust delays of the network that change over time, and this study used the rotary inverted pendulum (RIP) system as an object for the linear-quadratic regulator (LQR) controller to settle the pendulum in the upright direction. The outcomes have demonstrated that the pendulum rod maintained a steady state for 10 seconds without the compensator, but it stayed upright for 120 seconds after applying a compensator [6]. Another study proposed a fuzzy PID controller was implemented to regulate the DC motor. The comparing results with the traditional PID shows that the fuzzy PID controller is more effective with a significant delay through a wireless network [7]. PID and fractional order PID (FOPID) controllers were proposed to decrease time delay impact of control signal transmission wirelessly. The efficient values for controller gains have been estimated using a particle swarm optimization (PSO) algorithm. The controllers are deployed to control the stepper motor via a wireless network. The researchers utilized MATLAB and true-time for simulating WNCS. The results showed that the FOPID controller is better than PID controller in dealing with the time delay effect [8]. Another research proposed a robust mixed H2/H∞ controller for the uncertain wireless network system over packet loss and time delay effects. MATLAB LMI toolbox is utilized to determine the control rule. The numerical example and simulation results confirmed the efficiency of the suggested strategy [9]. Finally, the fuzzy logic controller has been introduced to control the DC motor over Wi-Fi network using MATLAB and true-time. PSO technique was used to adjust the controller parameters. The effectiveness of the controller was assured through increasing network nodes by 33% without performance degradation [10].

The contribution of this work is summarizing the design and implementation of an optimized two closed-loop controllers over a wireless network for the RIP system. The pendulum and arm angles should be controlled simultaneously by a single input multiple output (SIMO) design approach, which is considered one of the complex control systems. Moreover, the complication of this design, an optimization technique is applied to find the appropriate wireless networked controller's parameters. Additionally, proposing a robust controller has the capability to reduce the time delay effects on the system stability, which is considered one of the main WNCS design challenges. FOPI-FOPD and PI-PD are used in this study to control the RIP nonlinear model wirelessly. IEEE 802.15.4 standard has been considered to demonstrate the wireless connection of WNCS. RIP system utilized as a controller's target. MATLAB and true-time were used to obtain the simulation results. Also, in the experimental results, two nodes of ZigBee devices have been used to send the control signal from the controller to the actuator and receive the feedback signal from the sensor. The first ZigBee node has been connected to PC_1, which has the controller. Another ZigBee has been linked to the PC_2, which has RIP system. GWO technique has been utilized to tune the controller's parameters to control the system wirelessly.

2. WIRELESS NETWORKED SYSTEM

2.1. Wireless networked control system

The general structure of WNCS is represented in Figure 1 [11]. The sensor node is responsible for plant behavior monitoring in WNCS. Then, the reference node will receive data wirelessly to evaluate the sensor data [12], [13]. The control signal is delivered to the actuator based on the feedback signal to adjust its stability preceding failure. The time delay can occur when the signal is transmitted from the controller to the actuator in the feed-forward loop and the signal is transferred from the sensor to the controller in the feedback loop [14]. The total time delay (τ_{total}) can be formulated as (1).

$$\tau_{total} = \tau_{ca} + \tau_{sc} \tag{1}$$

When (τ_{ca}, τ_{sc}) is represented sequentially, the controller to actuator time delay and sensor to controller time delay.

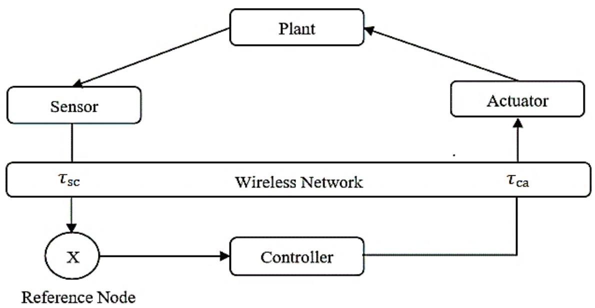


Figure 1. General structure of WNCS

2.2. RIP system outline

Since, the model of the RIP system is an underactuated, highly nonlinear, unstable, uncertain, and, multivariable system. Therefore, it is a good instance of a SIMO system architecture. RIP system has two degrees of freedom (2-DOF), the rotatable arm, and the rotatable pendulum rod. The arm is regulated directly, while the pendulum rod is indirectly controlled [15]. Figure 2 illustrates the diagram of the RIP system. The axis of the rotating arm is connected to an actuated rotary motor system. Lr is the arm length, Jr represents the inertia, and the ø represents the arm angle. The end of the arm is attached to the pendulum rod. Lp is the overall length of the pendulum, whereas Lp/2 is the distance from the rod's center of mass. The inertia around the pendulum's mass center is Jp. The pendulum's angle is θ, equal to zero when the pendulum in the upright direction and increases as the arm rotates [16]. The control objective is to maintain the vertical position of the pendulum rod [17]. The controller determines an appropriate force to apply to the arm, and then torque is generated by rotating the arm right and left to keep the rod in a vertical position. RIP is represented by the following equation using the Lagrangian theory [18], [19].

$$\left(J_r + m_p Lr^2\right)\ddot{\varnothing} + m_p L_r \left(\frac{L_p}{2}\right) \sin(\theta)\dot{\theta}^2 - m_p L_r \left(\frac{L_p}{2}\right) \cos(\theta)\,\ddot{\theta} = T - B\dot{\varnothing} \tag{2}$$

$$\frac{4}{3} m_p \left(\frac{L_p}{2}\right)^2 \ddot{\theta} - m_p L_r \left(\frac{L_p}{2}\right) \cos(\theta)\ddot{\varnothing} - m_p g \left(\frac{L_p}{2}\right) \sin\theta \ = 0 \tag{3}$$

The torque T is given as,

$$T = \eta_m \eta_g K_t K_g \frac{V - K_g K_m \dot{\varnothing}}{R_m} \tag{4}$$

The physical parameters of the RIP system are shown in Table 1. Solving the (2)-(4) and consideration of the parameters' values of Table 1, a state space model can be formulated as:

$$\begin{bmatrix} \dot{\varnothing} \\ \dot{\theta} \\ \ddot{\varnothing} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 39.32 & -14.52 & 0 \\ 0 & 81.78 & -13.98 & 0 \end{bmatrix} \begin{bmatrix} \varnothing \\ \theta \\ \dot{\varnothing} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 25.54 \\ 24.59 \end{bmatrix} V \tag{5}$$

$$Y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \varnothing \\ \theta \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V \tag{6}$$

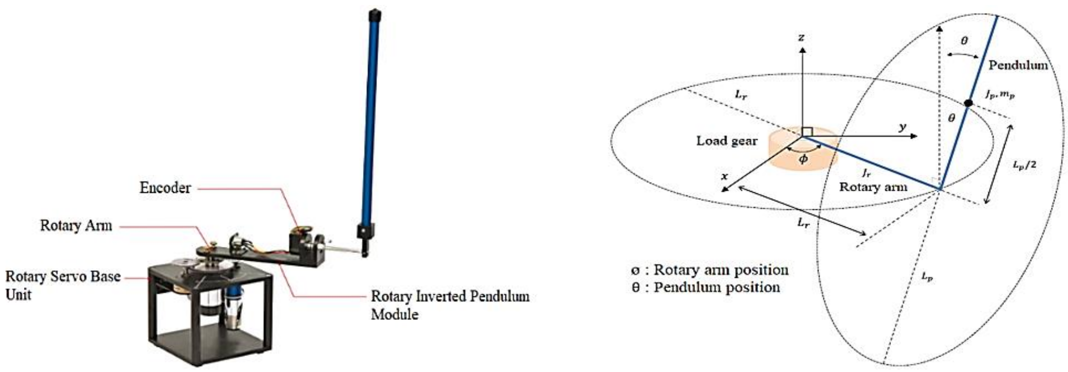


Figure 2. Schematic diagram of RIP system [5]

Table 1. Physical parameters of RIP

Parameters	Description	Value
K_t	Motor torque constant	0.0077
K_g	SRV02 system gear ratio	70
K_m	Back EMF constant	0.0077
R_m	Armature resistance	2.6
η_g	Gearbox efficiency	0.90
η_m	Motor efficiency	0.69
B	Viscous damping coefficient	0.0040
J	Moment of inertia at the load	0.0033
m	Mass of pendulum	0.1250
L_r	Arm length	0.2150
$L_p/2$	Length to pendulum's center of mass	0.1675
g	Gravitational constant	9.81

2.3. Wireless network protocol

ZigBee technology works on an open global standard based on IEEE 802.15.4. ZigBee networking component circuits with sensors represent contemporary categories for wireless low power consumption network communication techniques with several technological features such as low complexity, high effectiveness and reliability [20]. It supports a simple and easy connection between point-to-point and point-to-multipoint [21]. The operating frequency of the ZigBee protocol is 2.4 GHz, 926 MHz and 868 MHz. ZigBee supports a transmission bit rate is 250 Kbps and can communicate over a distance of 10 to 100 meters. Figure 3 shows the XBee S_2 module, which supports the ZigBee protocol and Funduino USB adapter [22].

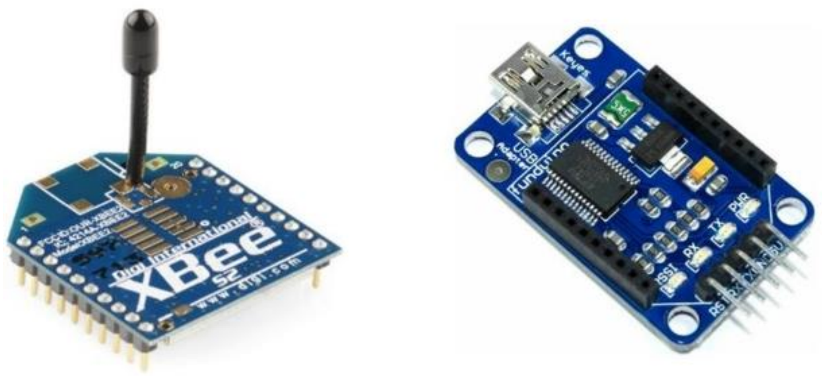


Figure 3. XBee S_2 wireless transceiver and USB adapter

3. CONTROLLER SYSTEM DESIGN

3.1. Control method

This work uses PI-PD and FOPI-FOPD controllers to control the RIP system. PI-PD is a 2-DOF theory achieved by a mathematical model. It has accomplished outstanding closed-loop performance in unstable and integrated systems [23]. As shown in Figure 4, the PI-PD controller comprises PI and PD portions. PD is applied for internal feedback to shift plant poles to appropriate locations, whereas PI is used for the external loop to regulate the plant following PD block action. In addition, PI-PD provides additional parameter adjustment options, hence establishing a flexible control architecture. From Figure 4, PD and PI may be represented consecutively as $C_{PD}(s)$ and $C_{PI}(s)$, as follows [24], [25]:

$$C_{PD}(S) = K_f + K_d(s) \tag{7}$$

$$C_{PI}(S) = K_P + \frac{Ki}{s} = \frac{K_P s + K_i}{S} \tag{8}$$

From (7)-(8), the control signal (U), which acts on the plant, can be written as:

$$U = \left(K_P + \frac{Ki}{s}\right) - (K_f + K_d(s)) \tag{9}$$

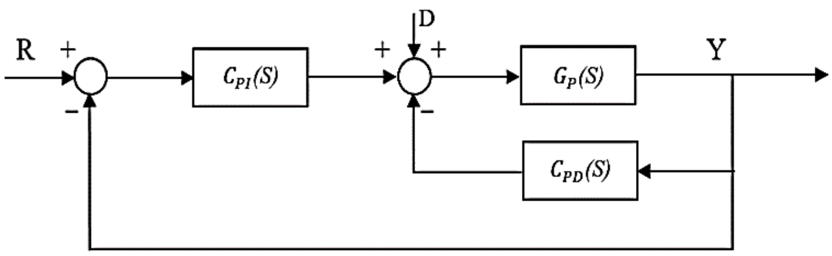


Figure 4. PI-PD control system

FOPI-FOPD and PI-PD controllers have the same strategy. But the fractional order controller contains fractional derivative and fractional integral components. Additionally to K_P, K_i, K_f, and K_d, there are two more performance-enhancing parameters (order of differentiator, order of integrator) that give the controller an additional degree of freedom [26], [27]. The mathematical representation of FOPI and FOPD can be written as [28], [29]:

$$C_{PD}(S) = K_f + K_d s^{\mu} \qquad 0 < \mu < 1 \tag{10}$$

$$C_{PI}(S) = K_P + \frac{Ki}{s^{\lambda}} \qquad 0 < \lambda < 1 \tag{11}$$

from (10)-(11), the control signal (U) which acts on the plant can be written as:

$$U = (K_P + \frac{Ki}{s^{\lambda}}) - (K_f + K_d s^{\mu}) \tag{12}$$

the previously described FOPI-FOPD will behave as a PI-PD controller when μ=1, λ=1 [30]. FOPI-FOPD controller gain should be fine-tuned for optimum performance and stability of the system [31], [32]. This research utilizes the grey wolf optimizer (GWO) method to determine the optimal parameters for reducing errors and achieving robust stability [33], [34]. The integral time absolute error (*ITAE*) criterion was implemented as a cost function.

$$ITAE = \int_0^{\infty} t\left|e(t)\right|dt \tag{13}$$

3.2. SIMO system design

RIP system is an excellent example of designing a SIMO system methodology. The two loops of FOPI-FOPD and PI-PD controllers are intended to stabilizing the RIP according to the SIMO structure technique shown in Figure 5 [35]. This design aims to simultaneously control the rotor arm and the pendulum rod [36]. The SIMO structure of the RIP system necessitates the designing of two different control units. The first one regulates the arm, whereas the second handles the pendulum simultaneously [37], [38]. The control signal which acts on the RIP system can be written as:

$$U = [(K_{p1} + \frac{Ki1}{s^{\lambda 1}}) - \left(K_{f1} + K_{d1}s^{\mu 1}\right)] - [\left(K_{P2} + \frac{Ki2}{s^{\lambda 2}}\right) - \left(K_{f2} + K_{d2}s^{\mu 2}\right)] \tag{14}$$

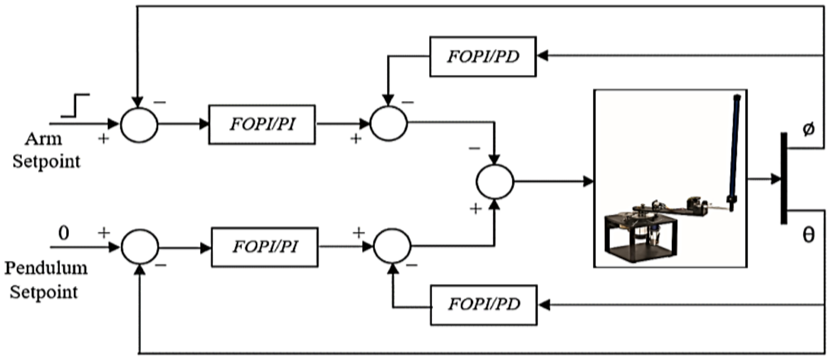


Figure 5. RIP SIMO controller structure

3.3. Optimization algorithm

Grey wolves' optimization algorithm approach proposed by Mirjalili *et al*. [39] distinguishes the four classes of grey wolves. Alpha (α) is the first class, which is responsible for decision-making and group leadership. The second class is a beta wolf (β) which advises the alpha. Delta wolf (δ) is the third class, which provides information to the other classes. The last class is omega wolf (ω) [40]. There are three hunting simulation operations, prey searching, prey encircling, and prey attacking [41]. GWO has been applied to obtain the controller's parameters' best values in the WNCS. The formulation of the wolves' movement can be expressed as:

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{X}\right|, \ \overrightarrow{D_\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{X}\right| = \overrightarrow{D_\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{X}\right| \quad (15)$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1} \cdot (\overrightarrow{D_\alpha}), \overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2} \cdot (\overrightarrow{D_\beta}), \overrightarrow{X_3} - \overrightarrow{X_\delta} - \overrightarrow{A_3} \cdot (\overrightarrow{D_\delta}) \quad (16)$$

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \quad (17)$$

3.4. Proposed Simulation and experimental structure

The block diagram of the WNCS using MATLAB and True-time simulator is illustrated in Figure 6. The FOPI-FOPD and PI-PD controllers are applied on the RIP to simultaneously control the arm and pendulum rod. The control and sensor signals are transmitted wirelessly. Time delay might occur in the arrival of the data packet when it is shared between the controller, actuator, and sensor. These delays may be led to the unaccepted performance of the WNCS. This necessitates designing a control system capable of reducing the effects of time delay. This study presents research on minimizing the effect of time delay on wireless network management via designing an optimal and robust controller.

Two control signals are presented in Figure 6. The first U presents the control signal generated by the controller on the controller side, which is introduced in equation (14). The other $\widehat{U}$ presents the control signal transmitted over a wireless network to the plant side with a time delay. At the plant side, the system output signal denotes by Y and at the controller side, $\hat{Y}$ represents the time delay affected system output signal after the feedback loop during transmission.

The experimental block diagram is designed using a MATLAB simulator, as shown in Figure 7. Two PC is used to implement WNCS, the first PC contains the controller side, and the second PC contains the RIP system side. Two Xbee S_2 modules, which support ZigBee protocol, have been utilized as coordinator and router. XCTU software has been used to configure the two ZigBee to make point-to-point network connections. The first node is set as a coordinator, connected with PC_1, and the second node is designated as a router associated with PC_2. These nodes are connected with USB adapters and PC_S through USB serial ports.

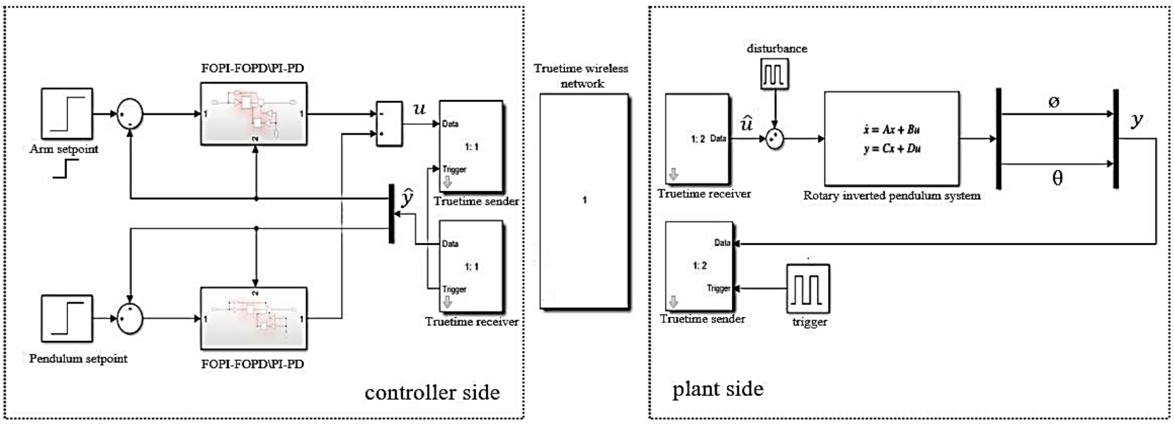


Figure 6. Block diagram of WNCS using MATLAB and true-time simulator

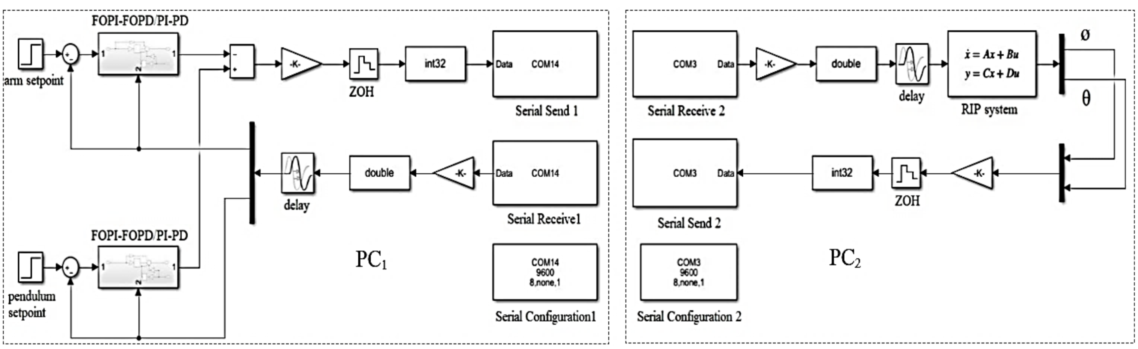


Figure 7. WNCS experimental block diagram

In the implementation of WNCS, as shown in Figure 8, the MATLAB Simulink runs for the two PC_S simultaneously. The control signal is transmitted from the serial sent to the coordinator node through the USB serial port. The router node is received the control signal from the coordinator, which is sent to the RIP system from the serial received through the USB serial port. The coordinator node sends and receives the control and feedback signal. The router node receives the control signal from the coordinator and then sends the feedback signal, on which the controller depends to improve system performance. 20 meters is considered as a distance between the two PCs.

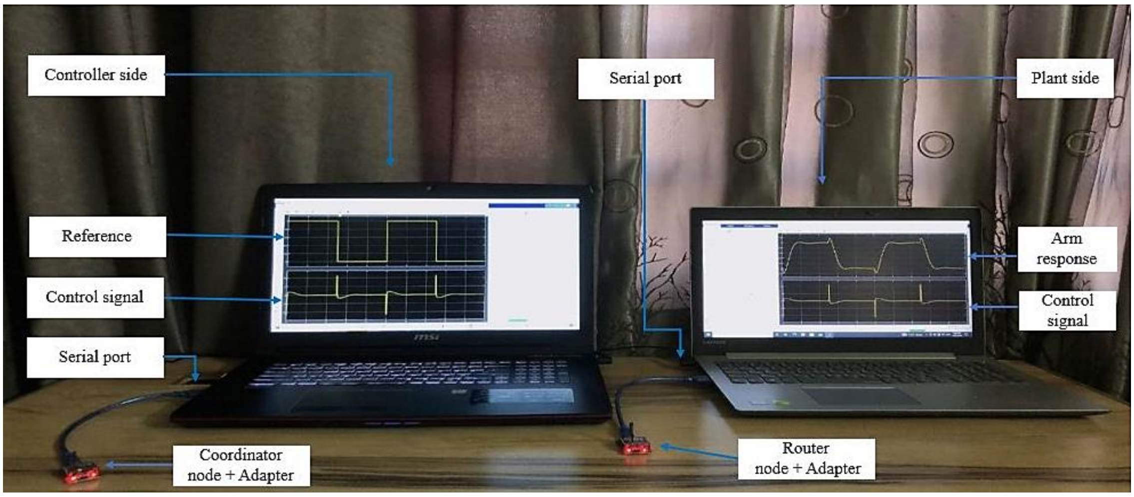


Figure 8. Implementation the WNCS

4. RESULTS AND DISCUSSION

This study has applied multiple time delay durations to the simulation and experiment WNCS. For each time delay, the system response and ITAE are considered in comparing the performances of the two controllers. As described previously, RIP system is a SIMO design methodology example. The pendulum should stay in the vertical position corresponding to the arm's stability. In the case of an unbalanced pendulum, the controller creates an appropriate control signal to produce a rotating movement that maintains the vertical position of the pendulum rod. When a time delay occurs while transmitting the control signal, the system actuator doesn't completely receive the supplied signal from the controller. This causes a number of disturbances in the system, and when time delays increase, the system may become unstable. The proposed controllers were applied to the RIP to regulate the pendulum rod's upright position. A unit step was provided as a reference input for both controllers at the arm. The same parameters are utilized for both controllers for a fair comparison, including extra fractional order controller parameters (μ and λ) to improve the system performance when time delay happens. Figure 9 illustrates the simulation and experimental results of the control signal for both controllers, which were transmitted over a wireless network.

Figures 10(a) and 10(b) illustrate the time response of the pendulum and the arm angles when applied the two controllers over a wireless network without time delay. In Figures 11(a)-11(d) the results showed that the fractional order controller is better than the integer order controller by minimizing the time delay impact produces over the wireless network. The improving ratio of the error of using the FOPI-FOPD controller without time delay is 38.135%, and with 10ms time delay is 41.457%, but after applying 15ms delay, the system goes to an unstable state when using the PI-PD controller, whereas the system stability achieved within two seconds when applying the FOPI-FOPD controller. From Figures 11(a)-11(d), we can notice that the proposed controller could handle time delays that occur through sending and receiving the signal over a wireless network, leading to more reliability for WNCS. Table 2 states the influence of increasing the time delay on the ITAE in both the FOPI-FOPD and PI-PD controllers for simulation and experiment cases.

Table 2. ITAE with and without time delay

WNCS	ITAE without delay	ITAE with 10 ms delay	ITAE with 15 ms delay
Simulation FOPI-FOPD	0.2203	0.2258	0.2287
Experiment FOPI-FOPD	0.2289	0.2332	0.2515
Simulation PI-PD	0.3561	0.3857	2.6291
Experiment PI-PD	0.3677	0.3959	2.8870

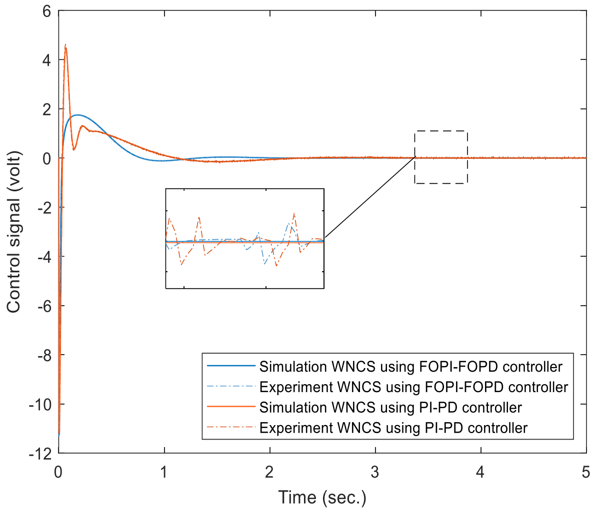
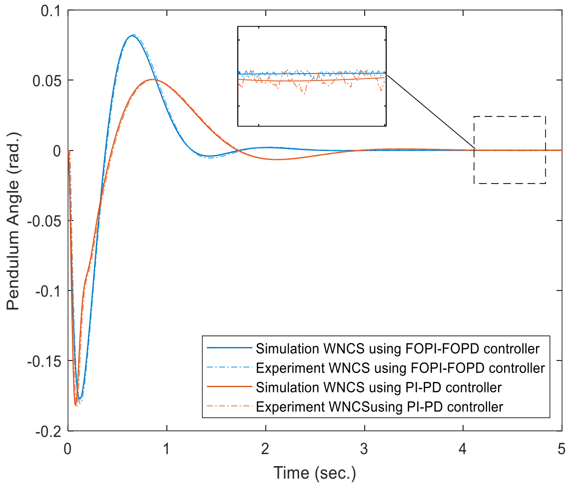
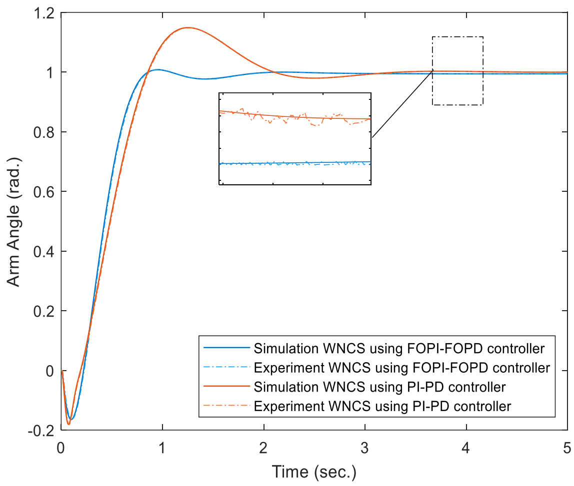


Figure 9. The control signal for both controllers



(a)



(b)

Figure 10. Simulation and experiment results of WNCS (a) pendulum angle and (b) arm angle

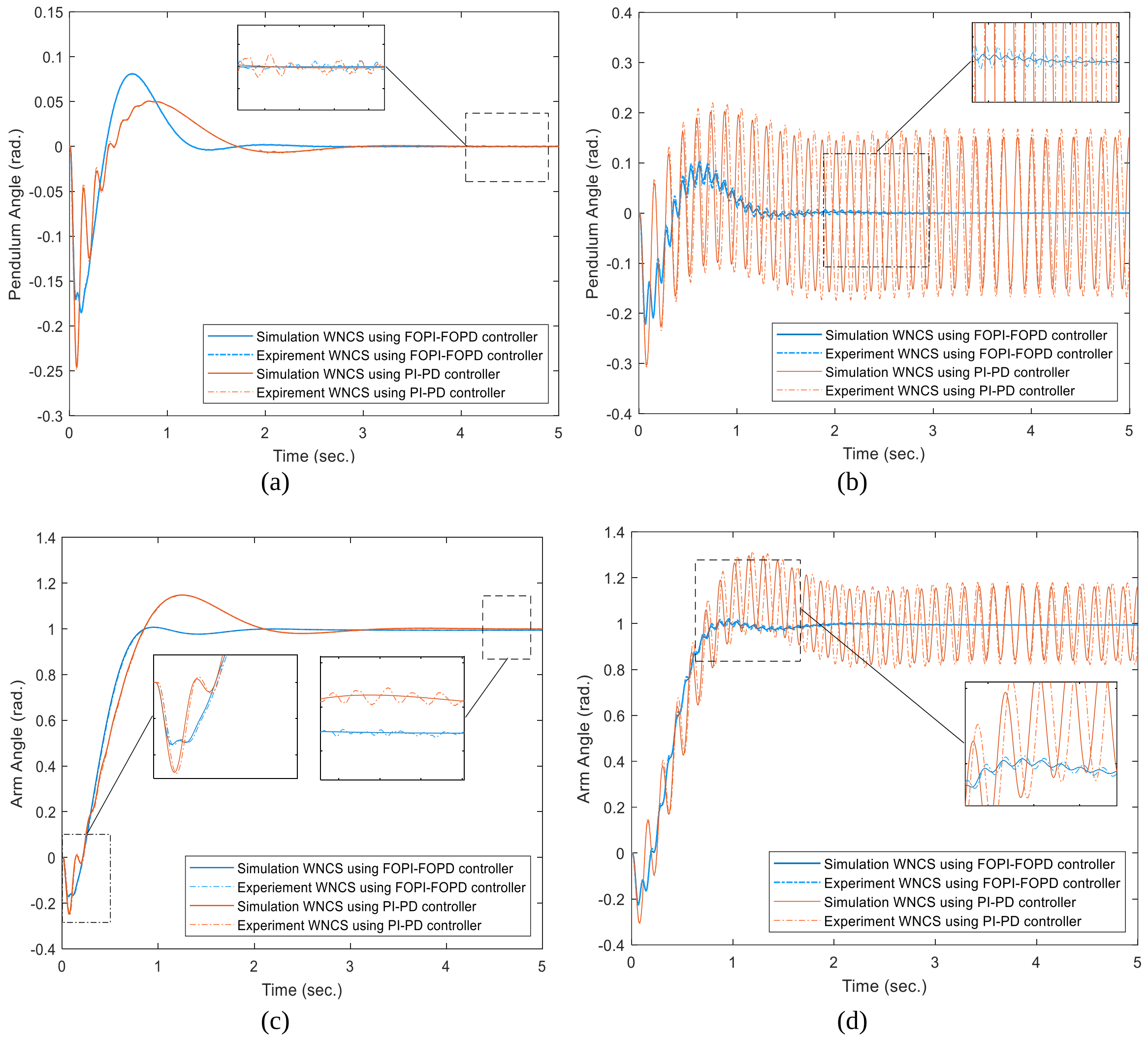


Figure 11. Simulation and experiment results of WNCS with time delay: (a) pendulum angle with 10 ms time delay, (b) pendulum angle with 15 ms time delay, (c) arm angle with 10 ms time delay, and (d) arm angle with 15 ms time delay

5. CONCLUSION

Reducing the effect of the time delay during the transmission of the control signal is essential to maintaining the system's stability to be controlled wirelessly, which leads to more reliability for the WNCS. In this work, two controllers have been applied to the RIP over a wireless network to reduce the time delay effect on the system performance. A time delay of 0 to 15 seconds is considered at the time delay effect cancellation test. The simulation results proved that the FOPI-FOPD controller is more effective than the PI-PD controller in handling the influence of time delay on system stabilization. Validation of the results was accomplished experimentally, and verified the simulation stats. Also, FOPI-FOPD is superior to the PI-PD controller in decreasing the oscillation of the arm and pendulum rod, which occurs due to time delay.

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