Packet loss compensation over wireless networked using an optimized FOPI-FOPD controller for nonlinear system

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Article Info

Article history:

Received Jul 2, 2022
Revised Aug 5, 2022
Accepted Aug 14, 2022

Keywords:

Integer and fractional order PI-PD
Optimization technique
Rotary inverted pendulum
ZigBee protocol

ABSTRACT

Wireless networked control systems (WNCS) consist of an actuator, sensor, and controller communicating over wireless networks in place of traditional point-to-point wired connection. Due to their main advantages, a decrease in maintenance costs, more flexibility, and safety could be achieved. As a result, it attracted a great deal of interest, but packet losses and time delays in the wireless network through transmitting and receiving the data are considered very challenging issues, which impair the output accuracy of the WNCS and can affect the entire system stability. In this study, integer-order proportional integral-proportional derivative (PI-PD) and fractional-order PI-PD (FOPI-FOPD) controllers are proposed to reduce the effect of expected packet loss in a WNCS to improve system performance. At high packet loss percent, the PI controller is introduced to act as a compensator in the feed-forward loop to keep the system stable. MATLAB/Simulink and Truetime simulator are used to simulate the WNCS. The rotary inverted pendulum (RIP) is utilized as the object of the controllers. Grey wolf optimization (GWO) algorithm is used to find the optimal controllers and compensator parameters. The simulation results showed that the FOPI-FOPD is superior to PI-PD in the packet loss compensation.

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1. INTRODUCTION

The evolution of the sensor technology has permitted the technologies of wireless communication to be provided not just for offices and homes use but for industrial purposes, like manufactories, industrial supervision, and control networks. Sensor nodes in wireless networked control systems (WNCS) are linked to the physical process, which collects and sends the data wirelessly to the controller. Based on the sensor data, the controller calculates control commands and sends them to the system actuators [1], [2]. Several benefits are provided by WNCS systems over traditional wired control systems, including more adaptability, simpler installation, and lower overall costs. It's also possible to use WNCS in places when there is a possibility that chemicals or vibrations may affect the equipment [3]. Although, wireless media characteristics affect the WNCS execution. System stability may be degraded due to rising packet loss, which leads to unreliable WNCS. So, a strong control system should be proposed to achieve reliable and real-time performance [4].

The researchers attempted to reduce the packet loss effect on system stability during transmitting the signal to and from the plant. Proportional derivative (PD) controller has been used to control multiple pendulum cart over a wireless network. They used Kalman filter to reduce the effect of packet loss of the data in network transmission [5]. Another study suggested three compensators, predictive compensator in the feed forward loop, modified linear quadratic regulator (LQR) compensator in the feedback and combination between them, and the results were simulated using MATLAB/Simulink and Truetime at multiple packet loss states [6]. Proportional integral derivative (PID) controller is used to control the inverted pendulum over a wireless network. The results showed that the combined compensator was more efficient than others, but they did not show the results of the pendulum angle. The impact of packet loss on DC motor has been studied on two scheduling algorithms, rate monotonic (RM) and earliest deadline first (EDF) in WNCS. The comparison results between these algorithms showed that EDF scheduling technology appears more suitable than RM for WNCS [7]. Also, a state predictor-based output feedback controller designed to compensate time-varying network delays, rotary inverted pendulum (RIP) was used as a plant and LQR controller to stabilize the pendulum rod. The results showed that the pendulum rod remained in the stable state for ten seconds without using the compensator but the pendulum rod remained stable for 120 seconds with the presence of the compensator [8]. A predictive PID controller has been proposed to decrease the effect of the packet dropout with comparable properties to model-based predictive control (MBPC). The experiment results using Truetime simulator appeared that the performance of the predictive PID controller was as good as the MBPC with the feature of having a simple structure [9]. Furthermore, a fuzzy PID controller was introduced to control the DC motor and comparison the results with a conventional PID controller. The result showed that the fuzzy PID controller is more efficient than a conventional PID controller with a large delay that occurs over a wireless network [10]. Fractional order PID (FOPID) and PID controllers were suggested to minimize the time delay effect. They used a particle swarm optimization technique to estimate the optimal value of controller gains and applied these controllers on a simple stepper motor over a wireless network [11]. Another research proposed an $H_2/H\infty$ controller for uncertain wireless sensor network systems in the presence of packet loss and time delay [12]. Finally, fuzzy logic controller has been presented to reduce the impact of the time delay on the DC motor over the Wi-Fi network. They used particle swarm optimization (PSO) technology to optimize the controller parameters [13].

In this work, two controllers, fractional order proportional integral-proportional derivative (FOPI-FOPD) and PI-PD, were applied to a nonlinear system over the 802.15.4 wireless network to overcome the disadvantages of the WNCS. The RIP system was used as the controller's objective. MATLAB Simulink and Truetime have been used to simulate the WNCS at multiple states of packet loss rates. The results appear that the control system can handle high packet loss rates when applied FOPI-FOPD controller batter than when applied PI-PD controller. On the other hand, the PI controller was used as a compensator in the feed-forward loop when the packet loss rate raised over 85%. The results appear that the compensator can improve the performance of the controllers at a high rate of packet loss. Grey wolf optimization (GWO) technique was used to find the optimal parameters of the controllers to control the RIP system over a wireless network.

2. WIRELESS NETWORK SYSTEM

2.1. RIP system overview

The RIP system model is an underactuated system. It has two degrees of freedom (2-DOF) consisting of a rotating arm and rotating pendulum rod. However, only one of them (the angle of ARM) is actuated, and the other is only indirectly controlled. RIP is an excellent example of designing a single-input multi-output (SIMO) system. The diagram of RIP is illustrated in Figure 1. The rotary arm axis is linked to the rotary servo system and is actuated. The length of arm is Lr, Jr is the moment of inertia, and the arm angle is ø. The pendulum rod is connected to the end of the arm. Lp represents the total length of the pendulum rod, and the length to the rod center of mass is Lp/2. The moment of inertia about the pendulum center of mass is Jp. The angle of the pendulum rod is θ, which is equal to zero when it is upright in the vertical position, and it is increased when the arm is rotating [14].

The control target is to preserve the pendulum rod in a vertical direction [15]. The controller turns the arm left and right to produce a torque on the rod to remain it is in the upright position. The controller will estimate the suitable force to be applied to the arm. Using the Lagrangian method, the equation of RIP is as follows [16], [17]:

$$(J_r + m_p Lr^2)\ddot{\phi} + m_p L_r \left(\frac{L_p}{2}\right)\sin(\theta)\dot{\theta}^2 - m_p L_r \left(\frac{L_p}{2}\right)\cos(\theta)\,\ddot{\theta} = T - B\dot{\phi} \quad (1)$$

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

The torque T is given as, $T = \eta_m \eta_g K_t K_g \frac{V - K_g K_m \dot{\phi}}{R_m}$ (3)

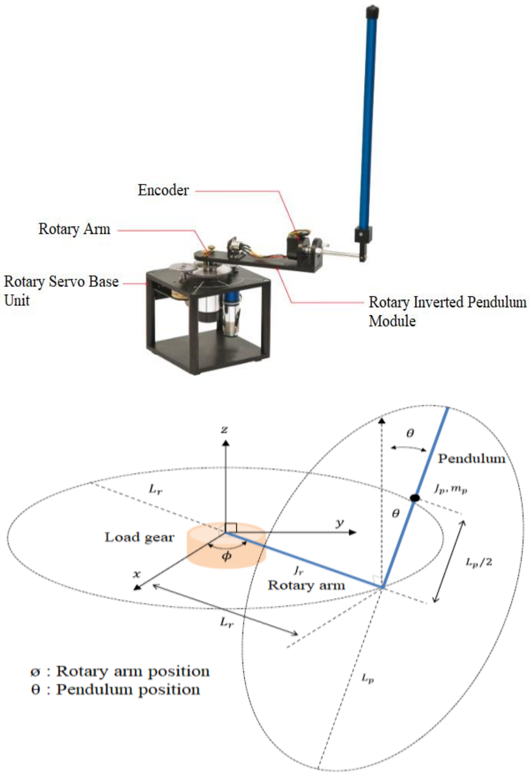

Figure 1. Schematic diagram of RIP system [8]

Table 1 as show in the physical parameters of the RIP system. Solving (1)-(3) and values from Table 1, a state space model is formed, which is written as,

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 39.32 & -14.52 & 0 \\ 0 & 81.78 & -13.98 & 0 \end{bmatrix} \begin{bmatrix} \phi \\ \theta \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 25.54 \\ 24.59 \end{bmatrix} V \tag{4}$$

$$Y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \phi \\ \theta \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V \tag{5}$$

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

2.2. Wireless network controlled system

The general structure of WNCS is illustrated in Figure 2 [6], [18]. In WNCS, the sensor node is accountable for monitoring the plant parameters. Then the data is transmitted wirelessly to the reference node that analyzes the data from the sensor [19]. Depending on the feedback signal, a control signal is transmitted to the actuator to regulate its stability before the failure occurs.

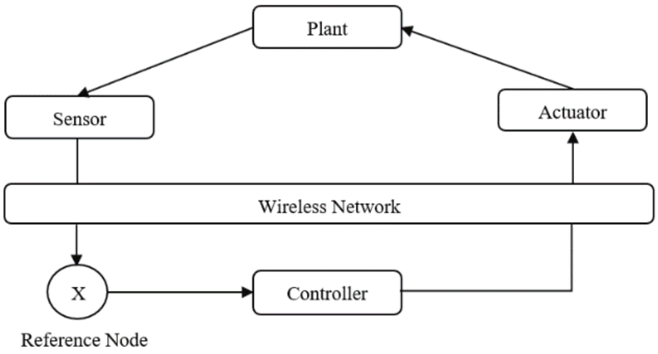

Figure 2. WNCS general structure

3. CONTROLLER SYSTEM DESIGEN

3.1. Control strategy

PI-PD and FOPI-FOPD controllers are used to control the plant. PI-PD controller is a mathematical model initiated theory. It has achieved excellent closed-loop performance in unstable and integrating processes [20]. PI-PD controller contains PI and PD parts, as shown in Figure 3. PD is used in interior feedback to move the plant poles to suitable places, while the PI part is used in the exterior loop for regulating the system after PD block action. Furthermore, PI-PD offers additional parameter adjusting possibilities, hence achieving a flexible control design [21]. At Figure 3, $G_P(s)$ and D(s) demonstrate the controlled plant and disturbance, consequently [22], [23]. When $G_P(s)$ is:

$$G_P(S) = \frac{N_P(S)}{D_{P(S)}} \quad (6)$$

PD and PI can be expressed as $C_{PD}(s)$ and $C_{PI}(s)$, sequentially and as follows:

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

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

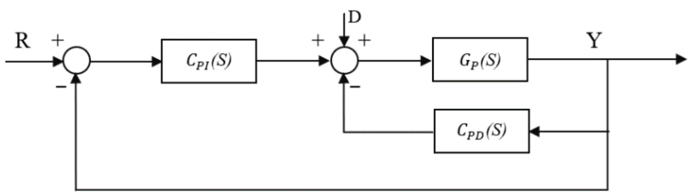

Figure 3. Single input single output control system with PI-PD controller [24]

FOPI-FOPD controller is the same approach as the integer PI-PD controller, but it has a fractional derivative and fractional integral elements. In addition to K_P, K_i, K_f, and K_d, there are two additional factors (λ order of integrator, μ order of differentiator) that provide the controller an extra degree of flexibility to improve performance [25], [26]. FOPI and FOPD it is represented by mathematical (9) and (10) [27].

$$C_{PD}(S) = K_f + K_d s^{\mu} \; 0 < \mu < 1 \quad (9)$$

$$C_{PI}(S) = K_P + \frac{Ki}{s^{\lambda}} \; 0 < \lambda < 1 \quad (10)$$

When λ=1, μ=1, The FOPI-FOPD controller above will operate as a PI-PD controller [28]. FOPI-FOPD controller variables must be fine-tuned to achieve optimal performance and enhance system stability [29], [30]. This paper exploits the GWO technique to find the best factors to minimize errors and get robust stability [31], [32]. The integral time square error (ITSE) criteria have been applied as a cost function.

$$ITSE = \int_0^\infty te(t)^2 dt \quad (11)$$

The two loops of FOPI-FOPD and PI-PD controllers are designed to stabilize the RIP system in a SIMO design method illustrated in Figure 4 [33], [34]. So the upright pendulum position and arm angle stabilization can simultaneously be achieved [35]. The SIMO structure of the RIP system requires the designing of two various controllers. The first controller controls the arm, while the second controls the pendulum rod [36].

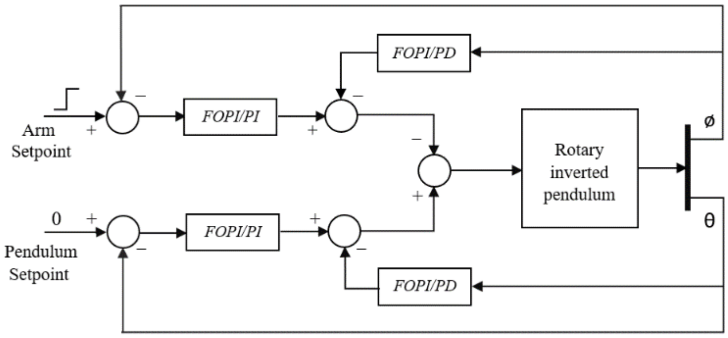

Figure 4. RIP SIMO controller illustration

3.2. Proposed compensator

As shown in Figure 5, the PI controller acts as a compensator to compensate for the packet loss that occurs through transmitting the signal over a wireless network caused by errors in data transmission or network congestion [37], [38]. This work applies the PI controller in the feed-forward loop when the packet loss rate reaches above 85 percent. Figure 5 shows the control system with the PI controller. The optimization technique is used to tune the PI parameters (Kpc, Kic) to find the optimal value which gives the desired performance. From Figure 5, the mathematical equation of the PI controller can be illustrated as (12):

$$C_{PI}(S) = K_{Pc} + \frac{K_{ic}}{s} = \frac{K_{pc}s + K_{ic}}{S} \quad (12)$$

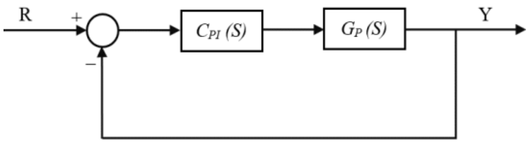

Figure 5. control system with PI controller

3.3. Optimization technique

Grey wolves is a swarm-based metaheuristic optimization technique suggested by Mirjalili *et al* [39] classified gray wolves into four classes. The first class is alpha (α), this class is accountable for making decisions and leading the group. The beta wolf (β) is the second class, and these wolves supply advice to the alpha. The third class is the delta wolf (δ), they present the information to alpha and beta. The fourth class is the omega wolf (ω) [40]. The simulation of the hunting process in GWO can be partitioned into three operations: searching for prey, surrounding the prey, and attacking the prey [41]. GWO has been utilized to get each controller's and compensator parameters' best values in the WNCS. The general mathematical of the motion of the wolves toward the prey can be formulated as follows [42].

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{X}\right|, \overrightarrow{D_\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{X}\right|, \overrightarrow{D_\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{X}\right| \quad (13)$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1}.(\overrightarrow{D_\alpha}), \overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2}.(\overrightarrow{D_\beta}), \overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3}.(\overrightarrow{D_\delta}) \quad (14)$$

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \quad (15)$$

3.4. Proposed schemes

The block diagram of the control system over a wireless network, as presented in Figure 6, is simulated using MATLAB and true-time simulator. The arm and rod were controlled simultaneously by FOPI-FOPD and PI-PD controllers while the control and feedback signals were sent over the wireless network. Data packets transmitted between actuator, controller, and sensor might be lost, leading to the control system's failure. This means designing a control system to handle packet losses and reduce their impact. This paper introduces a study about reducing the packet loss effect on control over a wireless network by designing an optimal and robust controller.

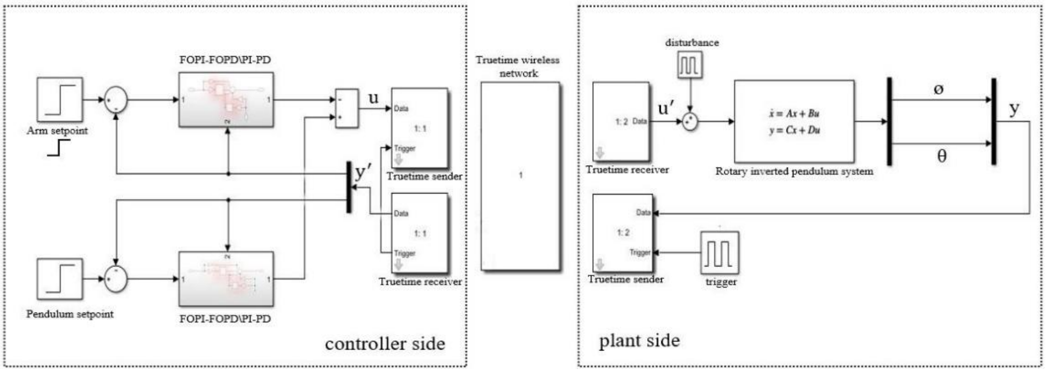

Figure 6. WNCS Simulink block diagram

As shown in Figure 7, there are two control signals for the system when u denotes the control signal at the controller side, and u' denotes the control signal at the plant side after packet loss through transmission. u' can be formulated as:

$$u' = u\,(1 - \delta_u) \tag{16}$$

when δ_u is the packet loss probability rate in the feed-forward loop, it changes between the value of 0 to 1. Similarly, y denotes the system output signal at the plant side and y'denotes the system output signal at the controller side after affecting by the packet in the feedback loop loss through transmission operation. y' can be expressed as:

$$y' = y\,(1 - \delta_y) \tag{17}$$

when δ_y is the packet loss probability rate in the feedback, it changes between the value of 0 to 1. The proposed controller can maintain the system at a stable state with a packet loss rate from 0 to 85%. In case of the packet loss rate increases above 85%, the PI controller has been used as a compensator to handle the packet loss rate rising. Figure 7 illustrates the system block diagram with the presence compensator. $\hat{u}$ can be formulated as:

$$\hat{u} = u'\,(K_{Pc} + \frac{K_{ic}}{s}) \tag{18}$$

when $\hat{u}$ represents the compensated control signal.

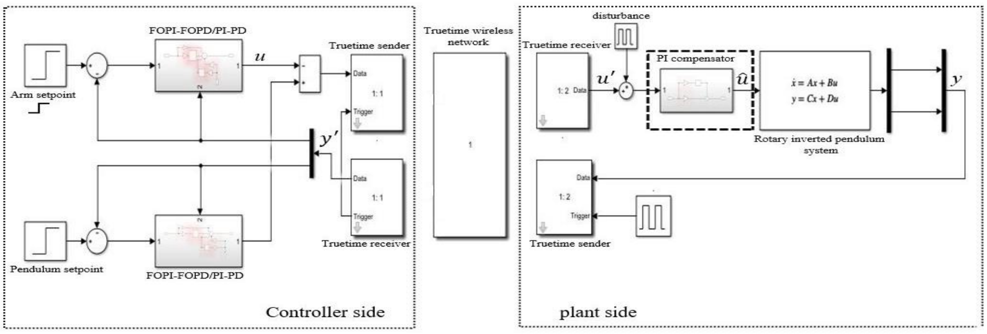

Figure 7. WNCS with compensator Simulink block diagram

4. RESULTS AND DISCUSSION

In this work, the packet loss rate (P_{loss}) is supposed to increase incrementally between 0.1-0.9. For each P_{loss}, the plant response and ITSE are considered in the comparison between the performance of the two RIP controlled system. As explained earlier, the RIP system is considered an example of designing the SIMO approach. The pendulum rod must remain in the upright position and take into consideration the stability of the arm at the same time. In the case of the unbalancing pendulum rod, the controller generates a suitable control signal to achieve a rotational move lead to maintaining the pendulum rod in the vertical position. When packet loss occurs, the actuator will not fully receive the signal generated by the controller, this leads to disturbances in the system being controlled, and with increasing package loss, the system may become unstable. In this work. ZigBee was utilized for wireless communication with the following parameters, the transmission bit rate is 250 Kbps, transmission power is 20 dBm, and receiver signal threshold is -40 dBm. In addition, the sampling time is 0.0014 s applied in the simulation.

The fractional and integer controllers have been applied to the RIP system to control the pendulum rod in the vertical position. The unit step response as a reference input was given at the arm for both controllers. For a fair comparison, the same parameters are used for both controllers with additional parameters of the fractional controller (λ and μ), improving the system performance when packet loss occurs. From Figures 8(a)-(f), it is obvious that the performance of the FOPI-FOPD controller is better than the PI-PD controller. Figure 8 shows the response of arm angle for both controllers with various P_{loss}.

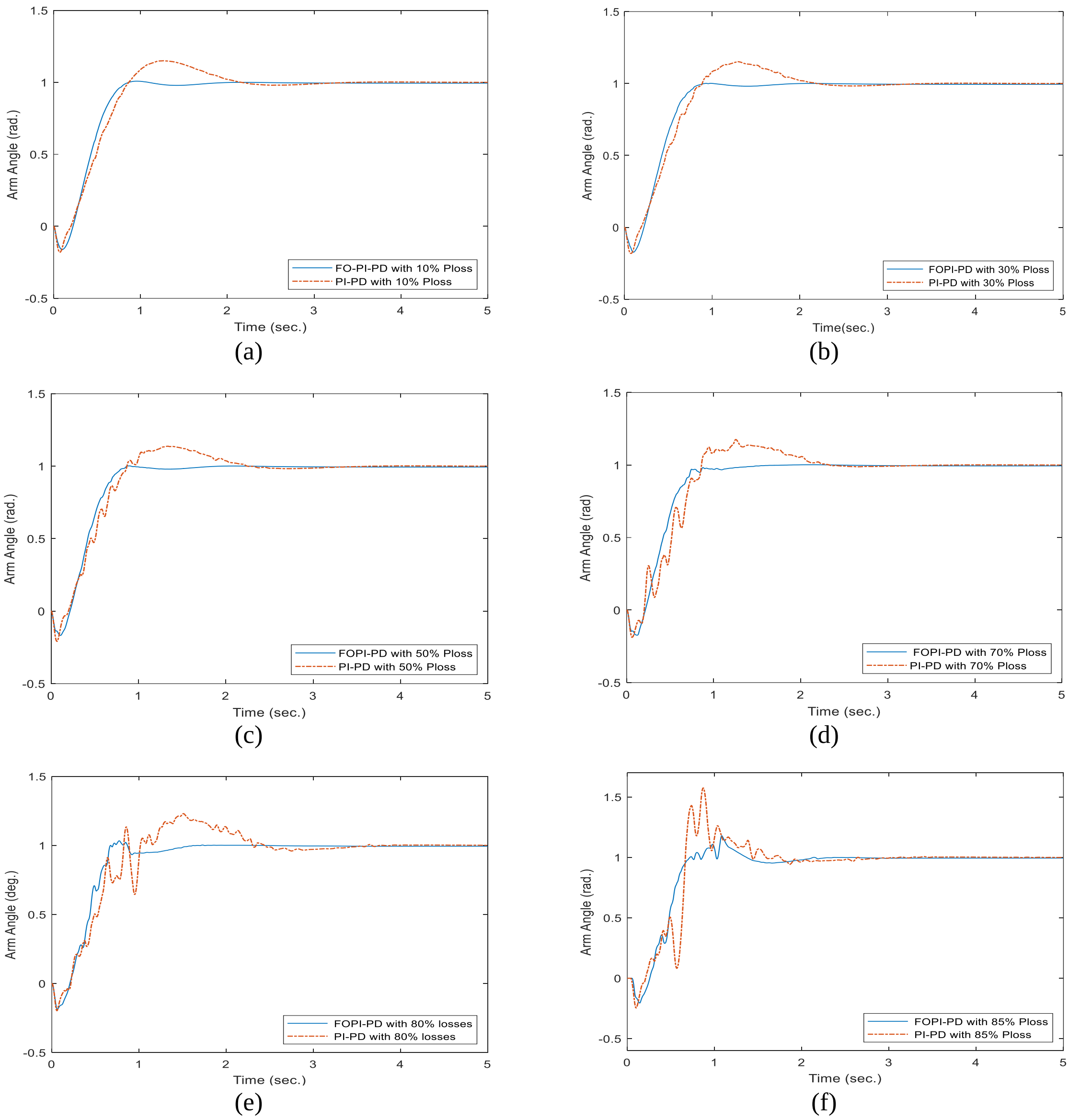

Figure 8. Simulation results of the arm angle response with various P_{loss} (a) P_{loss}=10%, (b) P_{loss}=30%, (c) P_{loss}=50%, (d) P_{loss}=70%, (e) P_{loss}=80%, and (f) P_{loss}=85%

The Figures 8(a)-(f) results showed that the FOPI-FOPD controller gave better performance than the PI-PD controller. The fractional controller reduced the impact of packet loss on the control system when transmitting the control signal wirelessly. Figures 9(a)-(f) illustrates the response of the pendulum rod with various P_{loss}. The result showed that the FOPI-FOPD controller could reduce the fluctuation produced by packet loss over a wireless network.

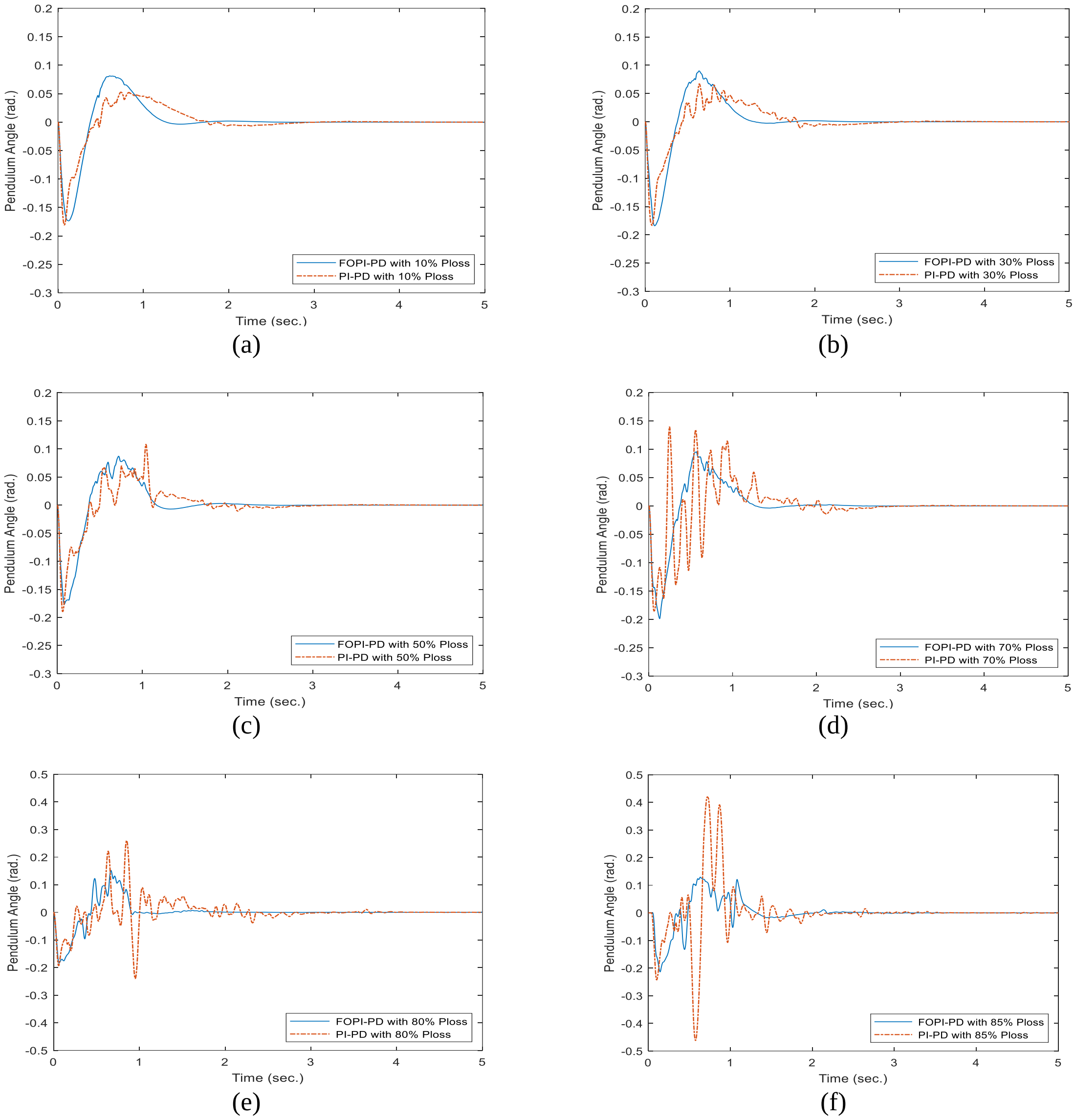

Figure 9. Simulation results of the pendulum rod with various P_{loss} P_{loss} (a) P_{loss}=10%, (b) P_{loss}=30%, (c) P_{loss}=50%, (d) P_{loss}=70%, (e) P_{loss}=80%, and (f) P_{loss}=85%

The system becomes unstable when the P_{loss} increases by more than 85%. The proposed PI controller can be used as a compensator to compensate for data losses when reaching 85%. Figures 10(a)-(d) shows the response of the arm and the pendulum rod for both controllers with P_{loss} between 0.85 to 0.92 using the PI compensator.

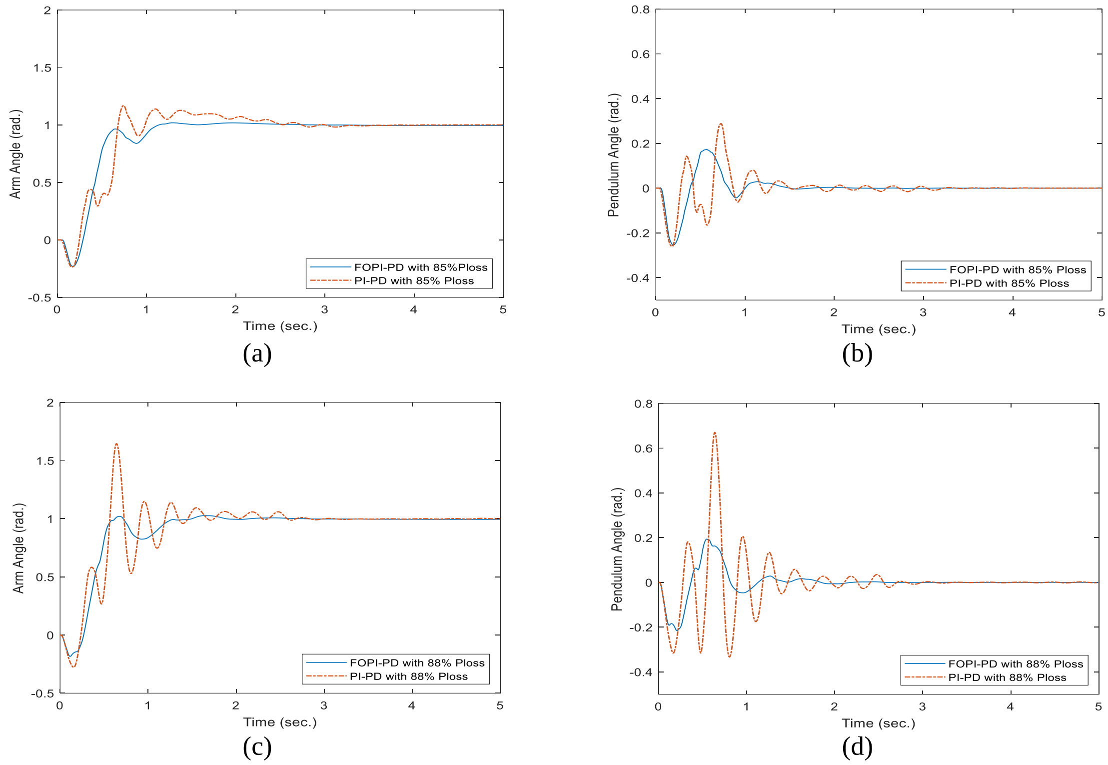

Figure 10. Response of arm and pendulum with PI compensator (a) arm response with P_{loss}=85 %, (b) pendulum response with P_{loss}=85%, (c) arm response with P_{loss}=88 %, and (d) pendulum response with P_{loss}=88%

In the case of applying PI-PD controller, at a packet loss rate above 88%. The compensator cannot compensate for the lost data, leading to an uncontrolled system and becoming unstable. However, in the FOPI-FOPD controller, the compensator can compensate for the lost data to 92%. Figures 11(a) and (b) showed the response of the arm and the pendulum rod with 92% P_{loss} when applied FOPI-FOPD controller and compensator. Figure 12 illustrates the effect of increasing the packet loss ratio on the ITSE in each FOPI-FOPD and PI-PD controller, also the action of the compensator is presented.

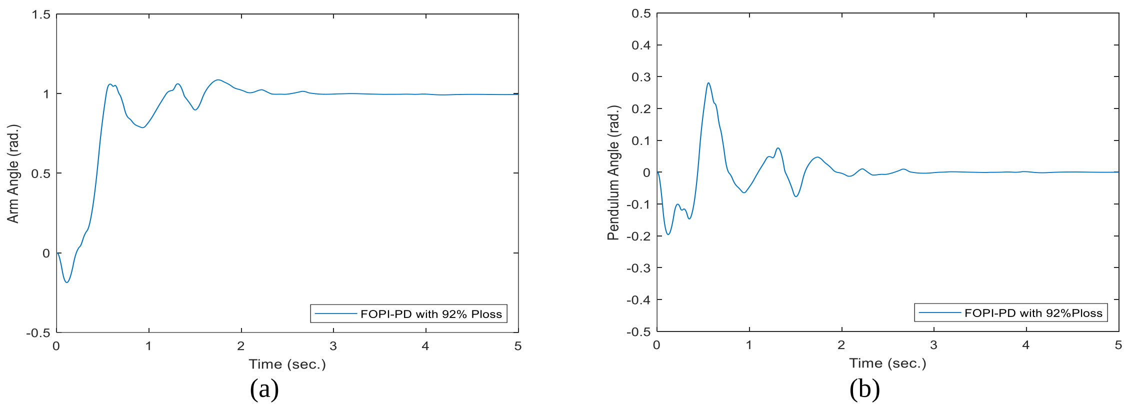

Figure 11. The response of the arm and pendulum 92% losses and the compensator (a) arm response with P_{loss}=92% and (b) pendulum response with P_{loss}=92%

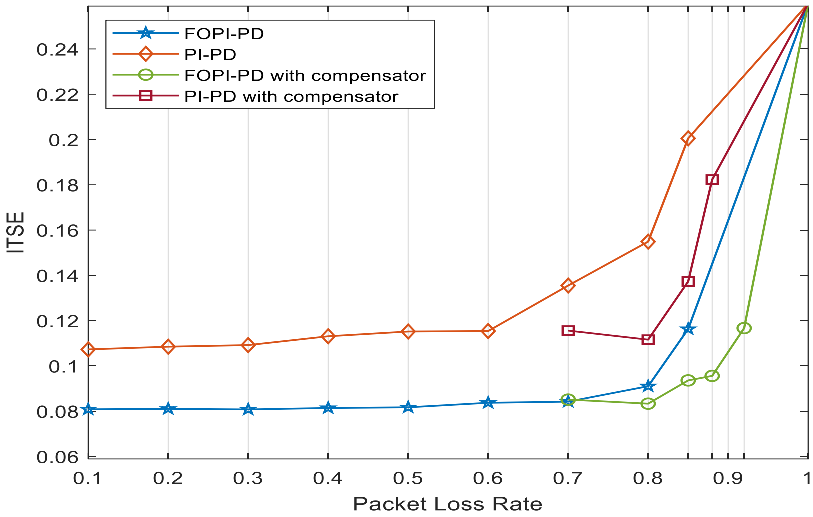

Figure 12. Packet loss ratio versus ITSE

5. CONCLUSION

WNCS has managed the unreliable control signal transmission between the controller and the plant. FOPI-FOPD and PI-PD controllers have been used to control the RIP system. The simulation results using the MATLAB/truetime simulator proved that the fractional-order controller is more efficient than the integer-order controller in reducing the effect of packet loss on the system's stability. The results showed the superiority of FOPI-FOPD on the PI-PD controller in reducing the oscillation in the arm and pendulum rod, which occurs due to packet loss. PI controller is proposed as a compensator to decrease the effect of high packet loss percentages above 85%. The results showed the compensator's ability to maintain the system in the stability region with P_{loss} from 85% to 92%.

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