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Design of an Optimal Controller for a Propeller-Pendulum System using the PSO Technique

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ABSTRACT

A new model for the non-linear propeller-pendulum system is derived in this study. The model takes into consideration the effects of external disturbances and the properties of the pendulum elements. Two systems with PID controllers are simulated. In the first system, Simulink is used to implement the system and tune the PID parameters. In the second system, a MATLAB script is used to simulate the system and tune the PID parameters. The scrip uses the Runge-Kutta method for solving the system's equation and uses particle swarm optimization (PSO) to tune the parameters. Further, both systems were investigated under two disturbance conditions. The performance of these systems is evaluated based on comparing the settling time, the peak overshoot, and the integral of the absolute errors (IAE). The results show that when there is no disturbance, both systems are capable of tracking the desired signal successfully. However, the results also show that the application of disturbances causes the first system to lose its smooth response. In contrast, the second system demonstrates a robust response and effective countermeasures to disturbance effects. The results of unit step disturbance are as follows: the settling time, peak overshoot, and IAE of the first system are 13.16s, 11.6%, and 1.706, respectively. Further, the settling time, peak overshoot, and IAE of the second system are 2.388s, 6.6%, and 0.299, respectively. It can be concluded that Simulink is not recommended to be used for tuning the PID controller in the presence of disturbances.

Keywords: PID controller, Non-linear system, Runge-Kutta technique, Simulink model, Integral of the Absolute Errors (IAE).

1. INTRODUCTION

The propeller-pendulum system is a pendulum that uses the propeller's propulsion to adjust its angular position. Such systems have practical applications in robotics and autonomous systems. In general, there are two factors that govern the motion of such a pendulum: the

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gravitational force and the thrust of the attached propeller. These two forces necessitate the use of a controller for the pendulum to adjust its position precisely. This makes the system an intriguing subject for study and research on dynamic control **(Salman and Saleh, 2022; Rafiuddin and Khan, 2023).**

The literature contains a wide range of control techniques for propeller-pendulum systems, for example, the PID controller, the sliding mode controller, the adaptive super-twisting controller, the linear quadratic regulator, the fuzzy logic controller, and the adaptive backstepping control (**Hamoudi, 2016; Saud and Mohammed, 2017; Saud and Hasan, 2018; Assael et al., 2021; Hamoudi and Rasheed, 2023)**.

Generally, PID controllers devote significant attention to being used in controlling many systems. This is because their handling and implementation are simple. Unfortunately, PID controllers operate effectively only on linear systems. However, non-linear systems can utilize PID controllers if an advanced tuning technique is employed to determine their parameters. Because of this, most research on propeller-pendulum systems controlled by PID focuses on finding a suitable way to make the PID parameters work better **(Nagaraj and Murugananth, 2010; Mohammadbagheri and Yaghoobi, 2011; Lucina et al., 2021).**

In this context, fuzzy logic is used to tune the PID gains, but unfortunately, such controllers require very careful drafting of logic rules to perform the tuning process correctly **(Taskin, 2017; Saleem et al., 2020; Phu et al., 2020).**

Alternately, there are many attempts to use AAN and genetic algorithms to determine the parameters of PID controllers. Such algorithms require a large amount of data in order to be learned, and they also involve complex operations **(Günel and Ankarah, 2017; Ahmad et al., 2021; Mishra et al., 2023).**

In addition, swarm optimization techniques have seen significant advancements in their capabilities, including the ability to handle problems with many variables and high dimensions, as well as being straightforward to construct. Several areas of study have successfully employed these techniques. Both classical and advanced controllers incorporate these techniques to improve their performance **(Shami et al., 2022; Bharathi et al., 2022; Pawan et al., 2022).** For example, gorilla troop optimization is used to solve the tuning problem of the PID controllers (**Ahmed and Al-Khazraji, 2023; Mostafa et al., 2023; Ghith and Tolba, 2023)**. Particle swarm optimization (PSO) is used to perform the tuning of the PID controllers **(Mustafa et al., 2020; Ahmed and Al-Khazraji, 2022; Rahayu et al., 2022).** Ant colony optimization is used for the tuning of the PID parameters **(Zhang and Zhang, 2021; Al-Khazraji et al., 2022; Wang et al., 2023)**.

Furthermore, it can be found in the literature that Simulink is used to simulate propeller-pendulum systems with a PID controller **(Oliveira et al., 2014; Salem et al., 2024)**. Actually, Simulink linearizes the system when it performs PID parameter tuning. Such linearization can affect the performance of the PID controller. One of the aims of this paper is to investigate the validity of using Simulink to tune the parameters of the propeller-pendulum system's PID controller.

A nonlinear propeller-pendulum system with a PID controller is introduced in this study. A new model for the system is derived that considers external disturbances and the effects of the pendulum elements (rod and propeller) on the system's dynamics. Two non-linear propeller-pendulum systems with PID controllers are investigated. In the first system, Simulink is used to implement the system and tune the parameters of the PID controller. In the second system, a MATLAB script is used to simulate the derived non-linear model. The scrip utilizes the Runge-Kutta method (ode45) for solving the system's non-linear model and uses particle swarm optimization (PSO) to tune the PID parameters. Both systems will be investigated under two different disturbance conditions (unit step and transient). The performance of them will be evaluated based on comparing the settling time, the peak overshoot, and the integral of the absolute errors (IAE). Further, the validity of using Simulink to tune the parameters of the PID controller in a propeller-pendulum system will be studied.

2. MATHEMATICAL MODEL

In order to exert effective control over the propeller pendulum system, it is necessary to acquire a precise mathematical model that accurately describes the system's dynamics. **Fig. 1** shows the schematic diagram of the propeller pendulum system.

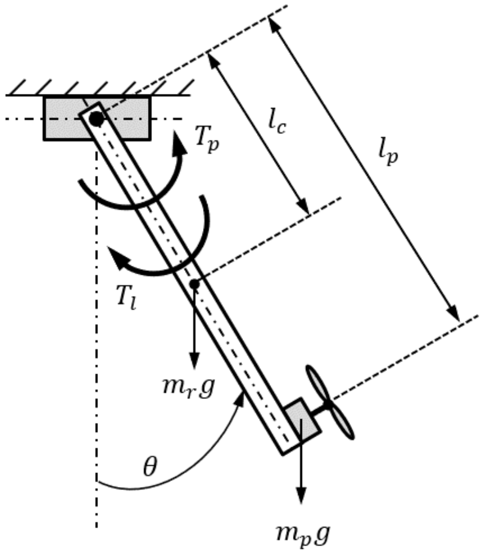

Figure 1. Schematic diagram of the propeller-pendulum system.

Fig. 1 shows that the propeller-pendulum system includes a DC motor that is connected at the end of the pendulum rod. A DC motor rotates the propeller, producing torque $T_p(t)$, which propels the rod at an angular velocity $\dot{\theta}(t)$ and acceleration $\ddot{\theta}(t)$. $T_l(t)$ is the disturbance torque. In such system, the motor DC input voltage is the control input $u(t)$, while the angle $\theta(t)$ is the control variable. From Newton's second law, the equation of motion of the propeller pendulum can be expressed as

$$J\ddot{\theta}(t) + C\dot{\theta}(t) + g\left(m_r l_c + m_p l_p\right)\sin\theta(t) = T_p(t) - T_l(t) \tag{1}$$

The variables J, m_r, m_p, and g represent the rod's moment of inertia, its mass, the mass of the propeller, and the gravitational acceleration (9.81 m/s^2), respectively. As shown in **Fig.1**, l_c represents the distance from the center of rotation to the rod's center of mass, and l_p represents the distance from the center of rotation to the propeller's center. The damping coefficient C, which signifies the viscous damping the pendulum induces, is included in the equation above. The input voltage u(t) and the torque T_p have the following relationship:

$$T_p(t) = k_m u(t) \tag{2}$$

Here, k_m represents the DC motor's constant. Now, by substituting Eq. (1) into Eq. (2), the following relationship can be obtained:

$$\ddot{\theta}(t) = \frac{-C\dot{\theta}(t) - g(m_r l_c + m_p l_p)\sin\theta(t) + k_m u(t) - T_l(t)}{J} \quad (3)$$

Going forward in the modeling process, it is preferable to rewrite the above equation in state-space representation. By assuming that $x_1(t)$ denotes the angular position $\theta(t)$ and $x_2(t)$ the angular velocity $\dot{\theta}(t)$, and applying these assumptions to Eq. (3), the subsequent equations can be written as

$$\dot{x}_1(t) = x_2(t) \quad (4)$$

and

$$\dot{x}_2(t) = \frac{-Cx_2(t) - g(m_r l_c + m_p l_p)\sin x_1(t) + k_m u(t) - T_l(t)}{J} \quad (5)$$

3. PID CONTROLLER

Industrial control systems commonly employ PID controllers as a type of feedback control system. The control signal in the PID controller is determined based on the error signal $e(t)$. This $e(t)$ is defined as the difference between the measured output and the reference signal **(Abdulwahhab and Abbas, 2020; Borase et al., 2021)**. **Fig. 2** shows how to use three mathematical terms in PID to generate the required control signal, naming the controller according to the first letter of each term. These terms are proportional, integral, and derivative. The proportional term that produces a control signal depends directly on the error signal gain K_p. The integral term generates the control action by combining the integration of the error signal and the gain K_i. The derivative term generates the control signal based on the time rate of the error signal and the gain K_d. Finally, the PID controller's control action is the sum of all three terms. The law of the PID controller can be expressed as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (6)$$

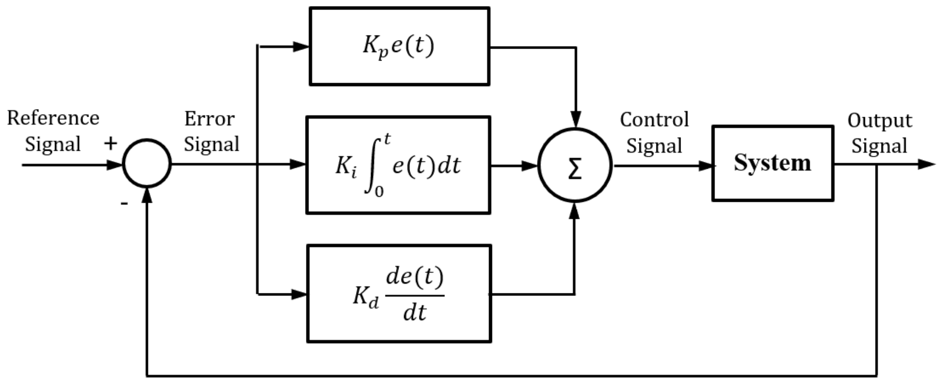

Figure 2. Block diagram of a system controlled with PID.

The design key of the PID controller is to find the right value of each of its gains: K_p, K_i, and K_d. Unfortunately, these parameters are often identified based on the trial and error. This in addition non-linearities handling are the major drawbacks of the PID controller. To overcome such drawbacks, an optimization technique is needed **(Reynoso-Meza et al., 2022)**.

4. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a computer technique used to solve optimization issues by emulating the social behavior of fish or birds. In this technique, a swarm of particles moves throughout the problem space to find the best solution. All particles change their locations and velocities based on their own and others' experiences. Generally speaking, machine learning, economics, and engineering are among the many disciplines where PSO is a useful and widely used instrument. PSO is a strong technique because it can quickly converge to excellent solutions, even in complex multidimensional domains. The ith particle's velocity can be expressed as follows **(Wang et al., 2018; Al-Araji and Ibraheem, 2019):**

$$v_i(t) = \theta v_i(t-1) + c_1 r_1 \left(p_{best,i} - x_i(t-1)\right) + c_2 r_2 \left(g_{best} - x_i(t-1)\right) \quad (7)$$

and the position of the ith particle $x_i(t)$ is expressed as

$$x_i(t) = x_i(t-1) + v_i(t) \quad (8)$$

The following points summarize the optimization process adopted in this paper:

1- Initialization:
- Define parameters: population size N_p, max iterations T_{max}, cognitive coefficient c_1, and social coefficient c_2.
- Initialize each particle's position and velocity randomly within the given bounds.
- Set each particle's personal best p_{best} to its initial position.
- Evaluate the fitness of each particle's initial position and update the global best position g_{best} if it's the best encountered so far.

2- Iteration Loop:
- For each iteration, update the velocity and position of each particle:
- The velocity is updated based on three components:
- The current velocity
- The cognitive component: the difference between the particle's best-known position p_{best} and its current position, scaled by $c_1$and a random factor r_1.
- The social component: the difference between the global best-known position g_{best} and the particle's current position, scaled by c_2 and a random factor r_1.
- The particle's new position is calculated by adding the updated velocity to its current position.
- Evaluate the fitness of the new position. If it's better than the particle's personal best fitness, update p_{best}. If it's better than the global best fitness, update g_{best}.

3- Termination:
- After reaching the maximum number of iterations, return the global best position as the optimal solution.

5. SIMULINK MODEL

Simulink supports rapid prototyping and testing of controlled systems. **Fig. 3** shows the constructed Simulink model for propeller-pendulum with a PID controller. This model is implemented to investigate the validity of using Simulink to tune the PID parameters for such a non-linear system. Simulink is provided with a PID tuner to calculate the optimal parameters of this controller. The tuner does such a task by linearizing the model and using optimization frequency-domain techniques. This tuner is interactive, allowing users to fine-tune response time and robustness for optimal performance. In the Laplace domain, the PID controller's law in Simulink is expressed as **(Dakheel et al., 2022).**

$$U(s) = \left(K_p + K_i \frac{1}{s} + K_d \frac{N}{1+N\frac{1}{s}}\right) E(s) \tag{9}$$

where $U(s)$ is the control signal in Lapalce domain, $E(s)$ is the error signal in Laplace domain, and N is a filter coefficient.

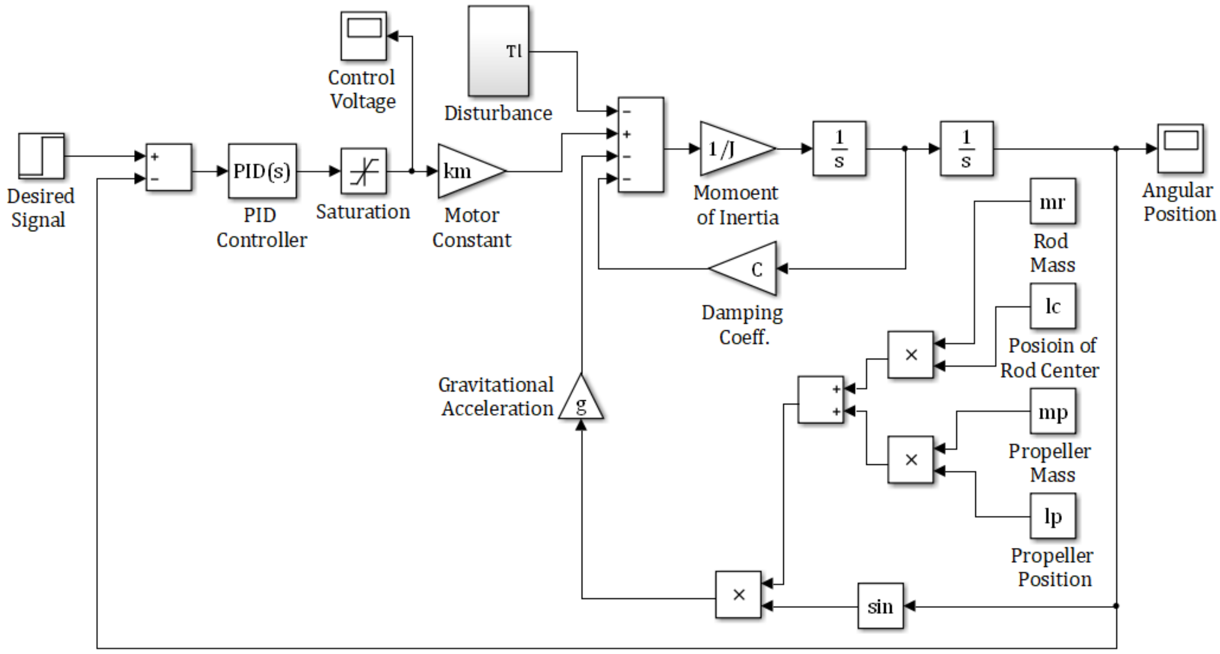

Figure 3. Simulink model of propeller-pendulum with PID controller.

6. CASE STUDY

In this section, two non-linear propeller-pendulum systems controlled with PID controllers are investigated. The first system is implemented using the Simulink model shown in **Fig. 3**. The second system is simulated using a MATLAB script. This script uses the Runge-Kutta (ode45) method to solve the system deferential equations (Eqs. (4) and (5)), and it utilizes the PSO to tune the PID parameters. The parameters used in the PSO process are listed in **Table 1**.

Table 1. Parameters used with PSO

Parameter	**Symbol**	**Value**
Population Size	N_p	25
Number of Iterations	T_{max}	50
cognitive coefficient	c_1	2
social coefficient	c_2	2

Table 2 provides the propeller-pendulum system's parameters. It is worth mentioning that the saturated voltage of the DC motor is ±50 V. The obtained optimal gains K_p, K_i, and K_d of both investigated are shown in **Table 3.**

Table 2. Specification of the propeller-pendulum system.

Parameter	**Value**	**Unit**
J	0.0106	$kg\ m^2$
C	0.0076	Nms/rad
m_r	0.1	kg
m_p	0.19	kg
l_c	0.15	m
l_p	0.3	m
k_m	0.0296	Nm/V

Table 3. Optimal parameters of the PID controllers

Parameter	First system	Second system
K_p	57.75	48.79
K_i	12.62	23.83
K_d	14.15	9.58
N	80.63	-

The next figures, which display the simulation results for both investigated systems, use the simulation time in different ranges in order to enhance clarity and display all the details. **Fig. 4** shows the responses of both systems without any disturbance. The results show that both systems are functioning properly. They have almost the same settling times. The results show that there is a slight advantage in peak overshoot for the second system, which is less than the first system by 5%. Furthermore, **Fig. 5** shows the control signals for the two investigated systems.

In this situation, the first system clearly has an advantage, as its control voltage is 27.28% lower than that of the second system. For the case without disturbance, it can be said that Simulink gives fair results in simulating non-linear propeller-pendulum systems and tuning its PID controller. In the next simulations, a unit-step disturbance is applied at time 2 s to both investigated systems. **Fig. 6** shows that the disturbance has no notable effect on the response of the second system. It also shows that the first system suffers considerable fluctuations in response. This occurs because of the non-linearity of the propeller-pendulum system, which becomes significant. Therefore, the PID controller of the first system was unable to track the desired signal effectively. The settling time for the first system is about 13.16 s, while the settling time for the second system is about 2.388 s.

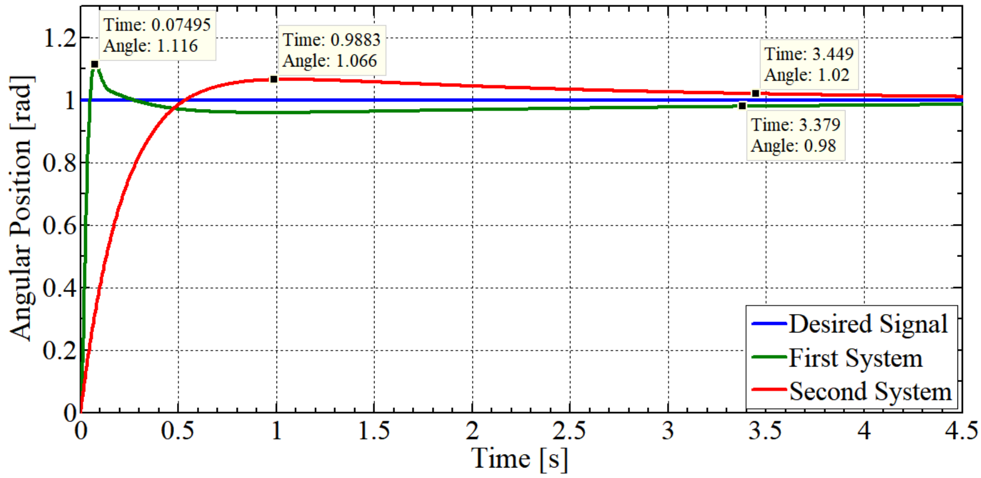

Figure 4. Response of the propeller-pendulum system with no disturbance

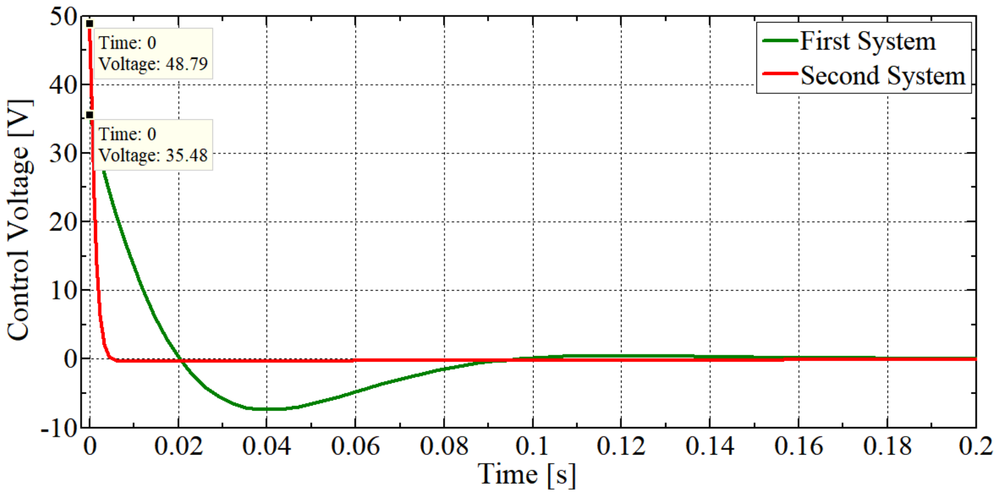

Figure 5. Control voltage for the simulated PID controllers with no disturbance

Additionally, **Fig. 7** shows the control voltage for both PID controllers, where there is no considerable difference from the case where no disturbance is applied. In this case, it can be concluded that Simulink cannot be used to tune the PID controller.

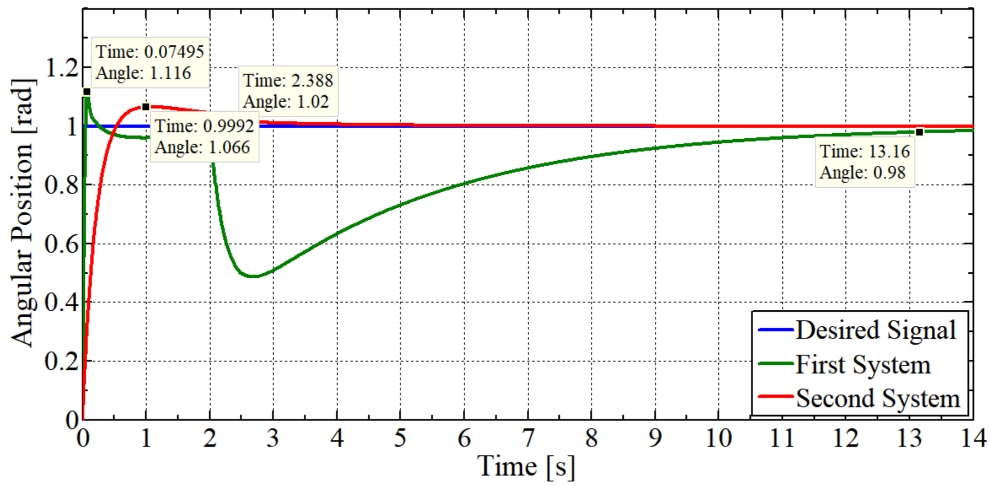

Figure 6. Response of the propeller-pendulum system with unit step disturbance

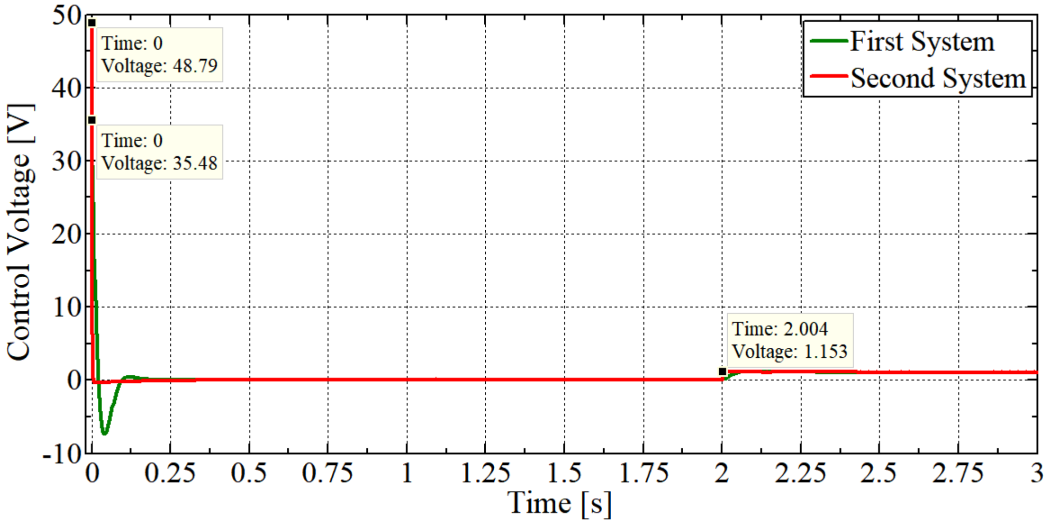

Figure 7. Control voltage for the simulated PID controllers with unit step disturbance.

Another type of disturbance is applied to the investigated systems. The mathematical description of this disturbance can be written as

$$T_l = 1 - \cos 4\pi t \qquad 2 \le t \le 2.5 \tag{10}$$

Figs. 8 and **9** depict the response and the control voltage for both investigated systems subjected to the disturbance given by Eq. (10). It is clear that the conclusion deduced earlier about the limitation of using Simulink to tune PID controllers is still valid. The PID controller, tuned with PSO, enables the second system to respond smoothly and track the desired signal effectively.

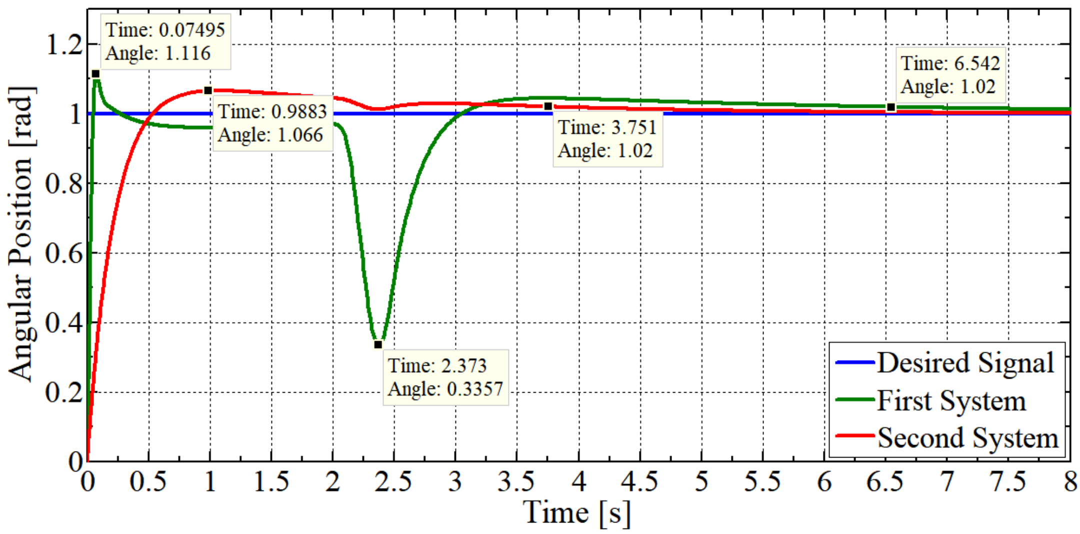

Figure 8. Response of the propeller-pendulum system with the disturbance given by Eq. (10)

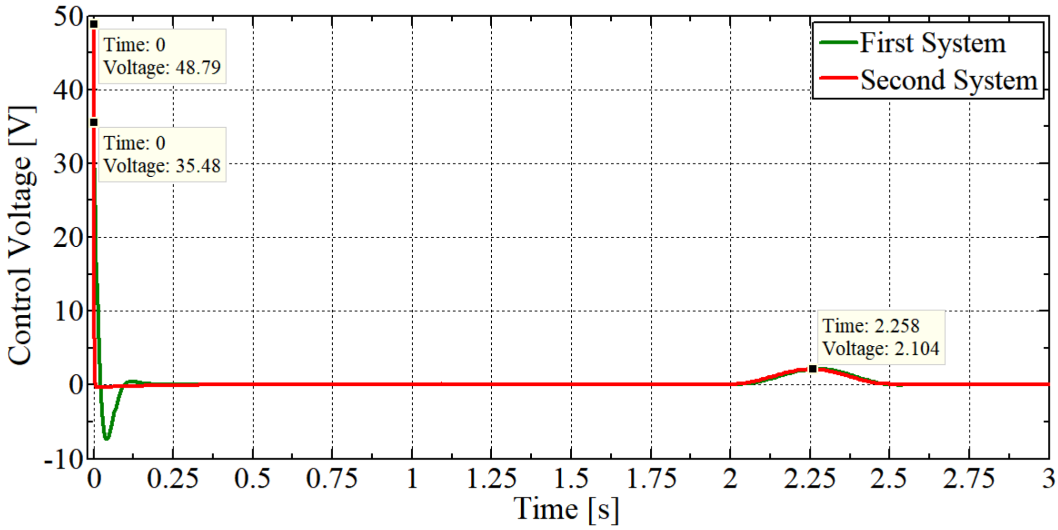

Figure 9. Control voltage for the simulated PID controllers with the disturbance given by Eq. (10)

In control systems, the Integral of Absolute Errors (IAE) is a performance index used to evaluate the error over time. IAE provides a scalar quantity representing the cumulative sum of the absolute values of the error signal. IAE is useful for assessing the performance of a controller in minimizing errors over time. IAE can be expressed as: **(Fernandez Cornejo et al., 2020)**

$$\mathrm{IAE} = \int_0^t |e(t)|\, dt \tag{11}$$

Generally, IAE is used to tune PID controllers to achieve the desired performance. Lower IAE values indicate better performance in terms of error minimization. **Fig. 10** shows clearly that the IAE index for the PID controller tuned with PSO is 0.299 and that for the PID controller tuned with Simulink is 1.708. This means that the IAE index for the PID tuned with the PSO is much smaller than that for the PID tuned with Simulink. Therefore, it can be said that it has better performance.

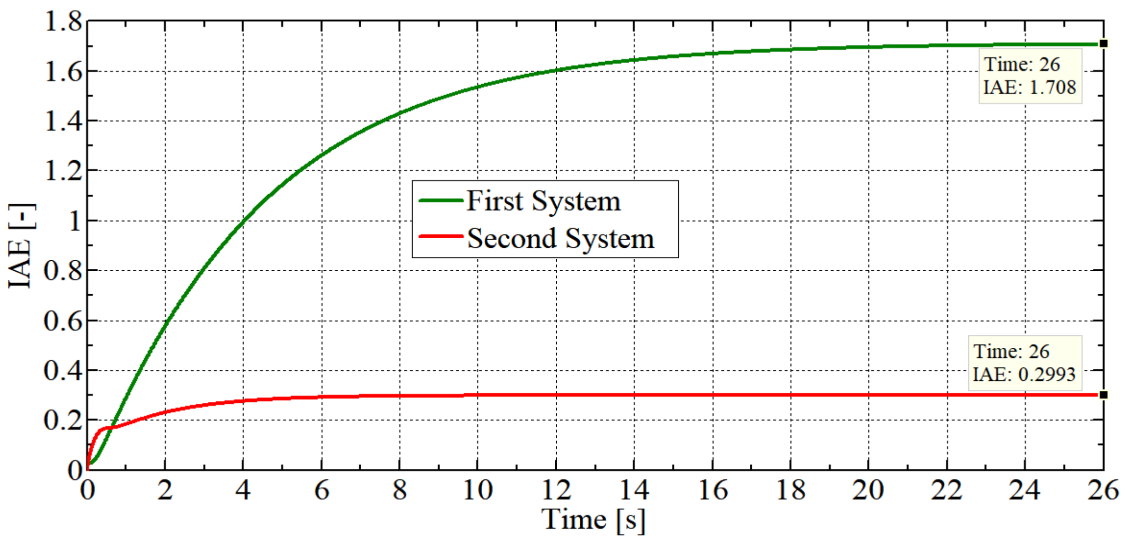

Figure 10. IAE index for both PID controllers

7. CONCLUSIONS

Two non-linear propeller-pendulum systems with PID controllers are investigated. In the first one, Simulink is used to simulate and tune the parameters of the PID controller. The second system is simulated and tuned using a MATLAB code containing the ode45 command and PSO. These two systems were studied under two disturbance conditions. The first disturbance is a unit step, and the second disturbance is a single half-sine wave (transient disturbance).

The results show that when there is no disturbance, both tuning PID controllers are capable of controlling the system successfully. However, the results also show that the application of disturbances causes the first system to fluctuate in response. This is due to the increased effect of system non-linearity. On the other side, the second system shows a non-fluctuating response with effective handling of disturbance effects. Therefore, using Simulink for tuning the PID controller in non-linear systems is not recommended.

Overall, the results can be summarized as follows: For no disturbance, the settling times are almost the same for both systems, while there is about a 5% increase in peak overshoot in the first system. For the unit step disturbance, the settling time and the peak overshoot of the first system are about 13.16 s and 11.6%, respectively. The settling time and the peak overshoot for the second system are 2.388 s and 6.6%, respectively. For the second disturbance (transient disturbance), the settling time and the peak undershoot of the first system are about 6.54 s and 66.5%, respectively. The settling time and the peak overshoot for the second system are 3.75 s and 6.6%, respectively. Furthermore, the IAE index for the first system is 1.708, and the index for the second system is 0.299. This indicates that the PID tuned with PSO has much better performance than the PID tuned with Simulink for nonlinear systems.

NOMENCLATURE

Symbol	Description	Symbol	Description
C	Damping coefficient, Nms/rad.	N	Filter coefficient
c_1	Cognitive coefficient	N_p	Population Size
c_2	Social coefficient	p_{best}	Particle's personal best
$E(s)$	Laplace representation of $e(t)$	r_1 and r_2	random factors
$e(t)$	Error signal, rad.	t	Time, s
g	Gravitational acceleration, m/s^2.	$T_l(t)$	Disturbance torque, Nm.
g_{best}	Particle's global best	T_{max}	Number of Iterations
IAE	Integral of Absolute Errors	$T_p(t)$	Propeller torque, Nm.
J	Moment of inertia of the rod, kg m^2.	$U(s)$	Laplace representation of $u(t)$
K_d	Derivative gain of PID	$u(t)$	Control signal, V.
K_i	Integral gain of PID	$v_i(t)$	Velocity of ith particle
k_m	Motor's constant, Nm/V.	$x_1(t)$	State space representation of $\theta(t)$, rad.
K_p	Proportional gain of PID	$x_2(t)$	State space representation of $\dot{\theta}(t)$, rad/s.
l_c	Distance from the center of rotation to the rod's center of mass, m.	$x_i(t)$	Position of ith particle
l_p	Distance from the center of rotation to the propeller's center, m.	$\theta(t)$	Angular position, rad.

m_p	Mass of the propeller, kg.	$\dot{\theta}(t)$	Angular velocity, rad/s.
m_r	Mass of the rod, kg.	$\ddot{\theta}(t)$	Angular acceleration, rad/s^2.

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Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تصميم متحكم مثالي لنظام دفع-بندول باستخدام تقنية تحسين السرب الجزيئي

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الخلاصة

تم اشتقاق نموذج جديد لنظام المروحة-البندول غير الخطي يأخذ في الاعتبار تأثيرات الاضطرابات الخارجية وخصائص عناصر البندول. و ايظا تم محاكاة نظامين غير خطيين للمروحة-البندول يحتويان وحدات تحكم تناسبي - تكاملي - تفاضلي. في المحاكاة الاولى، تم استخدام برنامج السيمولينك (Simulink) لتنفيذ النظام وضبط معلمات وحدة التحكم. في المحاكاة الثانية، تم استخدام برنامج الماتلاب (MATLAB) لمحاكاة النموذج غير الخطي المشتق. يستخدم البرنامج طريقة رانج - كوتا (Runge- Kutta) لحل معادلة النظام و استخدم تحسين السرب الجزيئي لضبط المعلمات. علاوة على ذلك، تم التحقيق في كلا النظامين تحت حالتي اضطراب. تم تقييم أداء هذه الأنظمة بناءً على مقارنة وقت الاستقرار، والزيادة القصوى، والتكامل المطلق للأخطاء. أظهرت النتائج أنه في حالة عدم وجود اضطرابات، يكون كلا النظامين قادرين على تتبع الإشارة المطلوبة بنجاح. ومع ذلك، أظهرت النتائج أيضًا أن تطبيق الاضطرابات يؤدي إلى فقدان النظام الأول لاستجابته السلسة. في المقابل، يظهر النظام الثاني استجابة مستقرة لمواجهة تأثير الاضطرابات. حيث ان النتائج اضهرت انه عندما يتم تطبيق اضطراب خطوة وحدة (unit step)، يكون وقت الاستقرار، والزيادة القصوى، والتكامل المطلق للأخطاء للنظام الأول هي 13.16 ثانية، 11.6%، و1.706 على التوالي. من ناحية أخرى، يكون وقت الاستقرار، والزيادة القصوى، التكامل المطلق للأخطاء للنظام الثاني هي 2.388 ثانية، 6.6%، و0.299 على التوالي. يمكن استنتاج أن استخدام برنامج السيمولنك غير مستحسن لضبط وحدة التحكم نوع تناسبي- تكاملي-تفاضلي في وجود اضطرابات.

الكلمات المفتاحية: وحدة تحكم تناسبي-تكاملي-تفاضلي , نظام غير خطي، تقنية رونج كوتا , نموذج سيمولينك , التكامل المطلق للأخطاء