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Design, modeling, manufacturing, and control of dual axis stabilized system

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Abstract. Recently, Inertial Stabilized Systems (ISS) are widely spread either in military or civilian applications. It's used to stabilize and point the onboard sensors. Therefore, the accurate modeling and control is a crucial factor to design a suitable control system. In this work, two axes gimbal system is designed, modeled, manufactured, and controlled. Firstly, the stabilized system is built using solid work software. Secondly, the system mathematical model is derived for the physical system with its actuators and encoders. Thirdly, the designed model is manufactured and integrated with the suitable motors; the overall open loop system model is implemented in MATLAB (Simulink). Finally, a modified PI-D structure is designed to stabilize the ISS in an efficient manner, the simulation results show the superiority of the designed controller's performance and robustness compared to the classical PID in transient and steady state responses.

1. Introduction

Nowadays, the Inertial Stabilized Systems (ISSs) affects a crucial role in several applications either civilian or military ones such as unmanned flying systems, robotics, and camera stabilization in image processing [1], [2]. Stabilization of these systems with a gimbal is indispensable to endure the continuous tracking sensor permanently pointing towards the target with a high degree of tracking performance [2]. The stabilization concept continuously guarantees the tracking of the line of sight (LOS) by isolating the on-board sensor from operating external disturbances [3]. Stabilization process is classically performed by employing the on-board sensor in a two-axis gimbal platform. The motion of each plane (azimuth and elevation) is derived by an actuator system; the angular position of each gimbal axis is measured with a highly sensitive encoder. Then, the difference between the gimbal angle which is the LOS angle (current state) and the desired angle is the error angle which is provided to a suitable control system [2].

The designed controller of the gimbaled system is a complex issue due to the precise requirement of high tracking performance and the cross-coupling between the gimbal axes [4]. Subsequently, numerous research studies are achieved in this topic to increase the system performance and decrease the coupling effect between the platform channels. PID controller could be considered as the most reliable controller that is appropriate for several systems past and nowadays due to its simplicity and low cost. In addition to its acceptable and sufficient performance with respect to its different structures [1], [4].

In this work, a suitable design of a two-axis gimbal platform is performed to stabilize the on-board camera that will be used in target tracking; the CAD design could guarantee the system static stability [5]. Moreover, it could satisfy the system requirements, the intended 3D solid platform is established using the SOLIDWORKS software. The manufacturing of the inner and the outer loops is performed using a 3D printing machine. Modeling is an essential factor before designing a control system. Consequently, the mathematical model of the designed system with its motor is performed to represent the overall system dynamics. Then, the different structures of PID controllers are designed for the actuation system and compared with the traditional one. This paper is constructed as the following; section II represents the CAD model design and the integration of the manufactured system, section III illustrates the mathematical model of the dynamic system, the designed control system with its different structures is performed in section IV, simulation results and analysis are analyzed in section V. In conclusion, section VI introduces conclusion and the future work.

2. CAD Model Design and Manufacturing

In our case study, ISS is used to stabilize the on-board camera. Likewise, is used as a tracking system in two planes (pitch and yaw) about the X and Y axes respectively. The 3D CAD model is designed in the SOLIDWORKS software as shown in Fig. 1. This type of structure enables monitoring of the model progress and the common interface between the developer and the 3D model of ISS. Primarily, each system's component is carried out according to a specific material with thermal and mechanical characteristics. Secondly, the requirements of system tolerances and the designed constraints are accomplished, the verification of the design assembly and disassembly is performed. Lastly, validation of the intersection between the designed components throughout motion is achieved.

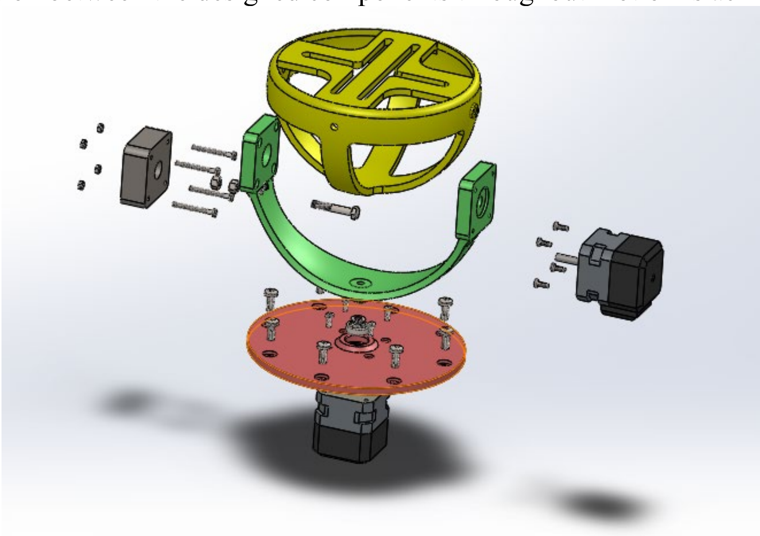


Figure 1. ISS CAD model

After the design verification, the visual approval of the considered structure is agreed, the on-board sensors (camera and IMU), besides the actuation devices which are two stepper motors are settled, and dummy loads are added to balance the masses distribution. The overall design is intended to minimize both the ISS's mass and size. In addition to accomplish symmetric mass distribution of the spinning components about the turning axes to reduce their moments of inertia [8].

Both gimbals of pitch and yaw channels are derived by stepper motors to perform the required function. The pitch and yaw motor parameters and the encoder parameters are tabulated in Table I, the IMU gyro and accelerometer range are ± 250 deg/sec and ± 2g respectively.

Table 1. Motor and the encoder parameters

Parameter	Pitch and Yaw motor	Encoder
Mass	1.23 Kg	0.13 Kg
Moment of Inertia	0.2791 Kg.m2	0.0003684 Kg.m2
Type	Bipolar Stepper	Optical incremental
R_a	3.5 ohms	-
I_a	1 A	20 mA
L_a	4.5 mH $\pm 20\%$	-
No. of leads/Output signal	4	2
Voltage	3.5 V	4.5 to 5.5 V
Frequency	1900 Hz	$\leq$60MHz
Step angle/Resolution	1.8 deg	1000 PPR

There are design restrictions in this structure such as the angular motion are $\pm 180^{o}$ in the yaw plane, and $\pm 50^{o}$ in the pitch, with angular velocity and acceleration of $120^{o}/s$ and $25^{o}/s^2$ respectively for both directions. On the other hand, the manufacture of the enhanced ISS model is performed. All of the designed portions of the Inertial Stabilized Platform (ISP) system are factory-made using a 3-D printer, the material of each part is chosen to achieve the appropriate strength and mass, the position of design supports, and its parts size are definite for improved model integration, and the manufactured model's weight is compared with its CAD model for verification purposes. In Fig. 2 the manufactured ISP parts are presented with its complete components such as bearings, belts, and bolts as well as electrical components such as motors with its encoders and drivers, the entire assembly is checked for flexibility of the desired motion.

Figure 2. Manufactured ISP with its component

3. Mathematical Model

The mathematical model of elevation (pitch) and azimuth (yaw) gimbals could be described as [6] with consideration of torque relation about the controllable axis could be presented as the following:

$$J_{ay}\dot{q}_a = T_{y-tot} + (J_{az} - J_{ax})p_a r_a + J_{xz}(p_a^2 + r_a^2) - J_{yz}(\dot{r}_a - p_a r_a) - J_{xy}(\dot{p}_a - q_a r_a) \quad (1)$$

Where $[J_{ax}\, J_{ay}\, J_{az}]$ ….. Mass moment of inertia.

[p q r] ….. Traditional notations for roll, pitch, and yaw.

In equation (1), T_{y-tot} is the total external torque about y (pitch torque) which is the motor torque added to the external torque. For simplicity, the products of inertia are considered to be very small. So, it could be neglected ($J_{xy} = J_{xz} = J_{yz} = 0$). In addition to, the symmetric shape would result in ($J_{ax} = J_{az}$). The equation (1) could be simplified to:

$$J_{ay}\dot{q}_a = T_{y-tot} = T_{motor} + T_{dist-y} \quad (2)$$

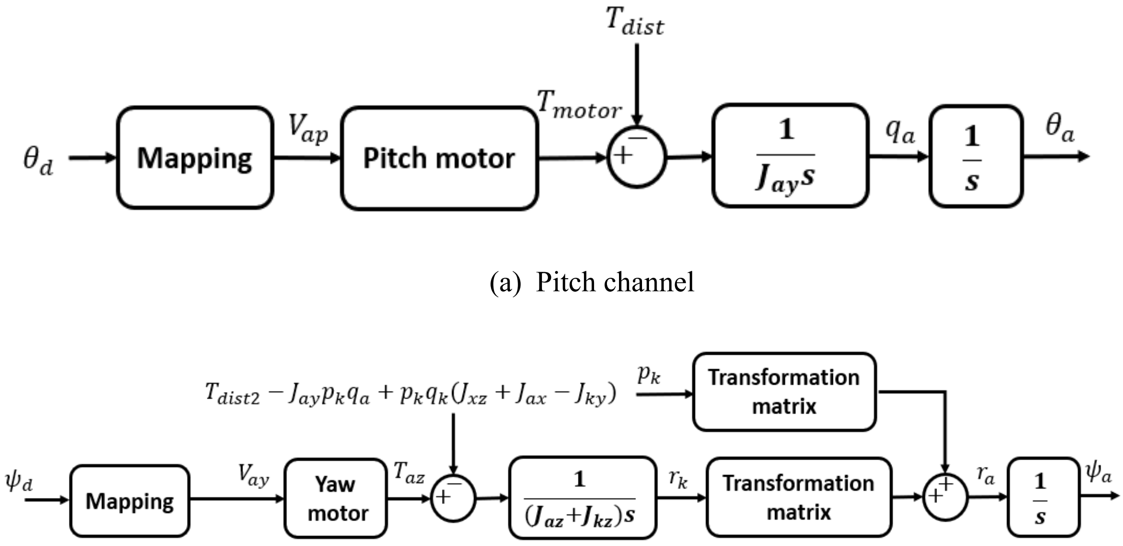
As shown in (2), the angular velocity in the pitch direction is not affected by the coupling between the motor and the pitch gimbal motion. On the other hand, the of motion in the yaw direction according to [6] could be derived as:

$$J_t\dot{r}_t = T_{z-tot} + T_{dist1} + T_{dist2} + T_{dist3} \quad (3)$$

In which, J_t is the total inertia about z of the two gimbal-axis, T_{z-tot} is the total torque about the yaw plane. T_{dist1}, T_{dist2}, and T_{dist3} represent the different gimbal external disturbances. For the simplified model and by assuming the products of inertia of the yaw gimbal are zero. So, the final equation is represented as:

$$(J_{az} + J_{tz})\dot{r}_t = T_{az} - T_{dist2} - J_{ay}p_k q_a + p_k q_k (J_{xz} + J_{ax} - J_{ky}) \quad (4)$$

Now, we could integrate the stepper motors with the two gimbals to investigate the pith and yaw channels dynamic model, the overall open loop model is presented as shown in Fig. 3. In either of azimuth or elevation direction, the input is the armature voltage of the Stepper motor, and the output is the angular velocity of the gimbal [10].



(a) Pitch channel

(b) Yaw channel

Figure 3. The dynamic model of the ISP

The pitch channel is tested by using the doublet input angle to the open loop structure to estimate and analyze the open loop performance of the dynamic system. As shown in Fig. 4, the pitch channel dynamics couldn't follow the desired input. There is a large steady state error. Also, the transient response should be improved through using a suitable controller.

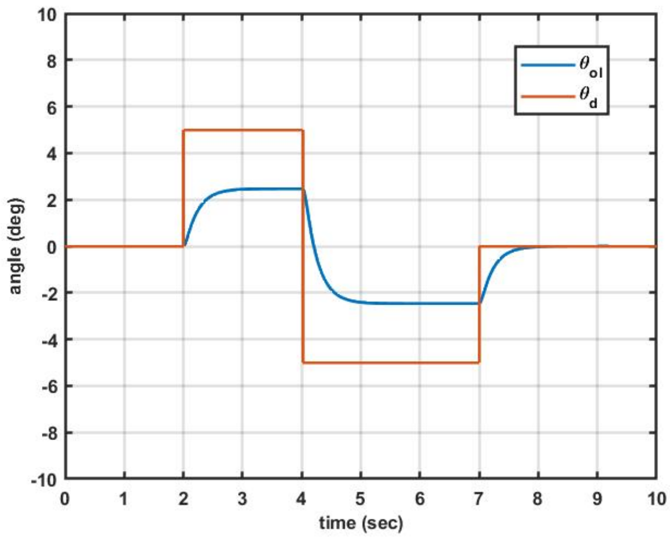


Figure 4. Doublet response for the pitch channel

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4. Control System Design

The designed controller purpose for ISP is to stabilize and hold the payload's direction (camera) steady in the desired location. Accordingly, there is a need for a motor to generate the desired gimbal torque according to the armature current. This torque is used to achieve the desired angle and reject the disturbance. Generating such a torque is the responsibility of the designed controller. Even though, the investigators tried to apply and put on several advanced control techniques, the traditional PID and is still the furthermost used method because of its modest structure, inexpensive costs, and sufficient performance [7], [9]. Therefore, the classical PID with modifications will be used to improve the system stability and increase the overall performance.

5. Applied Controller

The pitch channel for the ISP is used as the case study to test the designed controller, three types of PID controllers are applied and the comparative study is performed according to their performance. The first one is the classical PID in which the error between the desired pitch angle θ_d and the achieved angle θ_a is the input to the controller as shown in Fig. 5, the second the PID with a suitable filter as in MATLAB (Simulink) PID Toolbox as shown in Fig. 6, and the last one is the modified PI-D in which we deal with the angular rates which could be measured directly from the feedback gyro not with the angle. As well, in this modification there is no pure derivative term which cause undesirable effect that decrease the controller performance as shown in Fig. 7. In the designed modified controller, the pitch rate is the variable to be controlled in which the desired rate is prepared by using the desired angular position divided by the time constant τ, then it could be controlled directly by measuring the actual gimbal rate using rate gyroscope [11].

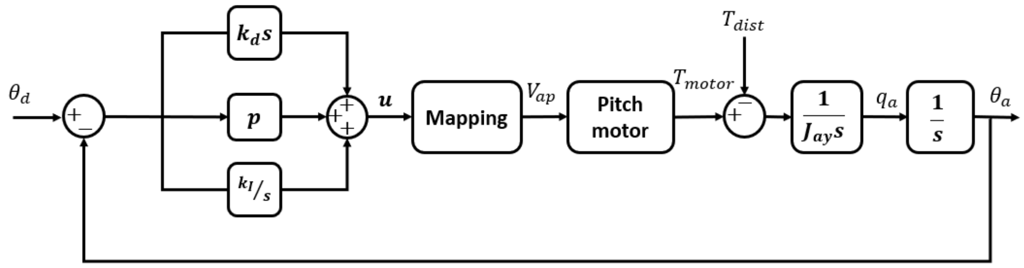


Figure 5. Classical PID structure

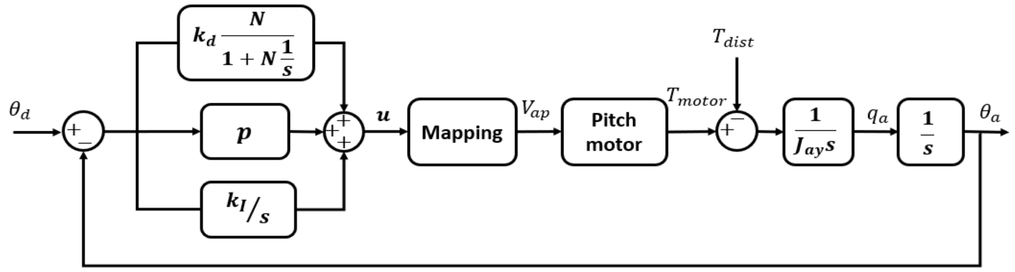


Figure 6. Classical PID structure with modified filter

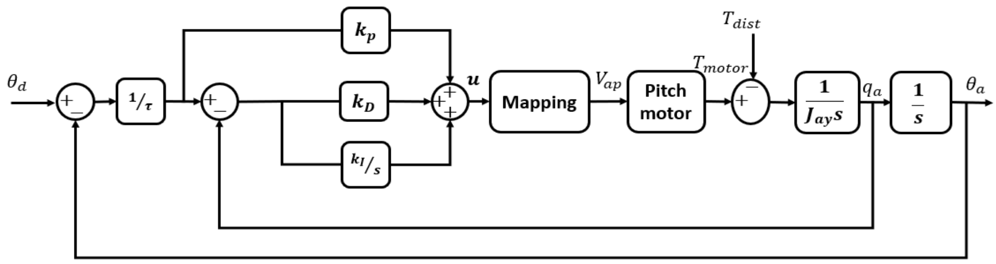


Figure 7. Modified PI-D structure

6. Simulation Results and Analysis

The performance of the modified controller should be evaluated and its performance must be verified in case of there is no disturbance or with external disturbances or model uncertainty, the standard doubled input is used to validate the controller performance. As shown in Fig. 8, the fast performance is for the PID with a suitable filter controller in comparison with the classical PID and the modified PI-D. But then, it has a large overshoot compared with the other controllers. The modified one has no overshooting and its response is faster than the classical controller. Therefore, the modified controller is the best performance and has an acceptable performance. This controller reliability should be validated. So, a model uncertainty will be added to check the controller reliability compared with the other controllers. As presented in Fig. 9, 20% uncertainties of the stepper motor parameters are added with an external disturbance represented as an additive Gaussian noise, the performance of the modified PI-D controller shows its superiority to withstand the model mismatches and the external disturbances. Also, it could be obviously cleared when the uncertainty increased to 50%. Table II represents the performance of each controller.

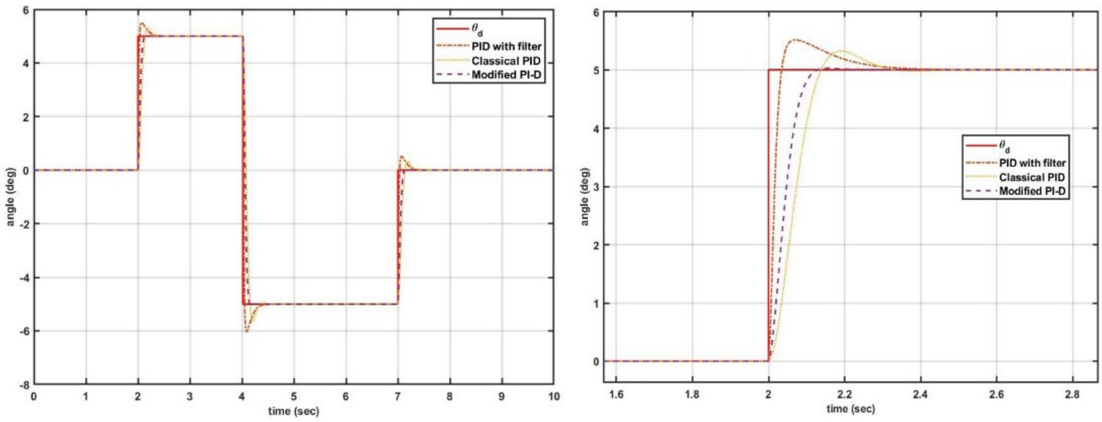


Figure 8. Doublet response for the different controllers

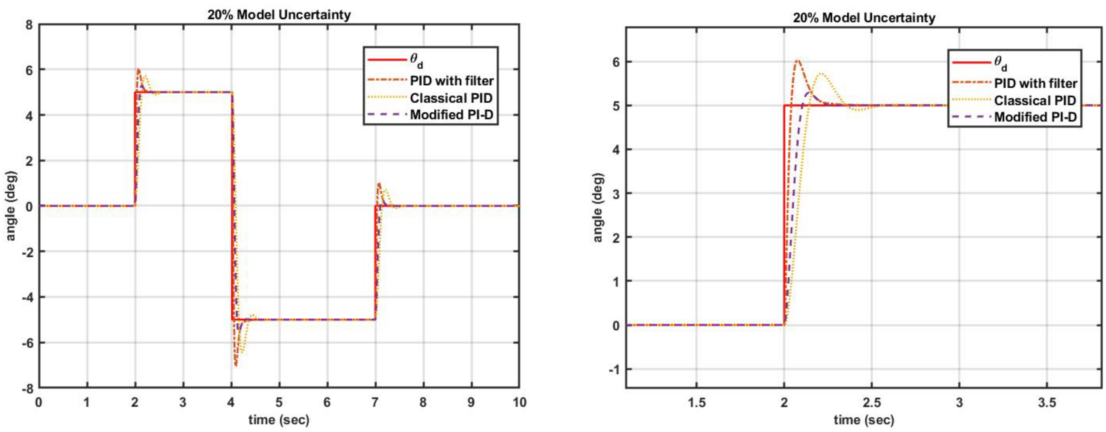
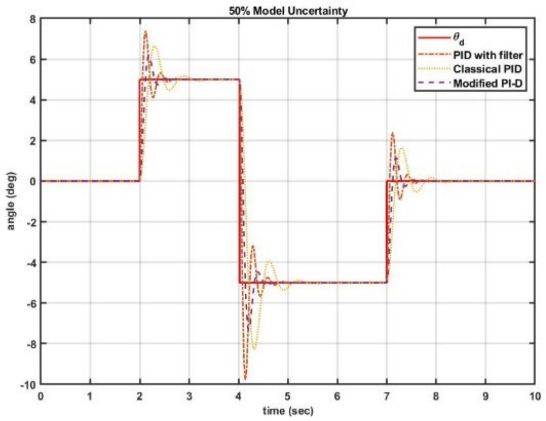


Figure 9. Doublet response for the different controllers with 20% uncertainty



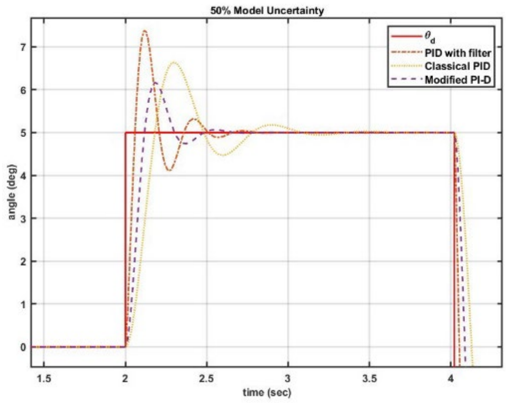


Figure 10. Doublet response for the different controllers with 50% uncertainty

Table 2. Comparison analysis for the Pitch channel

Uncertainty (%)	Rising time (sec)			Overshoot (%)			Pitch rate error (deg/sec)		
	PID-filter	Classic PID	Modified PID	PID-filter	Classic PID	Modified PID	PID-filter	Classic PID	Modified PID
0%	0.05	0.15	0.1	10	7	0.01	2	0.08	0.1
20%	0.061	0.17	0.1	22	17	2.5	12	1.21	1.3
50%	0.061	0.165	0.12	53	28	15	18	1.9	2

The performance of each controller is measured according to the concept of performance index which is related to the angle error in case of no uncertainty and also for all with high uncertainty value, Figure. 11 shows the performance index of each controller.

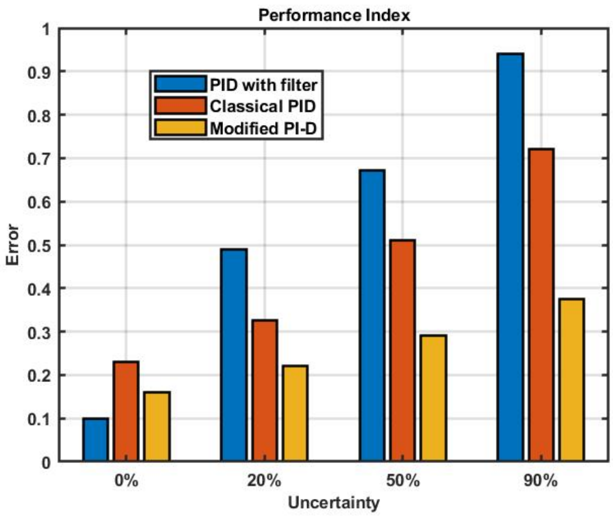


Figure 11. Controllers’ performance respect to the uncertainty

7. Conclusion and Future Work

In this paper, a dual gimbaled stabilized platform is designed, modeled, manufactured, and controlled. The designed CAD model has an efficient structure to perform the desired function in an acceptable manner, 3D printing with a specified material is used to manufacture this ISP, the mathematical model of the gimbaled platform with the applied motor is derived, tested, and ready to be controlled. Finally, three different types of PID controller which is an efficient and sufficient controller is simulated with the designed model, the modified PI-D controller shows its superiority rather in robustness, fast, and disturbance rejection. So, it will be implemented on the suitable high-speed processor to be applied with the overall model.

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