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Enhancing Quadrotor UAV Efficiency Amidst Turbulent Winds in Mangrove Area: A Hybrid PID-Grey Wolf Optimizer Control Approach

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Abstract:
Quadrotor Unmanned Aerial Vehicles (UAVs) offer versatile platforms for various applications including disaster response and environmental monitoring. However, their effective utilization in wind-disturbed environments such as mangroves poses unique challenges due to complex wind turbulence, impacting flight stability and navigation accuracy. Traditional control systems often fall short of ensuring robust and precise control in such conditions. This study presents a hybrid control approach combining a Proportional-Integral-Derivative (PID) control system with the Grey Wolf Optimizer (GWO) for enhanced UAV performance in challenging conditions. The PID controller, known for its effectiveness in industrial control systems, provides a control loop feedback mechanism to minimize flight errors, while the GWO, a bio-inspired optimization algorithm, automates the process of tuning PID parameters. Preliminary results show that this hybrid PID-GWO system significantly improves the UAV's robustness and adaptability under varying wind conditions, outperforming the standalone PID controller. This research illuminates a new direction for optimizing UAV performance in wind-disturbed environments and suggests further exploration of bio-inspired optimization techniques in UAV control systems.

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***Abstract*— Quadrotor Unmanned Aerial Vehicles (UAVs) offer versatile platforms for various applications including disaster response and environmental monitoring. However, their effective utilization in wind-disturbed environments such as mangroves poses unique challenges due to complex wind turbulence, impacting flight stability and navigation accuracy. Traditional control systems often fall short of ensuring robust and precise control in such conditions. This study presents a hybrid control approach combining a Proportional-Integral-Derivative (PID) control system with the Grey Wolf Optimizer (GWO) for enhanced UAV performance in challenging conditions. The PID controller, known for its effectiveness in industrial control systems, provides a control loop feedback mechanism to minimize flight errors, while the GWO, a bio-inspired optimization algorithm, automates the process of tuning PID parameters. Preliminary results show that this hybrid PID-GWO system significantly improves the UAV's robustness and adaptability under varying wind conditions, outperforming the standalone PID controller. This research illuminates a new direction for optimizing UAV performance in wind-disturbed environments and suggests further exploration of bio-inspired optimization techniques in UAV control systems.**

Keywords*— PID, Hybrid Controller, UAV, Quadcopter, Mangrove Area, Grey Wolf Optimization.

I. INTRODUCTION

Quadrotor Unmanned Aerial Vehicles (UAVs) have emerged as versatile platforms with significant potential in various fields, including disaster response, environmental monitoring, exploration, and more. Their ability to operate remotely, reduced risk to human operators, and access to hard-to-reach areas make them invaluable tools in these domains. However, the utilization of UAVs in wind-disturbed environments, such as mangroves, presents a unique set of challenges.

Wind turbulence in mangrove environments is complex and dynamic, posing a threat to the stability of UAV flight and the accuracy of navigation. These disturbances can lead to increased trajectory tracking error and reduced overall stability, limiting the effective utilization of UAVs in such conditions. Conventional control systems, such as Proportional-Integral-Derivative (PID) controllers, which are widely used in industrial control systems, often struggle to provide robust and accurate control in wind-disturbed environments.

PID controllers operate based on a simple control strategy that calculates the error as the difference between a measured process variable and a desired set point. By adjusting a control variable, such as motor speed or control surface position, PID controllers aim to minimize this error over time. While PID control systems have been successful in various applications, their performance in wind-disturbed environments is limited by the need for careful manual tuning of their parameters.

In recent studies, researchers have innovatively combined PID control systems with bio-inspired optimization algorithms, like the Grey Wolf Optimizer (GWO), to tackle the challenges posed by wind-disturbed environments. Drawing inspiration from grey wolves' hierarchical structure and hunting behaviour, GWO exhibits remarkable global search capabilities in optimization tasks. This hybrid PID-GWO control system seeks to improve the adaptability and robustness of unmanned aerial vehicles (UAVs) under turbulent wind conditions by automating the parameter tuning process for PID controllers.

Previous investigations have produced promising results, both through simulations and real-world trials. These findings indicate that the PID-GWO control system significantly enhances UAV performance and stability across varying wind scenarios. Notably, it substantially reduces trajectory tracking errors and elevates overall stability, thereby enabling UAVs to navigate more effectively in challenging wind-prone settings such as mangroves.

A related study [1], focuses on modelling and control strategies for quadrotors, emphasizing stable hovering and low-speed manoeuvres, crucial for indoor mapping and confined spaces. The Newton-Euler formalism is used for modelling, and a PID controller is designed based on a linear model derived from nonlinear dynamics.

In another context [2], this research demonstrates successful modelling and control using PID controllers for stable hovering. Simulations validate the control process, but hardware implementation verification is needed. Future directions include applying control designs to actual quadrotor systems, addressing trajectory planning, obstacle avoidance, and exploring uncharted environments using minimum snap trajectory theory.

Shifting to quadcopter control [3], the focus is on PID methodologies for quadcopter control. A linear PID controller is developed for altitude, attitude, heading, and position control. The study highlights the complexities of quadcopter control due to their nonlinear and underactuated nature. The PID controller stabilizes the quadcopter, contributing to understanding dynamics and stabilization strategies.

A distinct approach [4], Explores modelling and control for 3D trajectory tracking of quadrotor UAVs. The proposed architecture includes an inner loop for attitude stabilization and an outer loop for trajectory tracking. Various control approaches (PID, LQR, MPC, FL, SMC) are assessed for their

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performance, and insights for selecting appropriate control strategies are provided.

Likewise [5], this research addresses trajectory-tracking challenges for nonlinear quadcopters. Compares Cascade PID controllers and explicit nonlinear Model Predictive Control (ENMPC) strategies through simulations. ENMPC excels in helical trajectory tracking compared to PID. Future research directions should address disturbance compensation in quadcopter systems.

A practical assessment [6] evaluates PID, LQR, and MPC controllers on a mini drone in indoor environments. MPC outperforms PID and LQR in terms of stability and robustness. Different control strategies have been explored for quadrotor tracking, each with its strengths and weaknesses.

In a control-focused context [7], this study introduces a cascade PID feedback control algorithm to stabilize the attitude of quadcopters when facing disturbances. The authors use the Newton-Euler method to create a mathematical model and derive both linear and nonlinear state space equations. Simulations demonstrate that the cascade PID algorithm is more robust and effective compared to traditional PID control.

Expanding on optimization [8], this research presents a unique method for optimizing quadrotor UAV controllers using metaheuristic algorithms. It introduces a new mathematical model, evaluates eight algorithms, and identifies the HGS algorithm as the most effective for optimizing PD and PID controllers for trajectory tracking. Challenges in traditional tuning are emphasized, and the study underscores the advantages of metaheuristics like genetic algorithms and differential evolution. Results validate the approach's feasibility and endorse the HGS algorithm's effectiveness in complex optimization.

II. System Modeling

The subsequent exploration of the quad rotor's kinematic and dynamic modelling will employ the Newton-Euler formalism. The study will proceed by positing certain assumptions that are crucial to this specific analysis [9].

- The structure is rigid and symmetrical.

The center of gravity of the quadrotor coincides with the body's fixed frame origin.

- The propellers are rigid.
- Thrust and drag are proportional to the square of the propeller's speed.

The movement of an Unmanned Aerial Vehicle (UAV) can be categorized into six distinct degrees of freedom. These comprise three degrees of freedom related to linear movement and three degrees of freedom related to angular movement, all centred around the UAV's mass center. Following Newton's second law, the dynamic equations governing the UAV's motion are outlined below.

$$\vec{F}=m\frac{d\vec{V}}{dt} \tag{1}$$

$$\vec{M}=m\frac{d\vec{H}}{dt} \tag{2}$$

Where $\vec{F}$ represents force acted on the quad-rotor UAV, m is the mass of the UAV, $\vec{V}$ indicates the velocity of the center of mass of the UAC, $\vec{M}$ is the resultant moment of force of the UAV and $\vec{H}$ is the moment of momentum of the UAV relative to the ground coordinates.

A. Linear Equation of Motion

The force acted on UAV includes gravity, rotor lift, and air resistance.

$$G = mg \tag{3}$$

$$F_i=\frac{1}{2}\rho C_i\omega_i^2= k_i\omega_i^2 \tag{4}$$

$$D_i=\frac{1}{2}\rho C_d\omega_i^2=k_d\omega_i^2 \tag{5}$$

Where G is the gravity of the UAV, F_i is the lifting force of the rotor, D_i is the resistance of the rotor, C_i is the lift coefficient of the rotor, C_d is the resistance coefficient of the rotor, ω_i is the angular velocity of the rotor. k_i is the lift coefficient and k_d is the resistance coefficient.

$\vec{F}$, the resultant lift of the quad rotors, is as follows:

$$\vec{F}=R\begin{bmatrix}0\\0\\\sum_{i=1}^4 F_i\end{bmatrix}=\begin{bmatrix}\cos\psi\sin\theta\cos\phi+\sin\psi\sin\phi\\\sin\psi\sin\theta\cos\phi-\sin\phi\cos\psi\\\cos\theta\cos\phi\end{bmatrix}\sum_{i=1}^4 F_i \tag{6}$$

Substitute equation (6) into (1):

$$\begin{cases}\ddot{x}=\left[(\cos\psi\sin\theta\cos\phi+\sin\psi\sin\phi)\sum_{i=1}^4 F_i-K_1\dot{x}\right]m^{-1}\\\ddot{y}=\left[(\cos\psi\sin\theta\cos\phi-\sin\phi\sin\psi)\sum_{i=1}^4 F_i-K_2\dot{y}\right]m^{-1}\\\ddot{z}=\left[(\cos\theta\cos\phi)\sum_{i=1}^4 F_i-K_3\dot{z}\right]m^{-1}-g\end{cases} \tag{7}$$

Where (x, y, z) is the location of the center of mass of the UAV, K_i is the total resistance coefficient and g is gravitational acceleration.

B. The Angular Motion Equation

The relation between the angular velocity of the ruler angle ($\dot{\theta},\dot{\phi},\dot{\psi}$) and the angular velocity of the fuselage (p, q, r) is as follows:

$$\begin{bmatrix}\dot{\theta}\\\dot{\phi}\\\dot{\psi}\end{bmatrix}=\begin{bmatrix}p+p\sin\phi\,\theta+r\cos\phi\tan\theta\\q\cos\phi-r\sin\phi\\q\sin\phi\sec\theta+r\cos\phi\sec\theta\end{bmatrix} \tag{8}$$

Given the symmetry of the quad-rotor UAV's design and its uniform mass distribution, it is reasonable to consider that the UAV's center of gravity coincides with the center of the quad-rotor UAV. By considering angular momentum calculations, the equation governing the angular motion of the quad-rotor UAV's orientation can be expressed as follows:

$$\begin{bmatrix}M_x\\M_y\\M_z\end{bmatrix}=\begin{bmatrix}\dot{p}I_x-\dot{r}I_{xz}+qr(I_z-I_y)-pqI_{xz}\\\dot{q}I_y-pr(I_x-I_z)+(p^2-r^2)I_{xz}\\\dot{r}I_z-\dot{p}I_{xz}+pq(I_y-I_x)+qrI_{xz}\end{bmatrix} \tag{9}$$

Where (M_x, M_y, M_z) respectively represents the component of the resultant external angular momentum of the UAV around the axis of X, Y, and Z.

According to equation (9):

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}[M_x+(I_x-I_z)qr]/I_x\\ [M_y+(I_z-I_x)pr]/I_y\\ [M_z+(I_x-I_y)pr]/I_z\end{bmatrix} \tag{10}$$

Finishing equation (9) and equation (10):

$$\begin{cases}\ddot{\phi}=[M_x-\dot{\theta}\dot{\psi}(I_z-I_y)]/I_x\\ \ddot{\theta}=[M_y-\dot{\phi}\dot{\psi}(I_x-I_z)]/I_y\\ \ddot{\psi}=[M_z-\dot{\phi}\dot{\theta}(I_y-I_x)]/I_z\end{cases} \tag{11}$$

According to the 'X' flight model of UAV and theorem of momentum:

$$\begin{bmatrix}M_x\\ M_y\\ M_z\end{bmatrix}=\begin{bmatrix}l(F_1+F_4-F_2-F_3)\\ l(F_1+F_3-F_2-F_4)\\ \lambda(F_1+F_2-F_3-F_4)\end{bmatrix} \tag{12}$$

Where l is the distance between the motor shaft and the center of mass of the UAV, λ is the coefficient which links the lift and the twisting moment. Assuming the input of the system of the quad-rotor UAV as follows:

$$U=\begin{bmatrix}U_1\\ U_2\\ U_3\\ U_4\end{bmatrix}=\begin{bmatrix}F_1+F_2+F_3+F_4\\ F_1+F_4-F_2-F_3\\ F_1+F_3-F_2-F_4\\ F_1+F_2-F_3-F_4\end{bmatrix} \tag{13}$$

Where U_1 is the vertically controlled quantity, U_2 is the roll-controlled quantity, U_3 is the pitch controlled quantity and U_4 is the yaw-controlled quantity.

Integrate equation (11), (12), (13):

$$\begin{cases}\ddot{\phi}=U_2 l I_x^{-1}\\ \ddot{\theta}=U_3 l I_y^{-1}\\ \ddot{\psi}=U_4 l I_z^{1}\end{cases} \tag{14}$$

Assuming that the flight environment of the quad-rotor UAV is indoor or breeze outside, the resistance coefficient in equation (7), K_i will be negligible. Then integrate equation (14) and equation (7):

$$\begin{cases}\ddot{x}=[(\cos\psi\sin\theta\cos\phi+\sin\psi\sin\phi)U_1]m^{-1}\\ \ddot{y}=[(\cos\psi\sin\theta\cos\phi-\sin\phi\sin\psi)U_1]m^{-1}\\ \ddot{z}=[(\cos\theta\cos\phi)U_1]m^{-1}-g\\ \ddot{\phi}=U_2 l I_x^{-1}\\ \ddot{\theta}=U_3 l I_y^{-1}\\ \ddot{\psi}=U_4 \lambda I_z^{-1}\end{cases} \tag{15}$$

III. Controller Design

A. PID Controller Design

A conventional Proportional Integral Derivative (PID) controller amalgamates three control actions to modulate the control signal. Its primary function is to ensure there is no deviation between the feedback signal (process variable) and the desired output (set point). The Proportional (P) control evaluates the error and multiplies it by a constant P to produce an output. The Integral (I) control retains the error value over time until the error is nullified, addressing the Proportional control's steady-state issues. The Derivative (D) control can anticipate future system behaviour by contemplating the error's rate of change over time. An overarching equation for a typical PID is presented below.[10]

$$u(t)=K_p\left[e^{(t)}+\frac{1}{T_i}\int_0^i e(\tau)d\tau+T_d\frac{de(t)}{t}\right] \tag{16}$$

a) Altitude control law:

To control z, a PID control low is developed below:

$$\ddot{Z}_d=K_p(Z_d-Z)+K_d(\dot{Z}_d-\dot{Z})+K_i(Z_d-Z)dt \tag{17}$$

b) Heading Control law

To control the yaw angle ψ, we use another PID controller whose expression is as follows:

$$\ddot{\psi}_d=K_p(\psi_d-\psi)+K_d(\dot{\psi}_d-\dot{\psi})+K_i\int(\psi_d-\psi)dt \tag{18}$$

c) Attitude Control law

Two other PID controllers are used to control the roll and pitch angles ϕ and ϑ, which have the expressions as follows:

$$\ddot{\phi}_d=K_p(\phi_d-\phi)+K_d(\dot{\phi}_d-\dot{\phi})+K_i\int(\phi_d-\phi)dt \tag{19}$$

$$\ddot{\theta}_d=K_p(\theta_d-\theta)+K_d(\dot{\theta}_d-\dot{\theta})+K_i\int(\theta_d-\theta)dt \tag{20}$$

B. Grey Wolf Optimization Algorithm

The GWO algorithm, proposed in [6], is inspired by the social structure and hunting behaviour of grey wolves. In this algorithm, the wolves form a swarm and operate according to a hierarchical structure. The alpha wolf, depicted at the top of the hunting pyramid, assumes the role of making hunting decisions and leading the swarm. Within the social hierarchy of the wolf pack, the alpha, beta, and omega wolves hold the top three positions, respectively.

During the optimization process, candidate solutions are randomly generated, similar to other metaheuristic algorithms. Among these candidate solutions, the best, second best, and third best solutions correspond to the alpha (Xα), beta (Xβ), and delta (Xδ) positions, respectively. The remaining lower-ranked candidate solution corresponds to the omega (ω) position.

The hunting behaviour of grey wolves involves several stages, including tracking and approaching the prey, encircling it, and ultimately launching an attack. This mechanism is emulated in Figure 1 to guide the search process towards finding optimal solutions.

Algorithm 1 Pseudo-code of GWO

Initialization of grey wolves w_n where n= 1,2,......,N according to given upper bound (UB) and lower bound (LB) values.
Initialize **a**, **A** and **C**.
Evaluate the fitness of all search agents.
Select alpha, beta and delta as :
w_α= best search agent
w_β= second best search agent
w_δ= third best search agent
Initialize $i = 0$ and Max_it = Maximum number of iterations allowed.
while $i < Max\_it$ **do**
  for each search agent
    Update the position of current search agent according to (7).
  end for
  Update **a**, **A** and **C**.
  Evaluate the fitness of all search agents.
  Update w_α, w_β and w_δ.
  $i = i + 1$.
return w_α.

Fig. 1. Pseudocode of the grey wolf optimization algorithm

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the PID and GWO-PID controllers is tested in two scenarios: the 1st when there is no wind turbulence, and the 2nd when there is wind turbulence.

The parameters of the quadrotor used in the study are given in the table below:

TABLE I. UAV MODEL PARAMETERS

Parameter	Description	Value	Unit
m	Total UAV mass	1.32	Kg
l	Arm lenght	0.5	m
I_x	Moment of Ineria X	0.009363917	$Kg.m^2$
I_y	Moment of Ineria Y	0.009382320	$Kg.m^2$
I_z	Moment of Ineria Z	0.018393126	$Kg.m^2$
f	Maximum thrust	1.332*9.81	N
g	Gravitational acceleration	9.81	$m.s^2$
ωmax	Maximum rotor speed	1032	rad/s

Wind turbulence is typically expressed in terms of velocity fluctuations. It is not directly related to acceleration or wind power, although these factors can be influenced by turbulence.

The standard unit for measuring wind velocity is meters per second (m/s). In this paper, we consider the wind turbulence acceleration to be 5 m/s, since the range is approximately between 5-20 m/s.

The PID and Hybrid PID parameters are listed in the table below:

TABLE II. PID PARAMETERS

Controller	PID			
Parameters	Altitude		Attitude[roll,pitch,yaw]	
	No wind	wind	No wind	wind
Ki	1.0	5	[1,1,1]	[1,1.5,0.8]
Kd	0.5	2	[0.5,0.5,0.5]	[0.1,0.2,0.05]
Kp	0.2	0.5	[0.05,0.05,0.05]	[0.05,0.1,0.02]

TABLE III. HYBRID PID PARAMETERS

Controller	Hybrid PID			
Parameters	Altitude		Attitude[roll,pitch,yaw]	
	No wind	wind	no wind	wind
Ki	15.0	2.35	[1.2,1.5,1]	[5,5,5]
Kd	15	15	[0.2,0.5,0.05]	[5,5,5]
Kp	0	0	[0.1,0.2,0.02]	[3.67,3.67,3.67]
Num of wolves	10	10	10	10
Max iteration	100	100	100	100

A. Simulation results without wind disturbance

1) Altitude Response

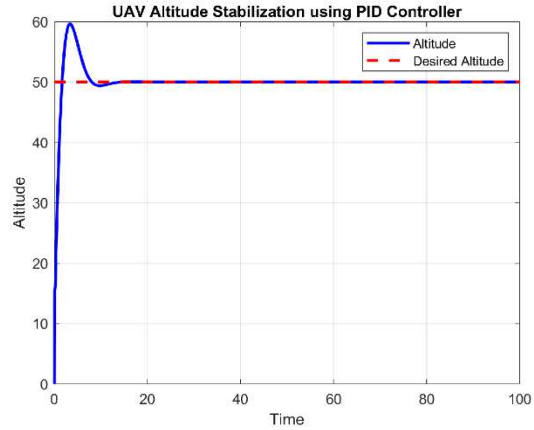

Fig. 2. UAV altitude response using PID controller (no wind effect)

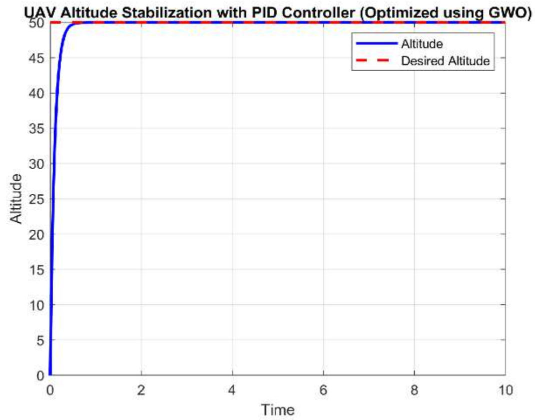

Fig. 3. UAV altitude response using PID+GWO controller (no wind effect)

2) Attitude Response

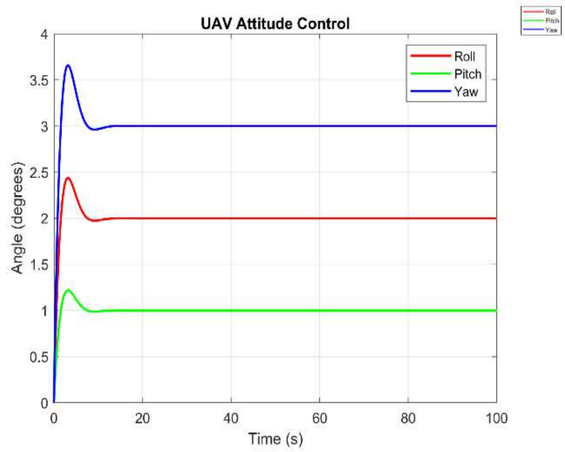

Fig. 4. UAV attitude response using PID controller (no wind effect)

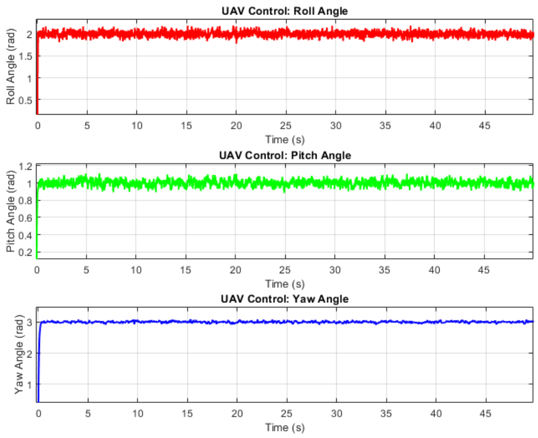

Fig. 5. UAV attitude response using PID+GWO controller (no wind effect)

B. *Simulation results with wind disturbance and GWO algorithm*

1) *Altitude response*

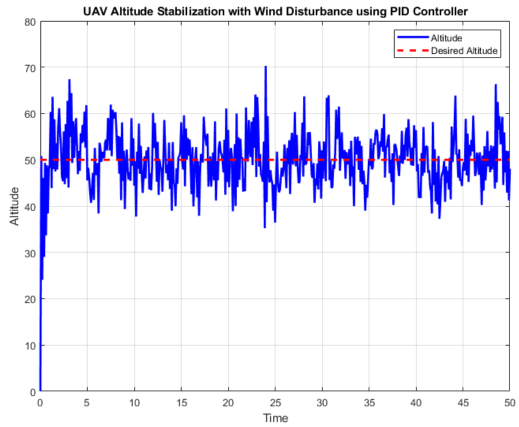

Fig. 6. UAV altitude response using PID controller (Wind Turbulence)

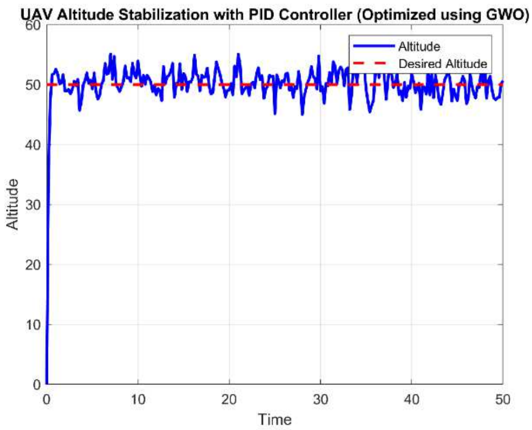

Fig. 7. UAV altitude response using PID+GWO controller (Wind Turbulence)

2) *Attitude response*

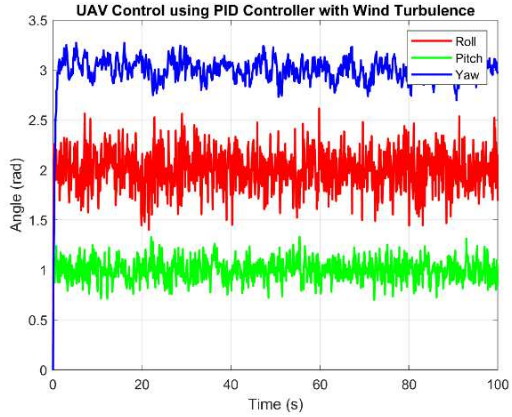

Fig. 8. UAV attitude response using PID controller (wind turbulence)

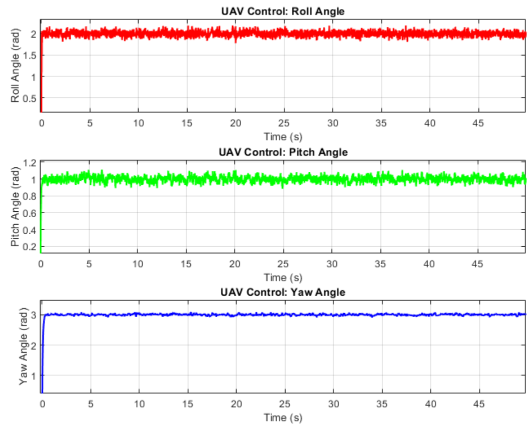

Fig. 9. UAV attitude response using PID+GWO controller (wind turbulence)

C. *Controllers Performance Analysis*

1) *PID and GWO+PID without wind turbulence*

a) *Altitude Response*

TABLE IV. CONTROLLERS' ALTITUDE PERFORMANCE WITHOUT WIND DISTURBANCE

Controller	Rise time	Overshoot	Settling time	Steady-state Error
PID (Altitude)	1.40	9.63	100.00	0
PID+GWO (Altitude)	0.3	-2.8422e-14	10	2.8422e-14

b) *Attitude Response*

TABLE V. CONTROLLERS' ATTITUDE PERFORMANCE WITHOUT WIND TURBULENCE

Controller	Rise time	Overshoot	Settling time	Steady-state Error
PID (Roll)	1.60	0.44	100	0
PID+GWO (Roll)	0.60	0.17	100	0
PID (Pitch)	1.60	0.22	100	0
PID+GWO (Pitch)	0.70	0.08	100	0
PID (Roll)	1.60	0.66	100	0
PID+GWO(Roll)	0.60	0.26	100	0

1) PID and GWO+PID with wind turbulence

a) Altitude Response

TABLE VI. CONTROLLERS' ALTITUDE PERFORMANCE WITH WIND TURBULENCE

Controller	Rise time	Overshoot	Settling time	Steady-state Error
PID (Altitude)	0.6	16.5897	49	4.7908
PID+GWO (Altitude)	0.4	22.7719	49.6	1.5958

b) Attitude Response

TABLE VII. CONTROLLERS' ATTITUDE PERFORMANCE WITH WIND TURBULENCE

Controller	Rise time	Overshoot	Settling time	Steady-state Error
PID (Roll)	0.2	0.86629	100	0.094552
PID+GWO (Roll)	0.2	0.59134	98.8	0.077117
PID (Pitch)	0.4	0.30295	100	0.011506
PID+GWO (Pitch)	0.3	0.28177	98.8	0.12367
PID (Roll)	0.8	0.30192	100	0.053816
PID+GWO(Roll)	0.9	0.27561	99.5	0.010887

Overall, from the results obtained of the following parameters: Rise time, Overshoot, Settling time and Steady State Error the performance of the PID+GWO controller showed better performance compared to the PID controller.

V. CONCLUSION AND FUTURE WORK

The challenges posed by wind-disturbed environments like mangroves significantly limit the effectiveness of Quadrotor Unmanned Aerial Vehicles (UAVs). In an attempt to overcome these challenges, this research developed a novel hybrid control approach combining Proportional-Integral-Derivative (PID) control systems and the Grey Wolf Optimizer (GWO). Our preliminary findings indicate that this hybrid PID-GWO control system significantly enhances the performance, stability, and adaptability of UAVs under varying wind conditions. This innovation marks a substantial improvement over traditional PID controllers, demonstrating the promise of hybrid control systems in optimizing UAV performance.

While the results obtained are promising, the research can be extended in several ways to further optimize the control system. Future research can explore integrating machine learning techniques like Reinforcement Learning into the control system for real-time adaptation to changing wind conditions. The adoption of adaptive control strategies such as Model Predictive Control (MPC) could offer enhanced performance by predicting the system's future behaviour and optimizing control inputs.

Moreover, bio-inspired optimization algorithms beyond the GWO can be explored for their potential advantages in tuning the control parameters. The development of more sophisticated simulation environments that accurately mimic complex wind disturbances would also be beneficial. Such environments would facilitate the testing and optimization of the control system in a variety of challenging scenarios.

Through continued research and exploration, we aspire to further enhance the robustness and adaptability of UAVs, expanding their potential applications and efficiency in challenging environments.

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