

Gimbal Control of an Airborne pan-tilt-zoom Camera for Visual Search

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This paper presents the development of an optimized visual search algorithm for unmanned aerial vehicle (UAV) equipped with Pan-Tilt-Zoom cameras, designed to account for platform dynamics and disturbances. The study involves the design and evaluation of various gimbal control strategies to stabilize the camera's orientation, ensuring effective area coverage despite UAV attitude changes. A comparative analysis of control methods, including Proportional–integral–derivative (PID), Disturbance Observer (DOB), Iterative Learning Control, Internal Model Control, Active Disturbance Rejection Control, and their combinations, highlights the importance of advanced controllers in maintaining camera stability under complex conditions such as coriolis, centripetal, and gyroscopic disturbances. The combination of PID and DOB provided superior disturbance rejection, making it a suitable choice for challenging flight scenarios. Additionally, an optimized coverage path planning algorithm was developed to maximize image coverage while minimizing flight time, turns, and overlap, taking into account field of view, resolution, and terrain constraints. Simulation results demonstrate the effectiveness of this approach, achieving full area coverage with enhanced efficiency. The framework developed in this study provides a solid foundation for reliable and precise UAV-based search operations, particularly in dynamic and complex environments.

Nomenclature

<i>ADRC</i>	=	Active Disturbance Rejection Control
<i>CD</i>	=	Cellular Decomposition
<i>CPP</i>	=	Coverage Path Planning
<i>DOB</i>	=	Disturbance Observer
<i>DOF</i>	=	Degree of Freedom
<i>ESO</i>	=	Extended State Observer
<i>FOV</i>	=	Field of View
<i>HFOV</i>	=	Horizontal Field of View
<i>ILC</i>	=	Iterative Learning Control
<i>IMC</i>	=	Internal Model Control
<i>IMU</i>	=	Inertial Measurement Unit
<i>ISP</i>	=	Inertially Stabilized Platform
<i>IBF</i>	=	Improved Back-and-Forth (Mode)
<i>LQR</i>	=	Linear-Quadratic Regulator
<i>LOS</i>	=	Line of Sight
<i>PID</i>	=	Proportional–integral–derivative
<i>PTZ</i>	=	Pan-tilt-zoom
<i>RBFNN</i>	=	Radial Basis Function Neural Network
<i>RL</i>	=	Reinforcement Learning
<i>UAS</i>	=	Unmanned aircraft systems
<i>UAV</i>	=	Unmanned aerial vehicle

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I. Introduction

Equipped with a gimbal mechanism, PTZ cameras allow for precise adjustments in both orientation and field of view (FOV), as illustrated in Figure 1. The gimbal's lower servo enables horizontal adjustments, or panning, while the upper servo allows vertical changes, controlling the camera's tilt. This configuration provides users with the ability to track objects smoothly, scan wide areas, and capture high-resolution images from multiple angles [1].

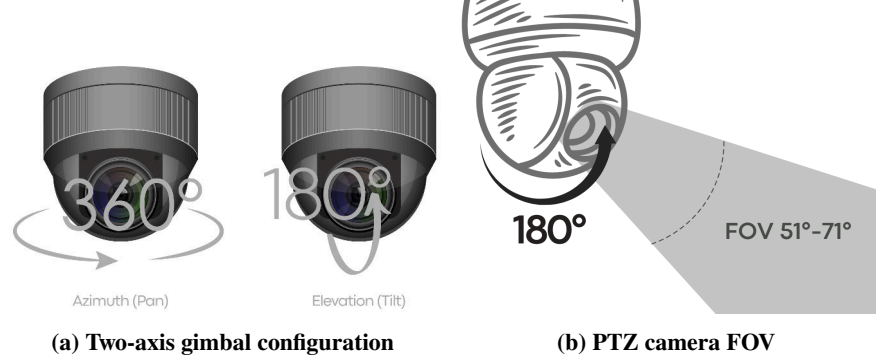


Fig. 1 PTZ camera capabilities: (a) Panoramic 360° pan and 180° tilt coverage provides near-complete spherical coverage around the camera. (b) PTZ cameras typically offer FOVs ranging between 51° and 71° [2].

As presented in Figure 1a, PTZ cameras provide 360° views with zoom functionality, differing from static cameras that utilize additional mechanical components like motors and belts for movement [3]. Although they share some structural characteristics with fixed cameras, PTZ cameras stand out for their ability to modify their FOV [2]. Offering nine unique movement combinations, PTZ cameras achieve extensive coverage with tilt functionality up to 180° along the horizontal axis, as shown in Figure 1b [2].

One challenge with PTZ cameras is their vulnerability to tampering, which some models mitigate by incorporating angle-feedback systems to detect unauthorized adjustments [3].

PTZ cameras are frequently paired with UAVs for applications like 3D scene reconstruction [4]. Well-known models include the Zenmuse P1, Hongpeng AP5600, Zenmuse X5S, and Phantom4 Pro, each offering distinct features that cater to professional needs, from high-resolution imaging to extended battery life for longer flight durations.

As illustrated in Figure 2, the quality of 3D models and other captured visuals tends to diminish with increased UAV altitude, affecting image and video sharpness. This observation highlights the impact of camera specifications like resolution and focal length on the quality and utility of PTZ cameras in aerial photography and videography.

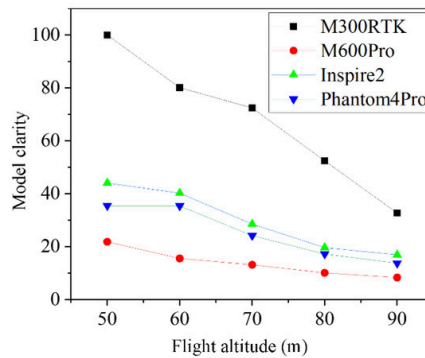


Fig. 2 Comparison Between 3D Model Clarity and Drone Flight Altitude [4].

Considering the mentioned above, the present research develops an optimized visual search algorithm for Pan-Tilt-Zoom cameras in an unmanned aerial vehicle (UAV), where dynamics and disturbances are considered. On the other hand, multiple strategies were designed and implemented to stabilize the camera's orientation during UAV operation changes. Moreover, a complementary comparison between control methods were included, allowing the understanding of camera stability and selection of the most suitable configuration.

II. Literature Review

A. Gimbal Control Techniques

PTZ cameras are essential for panning, tilting, and zooming to monitor areas or track objects of interest. Various gimbal control methods have been proposed in the literature to enhance stabilization, particularly on airborne platforms. PID controllers are widely employed for target tracking, and their performance can be optimized using techniques like Particle Swarm Optimization and Genetic Algorithm [1]. Studies have shown that a PSO-tuned PID controller outperforms traditional methods in stabilizing a 3-axis gimballed camera on UAVs by offering better stability and precision [5]. State feedback controllers have also been utilized, with one approach using a Linear Quadratic Regulator (LQR) to stabilize a two-axis gimbal, simplifying the control model by removing UAV-induced disturbances [6]. Fuzzy PID controllers have demonstrated significant improvements in stability and adaptability; for instance, Maher's fuzzy PID controller for a two-axis gimbal seeker in guided missiles outperformed conventional PI control in terms of overshoot, settling time, and rise time [7]. Neural networks, particularly Radial Basis Function Neural Networks (RBFNN), have been applied to enhance the attitude stabilization of inertially stabilized platforms (ISP), achieving up to a 42.1% reduction in attitude angle deviations compared to traditional methods [8]. Robust and adaptive controllers have also been explored, with robust inverse dynamics and sliding mode control addressing dynamic errors and external disturbances in 2-DOF gimbals on aviation vehicles, resulting in effective stabilization and trajectory tracking [9, 10]. Furthermore, image-based control methods, such as the Mean Shift algorithm, are used for target tracking by integrating image processing techniques with PID controllers to adjust camera orientation based on target position in real-time [11, 12]. Additionally, adaptive control strategies using fuzzy logic, such as a Fuzzy-PID compensator, have been shown to improve gimbal stability and reduce overshoot during aerial surveillance [13]. These methods collectively contribute to advancements in stabilizing PTZ cameras and gimbal systems, offering improved precision, faster response times, and greater adaptability in diverse aerial applications.

B. Coverage Path Planning Optimization

The field of UAV (Unmanned Aerial Vehicle) operations has recently seen significant advancements, particularly in Coverage Path Planning (CPP) and Search and Rescue missions. Key studies have introduced new algorithms and methodologies that improve the efficiency and applicability of UAVs in complex environments. In 2024, Kazemdehbashi and Liu presented an optimized CPP algorithm for UAVs that counteracts the adverse effects of wind, a critical challenge in SAR missions. Their algorithm maximizes search coverage under harsh weather conditions, ensuring effective UAV performance even in wind-compromised environments [14]. Alpdemir and Sezgin (2024) expanded UAV path planning by developing a hybrid method using reinforcement learning and ground-penetrating radar to detect buried objects. This approach improves terrain recognition and enables UAVs to detect objects in obscured conditions, addressing significant challenges in search missions across difficult terrains [15]. Fontenla-Carrera et al. (2023) conducted a benchmarking study of small fixed-wing electric UAVs with RGB cameras for photogrammetry in intertidal regions. Their work aids in selecting UAVs for specific photogrammetry tasks, optimizing UAV operations in varied environmental settings [16]. In 2023, Tchouchenkov, Segor, and Buller made strides in multi-robot coordination, developing a strategy for area reconnaissance using heterogeneous autonomous systems. This coordination is crucial for future SAR operations, where multi-robot systems can significantly extend coverage [17]. Tang et al. (2023) applied ant colony algorithms for LiDAR route planning in densely vegetated areas, enhancing UAV mission efficiency and safety in such challenging environments [18]. Mu et al. (2023) introduced an Improved Back-and-Forth (IBF) mode for UAV CPP, optimizing path length, computation time, and maneuverability in terrains with multiple restricted areas. This method reduces the complexity seen in traditional CPP approaches like Cellular Decomposition (CD) and Probabilistic Roadmap (PRM) [19]. Fevgas et al. (2022) provided a comprehensive survey of CPP methods, emphasizing energy efficiency and multi-UAV cooperation. Their work highlights the effectiveness of simpler patterns for regular shapes and the importance of energy-aware algorithms in extending mission duration [20]. Heydari et al. (2021) tackled the NP-hard problem of CPP in unknown environments using reinforcement learning (RL). They introduced a hybrid RL algorithm that combines simple zigzag movements with an RL agent, enhancing coverage efficiency and reducing computational demands [21]. Similarly, Ai et al. (2021) applied RL to maritime SAR missions, developing a model that prioritizes high-probability search areas while minimizing path length and avoiding obstacles, crucial for time-sensitive operations [22]. These studies represent significant advances in UAV-based CPP and SAR technologies, demonstrating the power of reinforcement learning, bio-inspired algorithms, and comprehensive benchmarking to overcome the challenges of complex environments.

III. Problem Formulation

The increasing reliance on UAVs for airborne imaging using PTZ cameras introduces several technical challenges that must be addressed to optimize performance in critical applications such as surveillance, search and rescue, and environmental monitoring. A primary challenge lies in maintaining the camera's stability and orientation despite the dynamic disturbances experienced by UAVs during flight operations. Disturbances such as wind, vibrations, and abrupt changes in vehicle attitude can significantly degrade image quality and complicate the visual search process. Additionally, an optimal visual search strategy is required to ensure complete coverage of a designated area, accounting for various factors including platform altitude, field-of-view (FOV) limitations, resolution requirements, and the type of terrain being monitored. The search strategy must balance these constraints while maximizing the effectiveness of the PTZ camera, which dynamically adjusts zoom and resolution based on the operational context. Thus, the problem statement can be formulated as follows:

Design an algorithm that optimally performs a visual search over a defined area using an airborne PTZ camera under dynamic platform conditions, while satisfying the following constraints:

- 1) **Camera stability and orientation control:** Ensure that the PTZ camera remains oriented towards the ground, maintaining image quality and precision despite UAV disturbances such as vibrations, wind, and attitude changes (e.g., roll, pitch, yaw).
- 2) **Search path optimization:** Develop a search strategy that accommodates the UAV's field-of-view, altitude, and terrain type while maximizing coverage and resolution, considering real-time camera adjustments (zoom and resolution).
- 3) **Efficiency and robustness:** The algorithm must be robust enough to handle variations in terrain and environmental conditions, ensuring complete search coverage with minimal overlap and high accuracy.

The goal is to enhance the UAV's imaging performance, ensuring high-resolution imagery and complete coverage of the target area, while accounting for platform dynamics and environmental constraints. This will directly improve the speed and accuracy of critical operations such as surveillance, disaster management, and environmental monitoring.

IV. Materials and Methods

A. Gimbal Model Proposal for the PTZ camera

The gimbal model is designed to stabilize the camera by compensating for the UAV's movements, with a focus on controlling the pitch angle. This model includes components like the controller, motor model, gyroscope, inertia, and disturbance blocks, simulating the system's various dynamics [23]. As illustrated in Figure 3, the schematic model for one gimbal is presented, and for this project, two interconnected gimbals must be implemented. The block diagram consists of several key components. The input reference defines the desired angle for gimbal control. For the inner gimbal (which handles tilt movement), the UAV's pitch angle, adjusted by 90 degrees, is set as the reference. This adjustment ensures the camera faces downward regardless of UAV pitch variations. For the outer gimbal (Pan movement), the reference angle is 0 degrees plus the UAV Yaw angle, to keep the camera steady despite yaw changes in the UAV. The error calculation block computes the difference between the reference angle and the actual gimbal angle. This error is then processed by the controller, which calculates the necessary control signal to minimize it. The controller's implementation will be further discussed in section IV.B.

The motor response block represents the motor model, In PTZ camera systems, gimbal motors commonly consist of Direct Current (DC) motors. Here, voltage serves as the input, while torque acts as the output, in accordance with Kirchhoff's voltage law [23]. Due to a load (camera) is attached to the DC motor, the output will be the angular velocity of the movable load attached (ω_m); the motor model transfer function [24] is given by 1.

$$G_m(s) = \frac{\omega_m(s)}{V_a(s)} = \frac{K_{TM}}{J_m L_a s^2 + [J_m R_a + L_a a_m]s + R_a a_m + K_e K_{TM}} \quad (1)$$

where; ω_m - Angular velocity, V_a - Nominal Voltage, K_{TM} - Torque Constant, K_e - Electromotive Force, R_a - Terminal Resistance, L_a - Terminal Inductance, J_m - Rotor Inertia, and, a_m - Damping Ratio. Feedback is provided by the gyroscope model, which measures the rate of change of the gimbal's angle, allowing the controller to make more precise adjustments [23]. Inertial Measurement Units (IMUs), comprising accelerometers and rate gyros, are typically employed for this purpose. They detect accelerations and angular motions of both the base and stabilized platform, enabling compensation for external disturbances. This stabilization ensures the retention of the LOS for the instrument

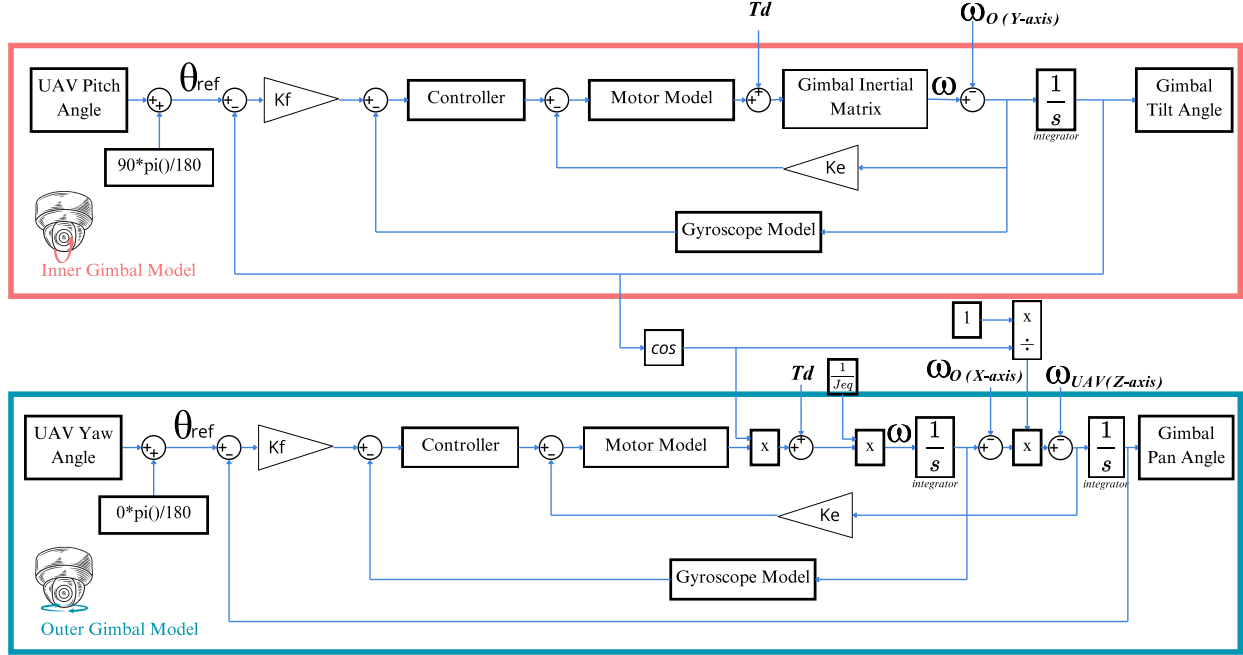


Fig. 3 Block Diagram of Camera Movement. where: ω_{UAV} : UAV angular velocity T_d : Disturbance torque (Inertial disturbances Coriolis and centripetal disturbances Gyroscopic disturbances), ω_o : Angular velocity Outer gimbal transformation, K_e : Electromotive Constant of the motor, θ_{ref} : Reference Angle, K_f : Frequency Gain

[25]. The Gyroscope sensor model's transfer function is presented in Equation 2.

$$G_{gyro}(s) = \frac{\omega_g^2}{s^2 + 2\zeta\omega_g s + \omega_g^2} \quad (2)$$

where ζ is the damping ratio, $\omega_g = 2\pi f_{BW}$; f_{BW} is the bandwidth of the gyro. The inertia block, represents the gimbal's moment of inertia. The model also incorporates disturbance handling to simulate external factors, like wind or UAV vibrations, that may impact the gimbal's stability. These disturbances are integrated into the system, requiring the controller to compensate for them. Another critical aspect of the model is the angular velocity transformation. The angular velocities of the UAV body frame are transformed to the outer gimbal and then to the inner gimbal to ensure the gimbal system accurately responds to the UAV's movements while maintaining the camera's orientation. The transformation process involves converting the UAV's angular velocities (ω_{UAV_x} , ω_{UAV_y} , ω_{UAV_z}) into the outer gimbal's angular velocities (ω_{O_x} , ω_{O_y} , ω_{O_z}) and subsequently to the inner gimbal's velocities (ω_{I_x} , ω_{I_y} , ω_{I_z}), ensuring accurate tracking of the UAV's movements.

Finally, angle transformation blocks ensure that the control is applied correctly across different axes. The actual gimbal angles, such as pitch and yaw, are compared to the reference angles, producing an error signal for the controller to adjust. The final output updates the gimbal's actual angle, which is continually compared to the reference for continuous stabilization control. Below, the mathematical models for Angular Velocities Transformations and torque disturbances are presented.

1. Angular Velocities Transformation

The motion of a PTZ camera gimbal is defined by three coordinate frames: the gimbal base frame, the outer frame, and the inner frame. The control of the line of sight (LOS) elevation is managed via the inner gimbal axis (y-axis), while azimuth control is executed through the outer gimbal axis (y-axis). Stabilization around the inner gimbal axis, known as cross-elevation, is essential for maintaining stability, although direct control over the cross-elevation axis is not applied but managed indirectly [26]. The kinematic relationships between the base, outer, and inner frames are governed by coordinate transformations, specifically through Euler angle transformations for a 2-axis gimbal. These

transformations are defined by the relative azimuth angle (η) between the outer and base frames and the relative elevation angle (ε) between the inner and outer frames [27]. The transformation from the base frame to the pan (outer) frame is expressed using a rotation matrix R_η , which depends on the relative azimuth angle $\eta(t)$, the angular rate vector of the base coordinate frame, ω_{base} , is related to the rate vector of the outer coordinate frame, ω_{PAN} , by the following relationship: $\omega_{\text{PAN}} = R_\eta \times \omega_{\text{BASE}} + \hat{\eta}$, where $\hat{\eta} = [0; 0; \dot{\eta}]$; $\dot{\eta}$ is the pan joint axis velocity.

The rate vector of the base coordinate frame, denoted as ω_{base} , is correlated with the rate vector of the outer coordinate frame, ω_{PAN} , by the following relationship, where $C\eta = \cos(\eta)$ and $S\eta = \sin(\eta)$:

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_{\text{PAN}} = \begin{bmatrix} C\eta & S\eta & 0 \\ -S\eta & C\eta & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_{\text{UAV}} + \begin{bmatrix} 0 \\ 0 \\ \dot{\eta} \end{bmatrix} \quad (3)$$

This is similarly applied to the angular rate vector transformation from the outer frame to the tilt (inner) frame. The transformation matrix for this frame, R_ε , depends on the relative elevation angle $\varepsilon(t)$, the angular rate of the tilt axis, ω_{TILT} , is given by: $\omega_{\text{TILT}} = R_\varepsilon \times \omega_{\text{PAN}} + \hat{\varepsilon}$, where $\hat{\varepsilon} = [0; \dot{\varepsilon}; 0]$. with $\dot{\varepsilon}$ representing the tilt joint axis velocity. Expanding this equation results in: (where $C\varepsilon = \cos(\varepsilon)$ and $S\varepsilon = \sin(\varepsilon)$).

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_{\text{TILT}} = \begin{bmatrix} C\varepsilon & 0 & -S\varepsilon \\ 0 & 1 & 0 \\ S\varepsilon & 0 & C\varepsilon \end{bmatrix} \times \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_{\text{PAN}} + \begin{bmatrix} 0 \\ \dot{\varepsilon} \\ 0 \end{bmatrix} \quad (4)$$

This model captures the kinematic relationships between the coordinate frames, describing how angular velocities are transformed between the gimbal axes [26, 27]. Using the rotation matrices in equations 3 and 4, the angular rates can be described as follows:

Outer(PAN):

$$\omega_{Ox} = \cos \eta \omega_{BASEx} + \sin \eta \omega_{BASEy}; \quad \omega_{Oy} = -\sin \eta \omega_{BASEx} + \cos \eta \omega_{BASEy}; \quad \omega_{Oz} = \omega_{BASEz} + \dot{\eta}. \quad (5)$$

Inner (TILT):

$$\omega_{Ix} = \cos \varepsilon \omega_{Ox} - \sin \varepsilon \omega_{Oz}; \quad \omega_{Iy} = \omega_{Oy} + \dot{\varepsilon}; \quad \omega_{Iz} = \sin \varepsilon \omega_{Ox} + \cos \varepsilon \omega_{Oz}. \quad (6)$$

2. Torque Disturbances:

This section focuses on modelling disturbances and angular velocity transformations within the UAV-mounted gimbal system to ensure stable control despite external disturbances [7]. The torque disturbances between the base and the pan subsystem are modelled using the equations from [7, 28, 29]. These equations are simplified by assuming $I_{xy} = I_{yx} = I_{xz} = I_{zx} = I_{yz} = I_{zy} = 0$ for both the inner and outer frames [28, 30]. The resulting equation used is as follows:

- Torque Disturbances in Inner Gimbal: The inner gimbal's torque disturbances, particularly in the pan-tilt mechanism, are captured by:

$$T_{\text{pan-tilt}} = (I_{zz\text{inner}} - I_{xx\text{inner}})\omega_{Ix}\omega_{Iz} \quad (7)$$

- Torque Disturbances in Outer Gimbal: The total torque disturbance $T_{\text{Base-Pan}}$ on the outer gimbal is represented by

$$T_{\text{Base-Pan}} = (T_{d1} + T_{d2} + T_{d3}) \cos(\varepsilon) + T'_d \quad (8)$$

This equation encompasses several disturbance types:

Inertial Disturbances (T_{d1}): These arise from mass distribution and rotational inertia, affecting stability via angular velocities and elevation angle ε .

$$T_{d1} = [I_{xx\text{outer}} + I_{xx\text{inner}} \cos^2(\varepsilon) + I_{zz\text{inner}} \sin^2(\varepsilon) - (I_{yy\text{outer}} + I_{yy\text{inner}})] \omega_{Ox}\omega_{Oy} \quad (9)$$

Coriolis and Centripetal Disturbances (T_{d2}): Caused by rotational motion and its interaction with the UAV's movement, described by:

$$T_{d2} = -[(I_{zz\text{inner}} - I_{xx\text{inner}}) \sin(\varepsilon) \cos(\varepsilon)](\dot{\omega}_{Ox} - \omega_{Oy}\omega_{Oz}) \quad (10)$$

Gyroscopic Disturbances (T_{d3}): Resulting from the gyroscopic effects, captured by:

$$T_{d3} = \dot{\varepsilon} \left[((I_{xx_{inner}} + I_{zz_{inner}})(\omega_{Ox} \cos(2\varepsilon) - \omega_{Oz} \sin(2\varepsilon))) - I_{yy_{inner}} \omega_{Ox} \right] \quad (11)$$

Additionally, other disturbances (T'_d) are modelled as:

$$T'_d = J_{eq} [\dot{\omega}_{Ox} \sin(\varepsilon) + \omega_{Ix}(\omega_{Iy} - \omega_{Oy})] \quad (12)$$

The equivalent moment of inertia J_{eq} is given by:

$$J_{eq} = I_{zz_{outer}} + I_{xx_{inner}} \sin^2(\varepsilon) + I_{zz_{inner}} \cos^2(\varepsilon) \quad (13)$$

B. Selection of the Controller

The effectiveness of a gimbal system depends significantly on the control technique employed, as it directly influences the system's responsiveness, stability, and ability to counteract disturbances. Several control techniques are available, each with its own strengths and disadvantages, tailored for specific operational environments and challenges. Table 1 provides a comprehensive comparison of five prominent control techniques—Proportional-Integral-Derivative (PID), Disturbance Observer (DOB), Internal Model Control (IMC), Iterative Learning Control (ILC), and Active Disturbance Rejection Control (ADRC)—focusing on their key features, advantages, and disadvantages in the context of UAV gimbal system control.

1. Controllers Features

PID: Utilizes proportional, integral, and derivative gains [31]. As a tuning method, Trial-Error is used.

DOB: Estimates and mitigates external disturbances using a filter base model that estimates and corrects the disturbance torques [32, 33]. Additionally, employs a nominal model for real time disturbance estimation.

IMC: Uses a process model to predict and counteract disturbances. The basic model utilization is presented below:

$$Q(s) = G(s)^{-1} G_d(s) \frac{1}{\tau_s + 1} \quad (14)$$

Where: $G(s)^{-1}$ is the inverse of the system's transfer function, $G_d(s)$ is the desired closed-loop response, modelled as a first-order system with time constant λ , and τ is a small time constant added for high-frequency roll-off to ensure properness [34].

ILC: Improves performance over repeated trials. The basic concept of ILC involves the following steps:

- Trial Execution: During the k -th trial, an input $u_k(t)$ is applied to the gimbal system, resulting in an output $y_k(t)$.
- Error Calculation: The error $e_k(t) = y_d(t) - y_k(t)$, where, $y_d(t)$ is the desired output.
- Update Rule: Based on the observed error, a new input $u_{k+1}(t)$ is computed to reduce the error in the next trial. This updated input is then applied in the subsequent trial [35].

ADRC: Combines disturbance estimation with feedback control signals. The basic model utilizes a cascade structure of the ESO [36].

C. Optimal Coverage Path Planning

To achieve optimal variable formulation for UAV path planning, several theoretical concepts are examined, including the relationship between altitude and camera resolution, image overlap vs. UAV speed, and path planning strategies such as the Boustrophedon method. These concepts are crucial for ensuring accurate and efficient aerial surveys.

1. Altitude vs. Resolution

UAV surveys often utilize nadir photography, where the camera is directed directly downward to simplify image capture and minimize the need for complex sensors or manual adjustments, as opposed to oblique photography [37]. The resolution of images, defined as Ground Sampling Distance (GSD), is influenced by the camera's parameters and the UAV's altitude. GSD represents the distance between adjacent pixel centers in the captured image. Assuming a camera with image dimensions of $P \times P$ pixels, the image resolution R_d is calculated as:

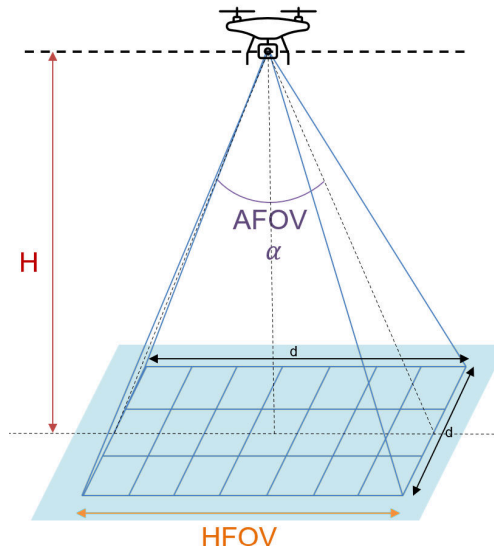
$$R_d = \frac{2 \cdot H}{P \cdot \tan^{-1} \left(\frac{\alpha}{2} \right)} \quad (15)$$

Table 1 Performance Comparison of Control Techniques for UAV Gimbal Systems

Controller	Advantages	Disadvantages
PID	<ul style="list-style-type: none"> • Effective for stabilizing dynamic systems and quick stabilization of gimbal orientation. • Minimizes steady-state errors and straightforward implementation. 	<ul style="list-style-type: none"> • Can be sensitive to noise if gains manually require manual tuning for optimal performance.
DOB	<ul style="list-style-type: none"> • Enhances disturbance rejection, especially at low frequencies. • Improves responsiveness and accuracy. 	<ul style="list-style-type: none"> • Requires a well-defined model. • Performance can degrade if the model is inaccurate or not adaptable
IMC	<ul style="list-style-type: none"> • Robust against disturbances and model mismatches. • Balances speed and stability for real-time applications. 	<ul style="list-style-type: none"> • Complexity in model development. • May be less effective for highly nonlinear systems without proper tuning.
ILC	<ul style="list-style-type: none"> • Continuous performance enhancement and Effective for similar maneuvers. • Straightforward implementation and control adaptation based on past iterations. 	<ul style="list-style-type: none"> • Requires repeated trials for optimal performance. • May not be suitable for one-time operations.
ADRC	<ul style="list-style-type: none"> • Provides real-time disturbance compensation. • Enhances control performance under complex conditions. 	<ul style="list-style-type: none"> • Complexity in implementation. • May require tuning of multiple parameters to achieve optimal performance.

Where, α is the Angular Field of View (AFOV) and H is the distance between the camera and the ground.

This relationship illustrated in Figure 4 shows that increasing altitude H decreases the image resolution, which highlights the importance of controlling altitude to capture detailed image data [37].

**Fig. 4 Sensing Distance and HFOV**

2. Image Overlap vs. UAV Velocity

Maintaining the desired overlap between consecutive images is critical for ensuring accurate photogrammetry. The UAV's speed must be adjusted based on the distance it travels between capturing images and the photo interval. This calculation ensures that the UAV moves at the correct speed to achieve the desired image overlap, which is necessary for high-quality photogrammetry surveys. The required speed, to maintain a specified overlap, is computed as follows [38]:

$$\text{Speed_desiredOverlap} = \frac{\text{Vertical_Image_footprint}}{\frac{100}{100 - \text{desired_vertical_overlap}}} \div (\text{photoInterval_s} + 0.1) \quad (16)$$

3. Boustrophedon Path: Optimized Sweep Path for Camera Coverage

A Boustrophedon path is a systematic coverage method where the UAV moves back and forth across the Region of Interest (ROI), similar to how a field is plowed. This path ensures complete coverage, with the desired overlap between images [39]. Key components of the path include:

- **Straight Sweep Paths:** The linear segments of the path where the UAV captures images, ensuring consistent coverage.
- **Turn Maneuvers:** Transitions between the end of one sweep and the beginning of the next, affecting overall flight efficiency [39].

The distance between successive sweeps is determined by the camera's Field of View (FOV) and the desired Ground Sample Distance (GSD). This method assumes:

- **Perfect Path Following:** The UAV follows the planned path without deviation.
- **Constant Airspeed:** The UAV maintains a constant speed throughout the mission, controlled by its autopilot [39].

The Boustrophedon method optimizes flight paths to ensure efficient area coverage with minimal flight time, making it a practical choice for real-world aerial surveys [39].

V. Results and Discussion

A. Parameters used in the implementation

The UAV gimbal control was tested in three phases: horizontal flight, pitch variations, and 3D maneuvers. In the first phase, a PID controller kept the gimbal perpendicular to the ground during minimal disturbances. The second phase introduced UAV pitch variations, where multiple control strategies like PID, DOB, IMC, ILC, and ADRC were compared to maintain the gimbal's orientation. In the final phase, during complex 3D maneuvers, PID + DOB controlled the outer gimbal, while PID + ADRC handled the inner gimbal, with the effectiveness of each strategy evaluated under significant disturbances. The values used in the implementation are taken from an existing study in [7].

1. Gimbal Control and Stabilization

- 1) The DC motor parameters for transfer function in equation 1 are the nominal voltage $V_a = 27\text{V}$, terminal resistance $R_a = 4.5\ \Omega$, terminal inductance $L_a = 0.003\ \text{H}$, rotor inertia $J_m = 0.0017\ \text{Kg m}^2$, torque constant $K_{TM} = 0.85\ \text{Nm/A}$, electromotive force constant $K_e = 0.85\ \text{V/rad/sec}$, and damping ratio $a_m = 0$.
- 2) The gyroscope values are $\zeta = 0.7$, $\omega_g = 50$.
- 3) Gimbal Dynamics: The inertial matrices of the gimbal equations to use will be equation 17 and 18. The gimbal's inertia values are considered using the inertial matrices from [9].

$$I_{\text{Inner}} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} = \begin{bmatrix} 0.065 & 0 & 0 \\ 0 & 0.069 & 0 \\ 0 & 0 & 0.07 \end{bmatrix} \quad (17)$$

$$I_{\text{Outer}} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} = \begin{bmatrix} 0.018 & 0 & 0 \\ 0 & 0.024 & 0 \\ 0 & 0 & 0.025 \end{bmatrix} \quad (18)$$

2. Optimized Coverage Path Planning for search applications

- 1) **Terrain simulation** A terrain of 300×300 meters is generated using a combination of sine and cosine functions, which is then added to a base altitude. The terrain data is organized in a grid format to facilitate the UAV's path planning. Specifications
- 2) **Height Calculation** The horizontal and vertical coverage in meters is calculated based on the camera's resolution and FOV. The Camera to Ground distance H , is determined by the minimum value between the horizontal and vertical coverage, according to equation 15.
- 3) **Camera Specifications** The selection process for a PTZ camera for UAV applications involved comparing various options. The chosen camera, the Drone Pan Tilt Gimbal Camera U30T, was selected due to its accessible information and support. While other cameras considered offered thermal imaging capabilities, these were not needed for the project. However, the implemented algorithm remains flexible and can be adapted to work with any PTZ camera by adjusting the input values to match the camera's specifications. The camera resolution is 1920×1080 pixels, with a FOV of 63.7° and a zoom capability of $30\times$.

B. Implementation Block Diagrams

1. Control Techniques

- PID: The diagram presented in Figure 3 represents the block diagram of the gimbal model, for PID implementation, the controller box is changed for a PID controller box.
- DOB: Figure 5 shows the Gimbal Model block diagram, which is now controlled using a DOB Controller.

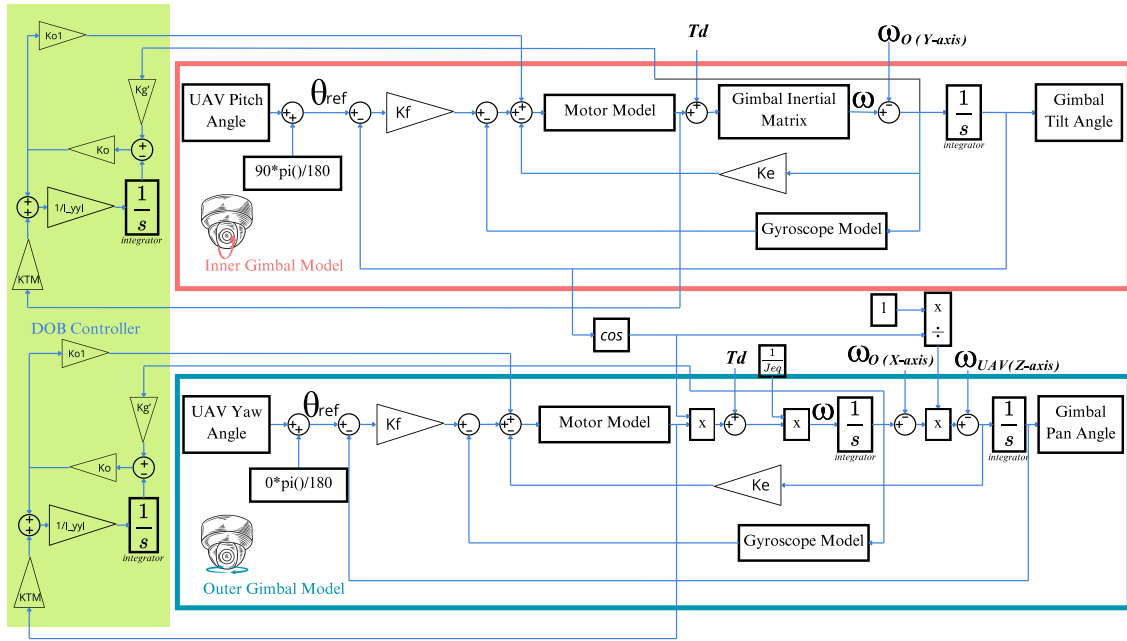


Fig. 5 Disturbance Observer Controller for a 2-axis Gimbal Mounted in a UAV with Disturbances

- IMC Controller: In the setup presented in Figure 3, the controller box is interchanged for a transfer function represented in equation 14, where $G(s)^{-1}$ is the inverse of the motor model transfer function (1).
- ILC Controller (Figure 6) Function updates the control signal based on the previous control input and the current error. It uses the equation [40]:

$$u_k(t) = u_k(t) + Le_k(t)$$

- Iteration error – (Reference Angle – Tracked Angle)

$$e_k(t) = \theta_r(t) - \theta_k(t)$$

where: $u_k(t)$: Control signal at the k -th iteration and time t , $e_k(t)$: Error signal at the k -th iteration and time t and L Learning matrix used to adjust the control signal based on the error.

- $\theta_r(t)$: Reference angle at time t . The Learning Matrix (L) is a constant matrix or gain that adjusts the learning process. The matrix determines how much the control signal is updated based on the current error.

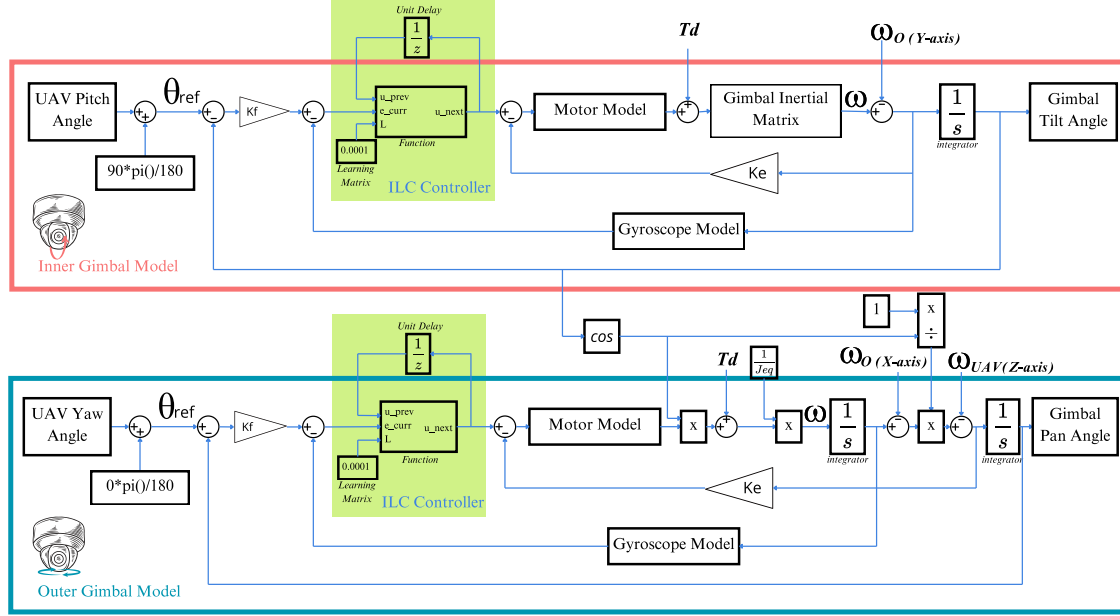


Fig. 6 ILC Controller for 2-axis Gimbal Mounted in a UAV with Disturbances

- PID + ADRC: The diagram in Figure 7 represents a gimbal control system mounted on a UAV, incorporating both PID and ADRC controllers.

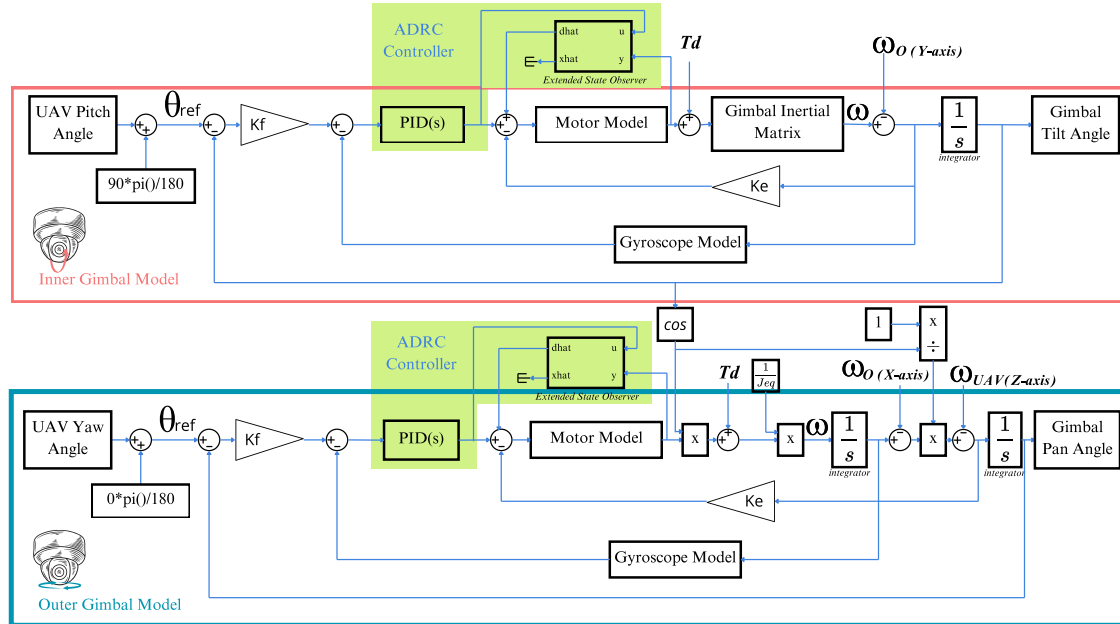


Fig. 7 PID+ADRC Controller for 2-axis Gimbal Mounted in a UAV with Disturbances

Additional controller combination like, PID+DOB and PID+IMC, where the PID controller box was included before the previous implemented controller.

2. UAV Model

A UAV model includes several essential components to simulate its flight behavior. The core components involve a rigid body representation that accounts for the UAV's position, velocity, orientation, and angular velocity. Aerodynamic forces and moments are modeled to reflect the interaction between the UAV's shape and the air. Propellers simulate thrust and torque, while actuators control flight surfaces. Sensors like accelerometers, gyroscopes, and GPS provide critical feedback for the UAV's control system. Additional elements such as environmental models, engine simulations, and structural representations can enhance the complexity of the simulation. By integrating these elements, the model approximates real-world flight conditions and allows for mission simulation and testing of control algorithms. The angular velocities of the Euler angles ($\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$) shown in Figure 8 were used to compute the angular transformation described in IV.A.1, where these angular velocities correspond to $\omega_{x,UAV}$, $\omega_{y,UAV}$, and $\omega_{z,UAV}$.

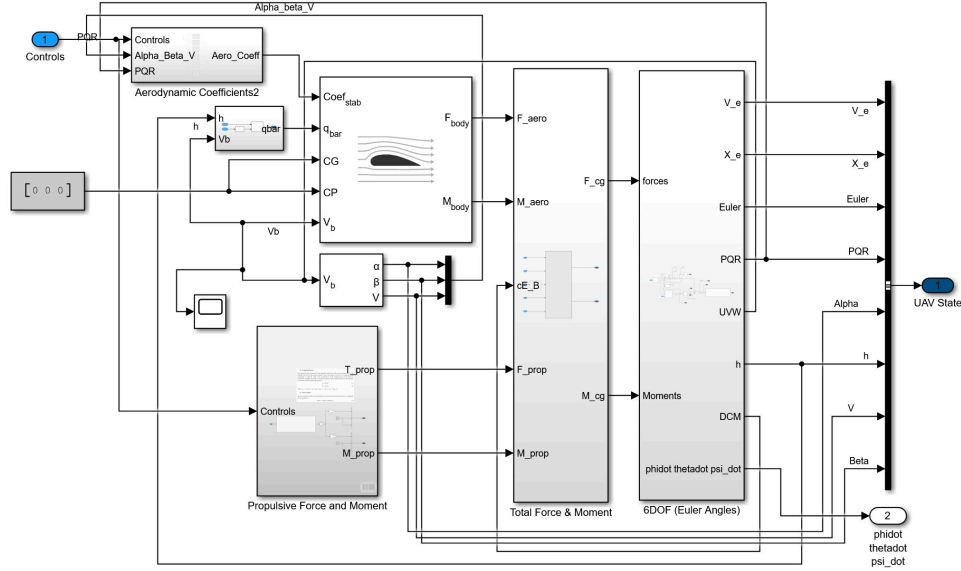


Fig. 8 UAV Model with Autopilot

3. Boustrophedon Coverage Path Planning

Boustrophedon CPP method ensures efficient terrain coverage while maintaining the necessary overlap between captured images, crucial for photogrammetry and aerial surveying. The algorithm's foundation includes key theoretical aspects such as altitude versus resolution, image overlap versus UAV velocity, and the Boustrophedon path planning method.

Initialization:

- **Setting Initial Variables:** Includes terrain dimensions, grid spacing, and UAV altitude. The relationship between altitude and camera resolution is critical, as the Ground Sampling Distance (GSD) affects how much detail is captured.
- **Computing Start Points:** Initial coordinates and incremental steps are calculated based on the camera's FOV and the required overlap.
- **Grid Spacing:** The half-width and half-height of the ground footprint are computed using the arc tangent function, which relates the FOV to footprint size at a given altitude.
- **Camera-to-Ground Distance:** The minimum value between the horizontal and vertical footprint dimensions is selected for accurate altitude estimation, ensuring conservative and effective coverage.
- **Terrain Generation:** A simulated terrain is generated using sine and cosine functions to simulate variations in altitude.
- **Altitude Set:** The UAV's altitude is updated relative to the current terrain elevation by adding the camera-to-ground distance to the terrain's base altitude.

- **Speed vs. Overlap:** Equation 16, ensures that the UAV moves at the correct speed to achieve the specified image overlap, which is crucial for high-quality photogrammetry and accurate terrain reconstruction.

Key Parameters: Table 2 summarizes the main parameters used in the path planning calculations:

Table 2 Key Parameters for Path Planning

$P_{width} \times P_{height}$	$R_{width \& height}$	d_{width}, d_{height}	α	H	H_{base}	$Altitude_{UAV}$
1920×1080 px	(1/50) m/pixel	(38.4, 21.6) m	63.7°	5.48 m	(106.33-07.03) m	$H_{base} + H$

The flowchart in Figure 9 outlines the entire process for UAV path planning over a given terrain using the Boustrophedon path method. It covers initialization, point assignment, boundary checking, and storing positions, providing a clear visualization of the steps involved.

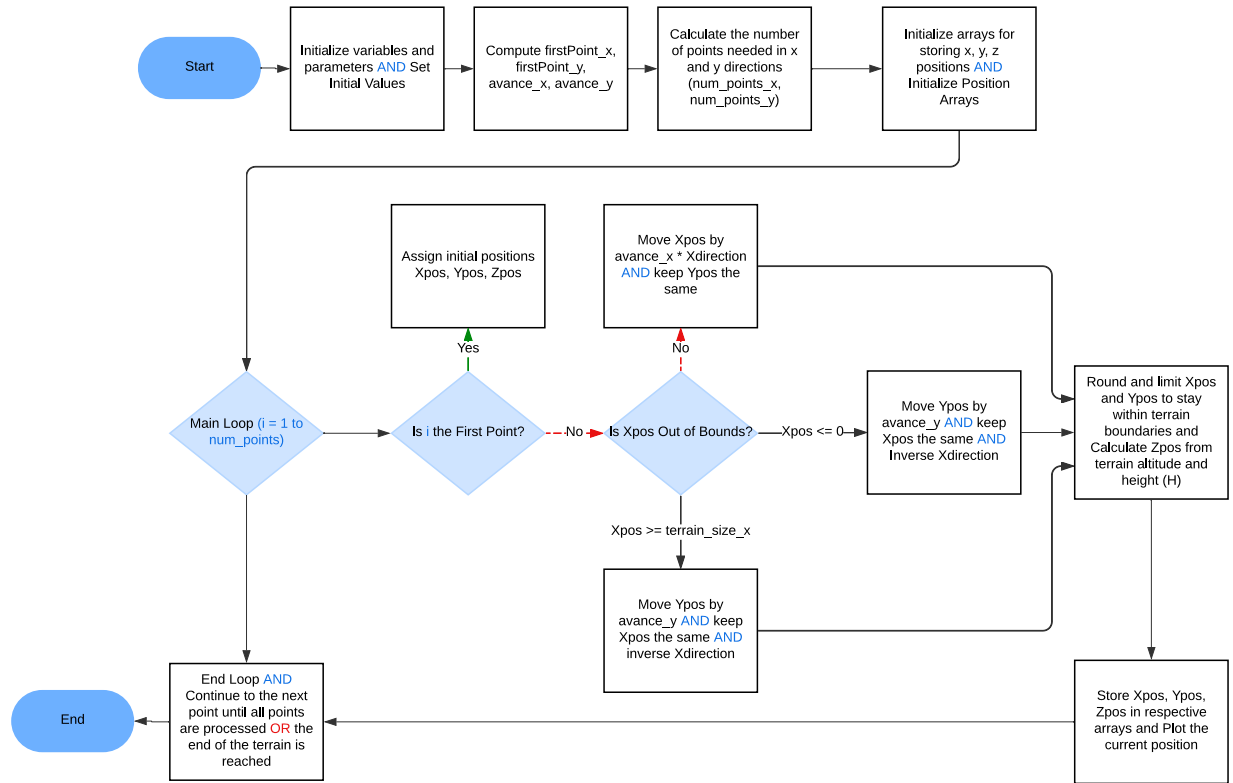


Fig. 9 Flow Diagram for Optimized Search Path Planning

C. Results

1. Objective 1: Gimbal Control for UAV-Based Aerial Imaging and Comparative Analysis of Control Strategies

The primary objective of this study was to ensure stable and precise control of a UAV-mounted gimbal camera, particularly under disturbances such as torque variations and changes in UAV attitude. The performance of several control strategies was evaluated to maintain camera orientation towards the ground during various flight maneuvers.

- 1) **PID Controller Performance** Initially, the PID controller was implemented during horizontal flight with minimal disturbances, serving as a baseline for comparison. However, in scenarios involving changes in UAV pitch and external disturbances, the PID controller exhibited limited robustness. Notable issues included overshooting and slower stabilization, making it less suitable for complex operational conditions.

2) **Advanced Control Strategies** To address the limitations of the PID control, more sophisticated methods were explored, including Disturbance Observer (DOB), Active Disturbance Rejection Control (ADRC), Internal Model Control (IMC), Iterative Learning Control (ILC), and a hybrid approach combining PID with DOB.

- **ADRC** showed the best overall performance, particularly in scenarios with complex 3D UAV maneuvers. It achieved fast stabilization, with minimal tracking error, and improved adaptability to changing UAV dynamics.
- **PID + DOB** demonstrated a strong balance between control accuracy and disturbance rejection. The hybrid approach excelled in managing disturbances while maintaining gimbal orientation, especially in the outer gimbal. This combination proved highly effective in stabilizing the system despite external torque disturbances.

Figure 10 presents the results of different gimbal control strategies for the pan movement of a UAV-mounted camera. The reference angle for the pan control is defined as 0 degrees plus the UAV's yaw angle, ensuring the camera remains steady relative to the ground despite any changes in the UAV's yaw orientation. Each colored line in the graph corresponds to the actual pan angles achieved by various controllers (PID, DOB, ADRC, ILC, IMC, and combinations) during flight. This comparison demonstrates the ability of each controller to compensate for yaw changes and keep the camera focused on a fixed direction, crucial for visual search operations.

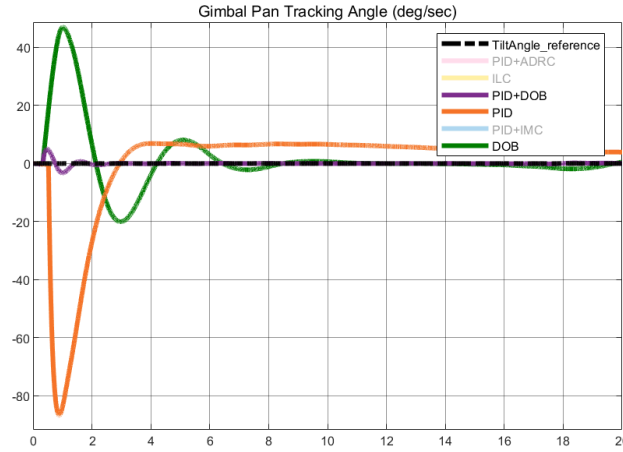


Fig. 10 Tracking gimbal pan angle with the functional implemented controllers

Figure 11 illustrates the performance of various gimbal control strategies (PID, DOB, ADRC, ILC, IMC, and their combinations) in maintaining the desired tilt angle of a UAV-mounted camera during flight. The reference tilt angle, defined as the UAV's pitch angle adjusted by 90 degrees, ensures that the camera remains facing downward despite variations in the UAV's pitch. The colored lines in the graph represent the actual tilt angles achieved by each control method over time, showing how effectively each strategy compensates for pitch changes. This comparison highlights the controllers' abilities to stabilize the camera's orientation for optimal visual search performance.

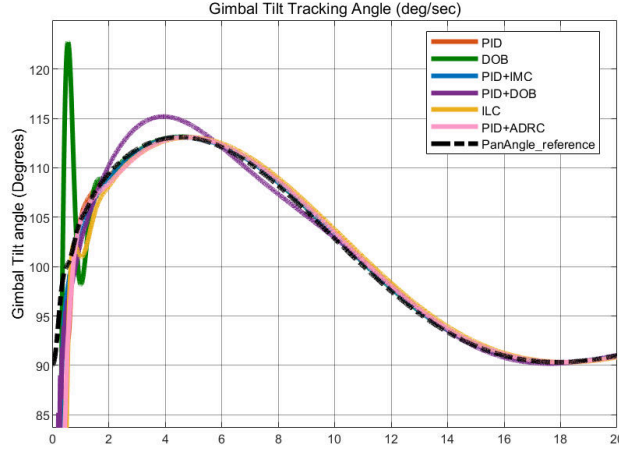


Fig. 11 Tracking gimbal tilt angle with all implemented controllers

Final Control Strategy

After evaluating the results, the **PID + DOB** (Figure 12a) configuration was selected for the outer gimbal, providing robust control against disturbances. For the inner gimbal, **PID + ADRC** (Figure 12b) was chosen due to its dynamic adaptation to UAV attitude changes and superior disturbance rejection. Together, these methods ensured optimal stability and camera orientation across different operational scenarios, particularly during demanding 3D maneuvers.

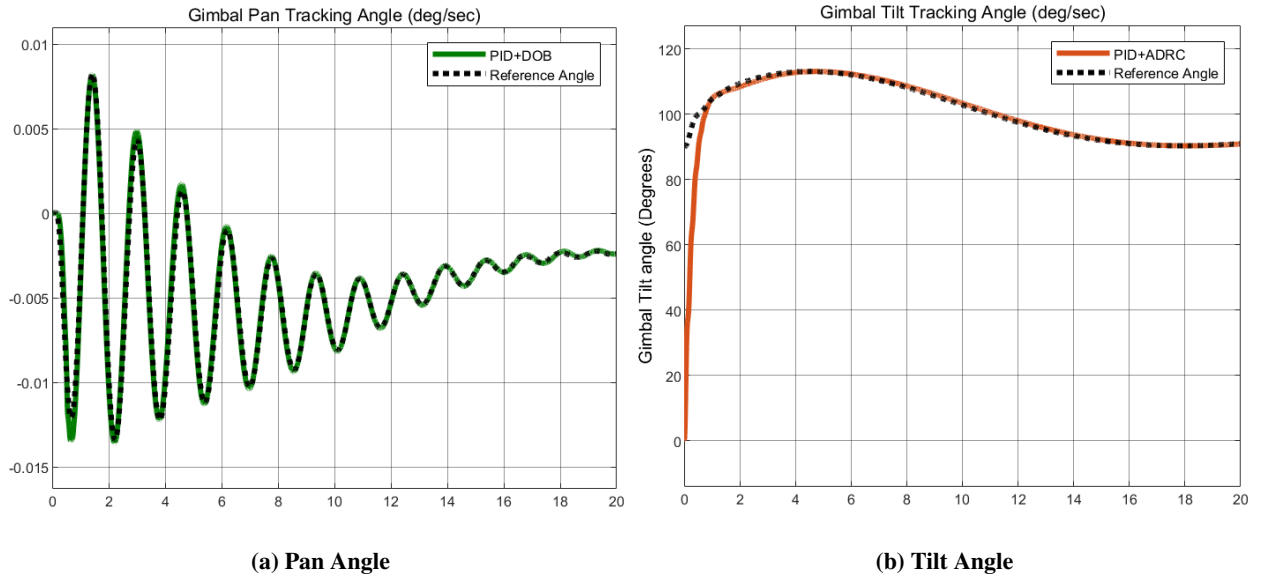


Fig. 12 Selected Method for Gimbal Tracking

2. Objective 2: Coverage Path Planning for Search Applications

The second objective focused on optimizing the coverage path planning (CPP) for UAV search applications over varying terrain types. The performance of a general CPP without optimization was first assessed, followed by an analysis of the optimized path.

- 1) **General Path Planning (Non-Optimized)** In the initial simulation, a general path was created for a $300\text{m} \times 300\text{m}$ terrain using a Boustrophedon pattern. The path exhibited significant overlap (over 90%), which resulted in excessive points, frequent turns, and inefficient flight times. This approach was deemed unsuitable for efficient

search operations, as it failed to minimize unnecessary movements and increase coverage efficiency. The general path planning strategy serves as a baseline for comparison against the optimized path. It adopts a dense grid with waypoints spaced 1×1 m apart, ensuring complete coverage of the area but resulting in significant overlap and inefficiency. This approach does not consider the camera's resolution or field-of-view and therefore reflects a naive but exhaustive coverage strategy, results for different terrain types are presented in Figure 13. The red lines show the flight path, and the multicolor surfaces represents the terrain.

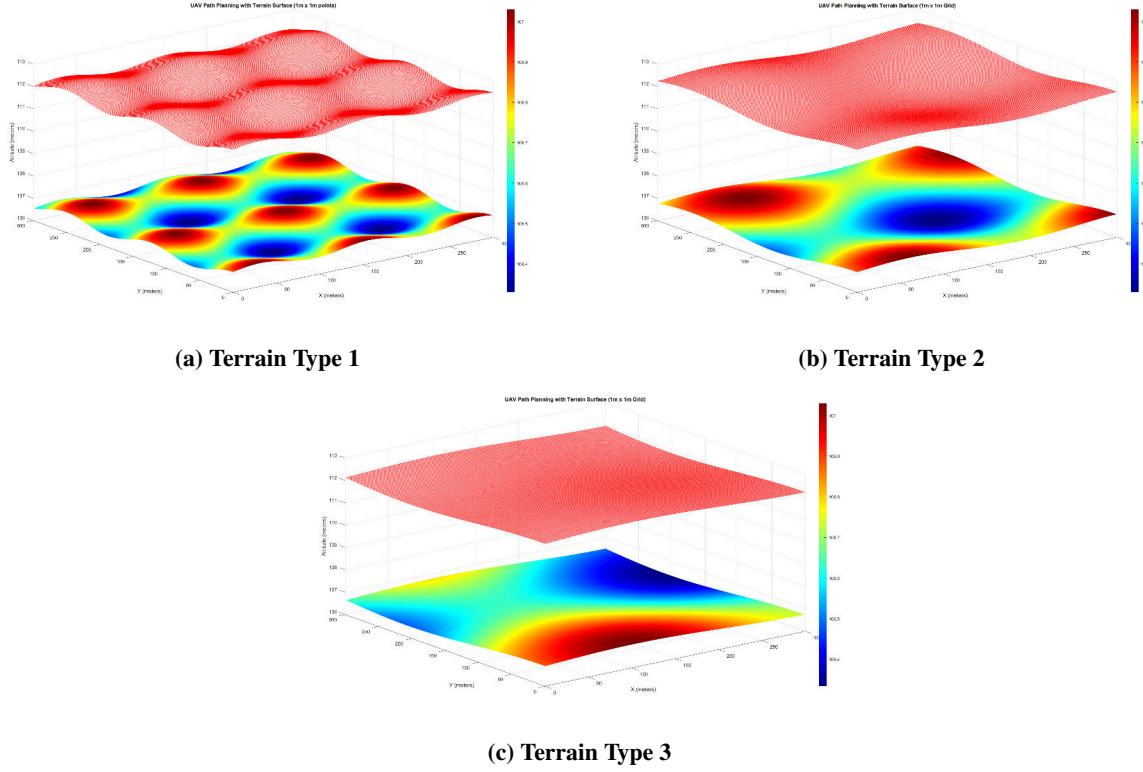


Fig. 13 General CPP for Different Terrain Types

2) **Optimized Path Planning** The optimized path leverages the camera's resolution and footprint to determine waypoint spacing. Starting with an initial distance of 19.2×10.8 m, the spacing increases to 30.72×17.28 m, reflecting the camera's ability to cover larger areas at higher altitudes. This adjustment reduces the number of waypoints and the total path length while maintaining complete and high-quality coverage.

Optimization of the CPP significantly improved flight performance by reducing the total flight distance, number of points, and turns. For all terrain types evaluated, the optimized path reduced the overlap to an appropriate level while maintaining full coverage of the area. Key improvements included:

- **Flight distance** reduced by more than 90% across all terrain types.
- **Flight time** and the number of points were dramatically lowered, improving operational efficiency.

Figure 14 show the optimized flight path (red pointed line) over the terrain (multicolor surface) and Table 3 presents the Flight time, distance, and number of waypoints results for the General and Optimized CPP.

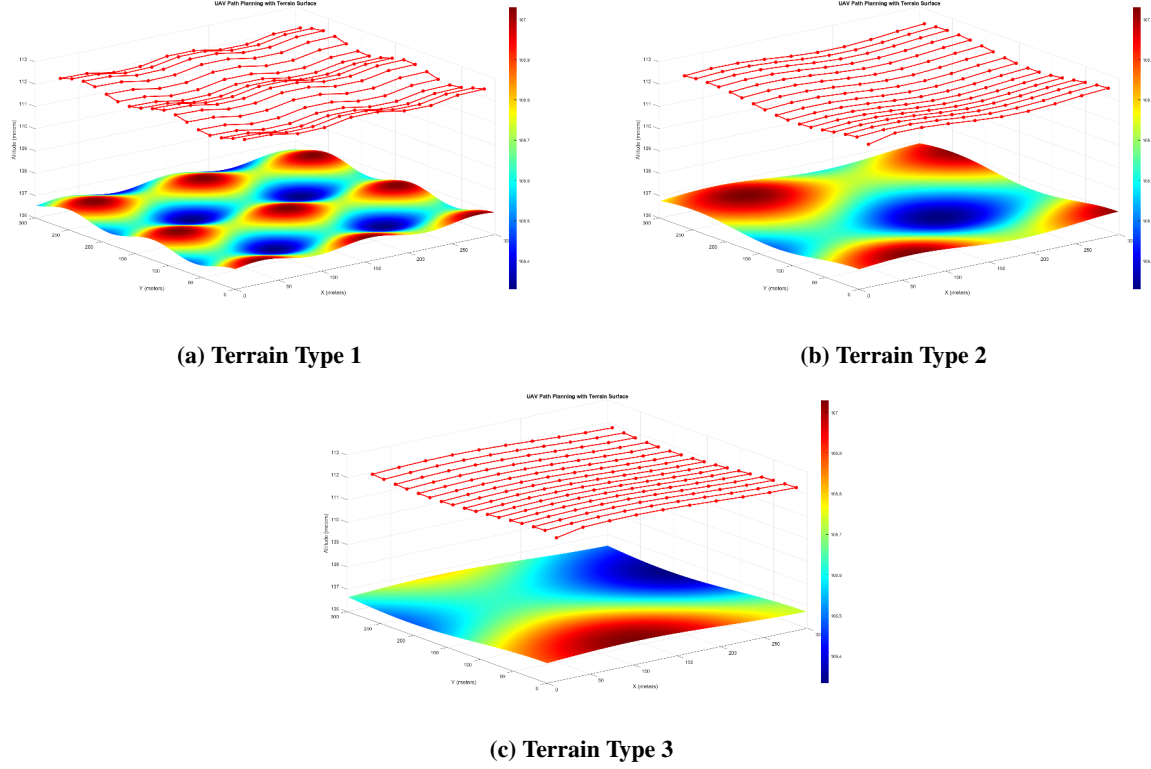


Fig. 14 Optimized CPP for Different Terrain Types

Table 3 Comparison of General and Optimized CPP for Search Applications Specifications

Terrain Type	Total Distance (General) (m)	Total Flight Time (General) (s)	Total Distance (Optimized) (m)	Total Flight Time (Optimized) (s)	Number of Turns (General / Optimized)
1	90001.33	18000.27	4976.70	228.0945	299 / 16
2	89999.54	17999.91	4976.66	228.09	299 / 16
3	89999.19	17999.89	4976.65	228.0945	299 / 16

These results demonstrate that an optimized CPP approach is crucial for practical UAV search missions. By increasing the spacing between waypoints to align with the camera's resolution and FOV, the optimized CPP achieves a remarkable 94.47% reduction in total path length compared to the general path. This reduction significantly decreases energy consumption, enhances flight efficiency, and ensures complete area coverage with minimal redundancy. Such improvements not only optimize resource usage but also extend the UAV's operational capabilities, making this approach invaluable for real-world applications.

VI. Conclusions and Future Work

A boustrophedon algorithm was successfully developed to optimize visual search operations using a UAV-mounted PTZ camera, accounting for platform dynamics. This was achieved by designing and testing control strategies for gimbal stabilization, ensuring comprehensive coverage of the target area.

The study demonstrated that stable and precise gimbal orientation is critical for effective UAV-based aerial imaging. While a standard PID controller performs adequately in simple scenarios with minimal interference, it proves insufficient in more complex cases involving rapid UAV attitude changes and significant external disturbances. Advanced control strategies such as Disturbance Observer (DOB), Internal Model Control (IMC), and Active Disturbance Rejection Control (ADRC) showed superior performance in maintaining gimbal stability under varying conditions. Among these,

the combination of PID with DOB delivered the most notable improvements in disturbance rejection, making it a highly suitable approach for maintaining the desired gimbal orientation in demanding operational environments.

In addition, the study successfully designed a search path planning algorithm that maximizes image coverage, considering constraints such as the field of view, resolution requirements, and terrain types. This ensured that the UAV covered the entire area of interest without leaving gaps or excessive overlap between adjacent passes. While the algorithm assumed constant altitude and simplified terrain modeling, this was validated through simulations. More complex issues, such as fluctuating altitudes and uneven terrain, were addressed by integrating precise distance-measuring sensors into the system. A qualitative comparison between general and optimized Coverage Path Planning (CPP) methods for various terrain types demonstrated the efficiency of the optimized approach, significantly reducing travel distance, flight time, and the number of turns. This optimization is crucial in real-world UAV applications, where operational efficiency is vital for search tasks. The combination of advanced control strategies and optimized path-planning algorithms thus provides a robust framework for achieving optimal performance in vision-based search operations using UAVs, particularly in dynamic and complex environments.

Looking forward, further enhancements are planned for both objectives. For Objective 1, additional constraints—such as cable restraint, friction effects, and dynamic disturbances like wind impacting the gimbal—will be integrated into the control strategies. Furthermore, the zoom capability of the camera will be incorporated to improve visual accuracy during search tasks. For Objective 2, more advanced methods, including reinforcement learning, will be explored to refine the search path optimization process. These future developments will contribute to creating a more robust and adaptable UAV system capable of operating effectively in increasingly complex and unpredictable environments.

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