UAV with High-reaction of robotic arm by geometry control Enhanced with AI

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Abstract. Unmanned Aerial Vehicles (UAVs) with robotic arms have revolutionized aerial manipulation, enabling advanced tasks such as object handling, infrastructure inspection, and emergency response. However, the integration of robotic arms introduces significant challenges due to dynamic coupling and external disturbances like wind, which can compromise system stability and performance. Traditional control methods have struggled to address these issues effectively, necessitating innovative solutions. This paper explores the application of geometric control to handle high reactions induced by robotic arm motions in UAVs. Geometric control leverages the intrinsic properties of the system's configuration space, offering a robust and mathematically rigorous approach to managing nonlinear dynamics and external perturbations. By addressing the dual challenges of internal coupling and environmental disturbances, this study provides a comprehensive framework for stable and precise aerial manipulation. The proposed methodology is validated through simulations and experimental results, demonstrating its efficacy in enhancing UAV stability and performance under challenging conditions. This research contributes to the advancement of UAV-manipulator systems, paving the way for more reliable and versatile applications in complex environments.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) equipped with robotic arms represent a significant advancement in aerial manipulation and autonomous systems. Such systems are designed to perform complex tasks like object grasping, infrastructure inspection, and disaster relief operations. However, incorporating robotic arms into UAVs presents unique challenges, particularly when considering the dynamic and unstable nature of aerial platforms. These challenges are exacerbated by the high reactions induced by the motion of robotic arms, which can disrupt the stability of the UAV, and by environmental disturbances such as wind[1].

Historically, balancing problems in drones with robotic arms have been a persistent issue. The dynamic coupling between the UAV and the attached manipulator introduces additional degrees of freedom, making the control problem highly nonlinear and complex. Early approaches relied on simplified models and conventional PID controllers, which often failed to address the coupling effects adequately[2].Moreover, external disturbances like wind have long posed challenges for maintaining stability and precision, particularly when the UAV operates in environments with unpredictable airflow[3].

These issues highlight the necessity for sophisticated control strategies that can take into consideration the complex dynamics of UAV-manipulator systems and offer reliable operation in a range of scenarios. One possible approach to these problems is geometric control. Geometric control provides a mathematically sound foundation for creating controllers that guarantee correctness and stability by utilizing the inherent geometric qualities of the system's configuration space. In contrast to conventional methods, geometric control offers instruments for assessing and reducing the impact of external disturbances while also naturally respecting the system's nonlinear character[4]. The high-reaction handling of robotic arms in UAVs through geometric control. Our approach seeks to address the dual challenges of internal dynamic coupling and external disturbances, providing a robust framework for aerial manipulation. The paper is organized as follows, The design of the drone under study is examined in Section 3, the geometric control approach and its application to UAVs with robotic arms, experimental results and analysis, and future directions are covered in Section 4. Section 2 discusses the research gap between issues, solutions, and research methodology .UAVs with robotic arms have shown great promise in aerial manipulation, several research gaps remain that hinder their widespread adoption and performance in real-world scenarios. Dynamic Coupling Complexity: The highly nonlinear and coupled dynamics of the UAV and its robotic arm are frequently not adequately addressed by current control approaches. Existing methods' simplified models could result in less-than-ideal performance on complicated and dynamic job [5]. Robustness to Environmental Disturbances: One major obstacle still facing UAVs is the impact of wind and other environmental conditions on their stability, particularly while performing high-precision jobs. Existing solutions frequently don't hold up well amid uncertain external circumstances. Real-Time Implementation: Because of their computing requirements, many sophisticated control algorithms, especially those based on geometric control, are challenging to implement in real-time. Progress requires bridging the gap between theoretical models and real-world implementations[6]. Scalability to Complex activities: The scalability of current control frameworks continues to be a crucial concern as activities get more complex, such as requiring many manipulators or simultaneous aerial and ground interactions. Experimental Validation: Although simulations offer insightful information, there is little experimental validation of actual UAV-manipulator systems. To validate theoretical models and control mechanisms, extensive testing in real-world settings is urgently needed.[7]

This research aims to address these gaps by proposing a robust geometric control framework capable of managing the dynamic complexities and environmental disturbances encountered in UAV-manipulator systems. The integration of real-time computational methods and extensive experimental validation ensures practical applicability and scalability for future advancements[8].

This work uses a simulation-driven methodology with sophisticated software tools to address the difficulties related to UAV-manipulator systems. The following crucial phases make up the methodology: Design a harmonious mechanical and electrical interface between the different mechanical parts such as the exoskeleton and robotic arms, their number of links, lengths, types of joints, their numbers and their method of movement. System Modeling: Develop a detailed mathematical model of the UAV-manipulator system, capturing the nonlinear dynamics, dynamic coupling, and environmental disturbances. Represent the system's

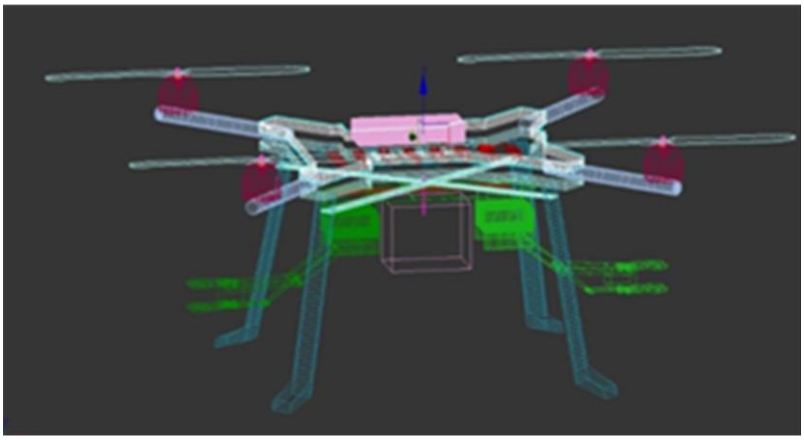


Figure 1. drone and robotic arm design

configuration space using geometric control principles to facilitate precise analysis and controller design[9].

Geometric Control Design: Design controllers based on geometric control theory to ensure stability, robustness, and accurate handling of high reactions from robotic arm motions. Incorporate compensation mechanisms for external disturbances like wind, leveraging robust control techniques to enhance performance in dynamic environments[10]. Simulation Framework: Implement the system model and control algorithms in a high-fidelity simulation environment (MATLAB/Simulink, ROS-based tools)[11]. Simulate various scenarios, including object manipulation tasks and operations under varying wind conditions, to evaluate system performance. Performance Metrics: Define key performance metrics such as trajectory tracking accuracy, stabilization time, and energy efficiency to quantify the effectiveness of the proposed control framework. Conduct comparative analysis with traditional PID-based controllers to highlight improvements. Iterative Refinement: Analyse simulation results to identify performance bottlenecks or areas for improvement.

2. Proposed design

Validate the geometric control framework through extensive simulation experiments, ensuring scalability to real-world applications. Prepare the framework for future integration with physical UAV-manipulator systems for experimental validation. This simulation-driven methodology provides a rigorous and efficient pathway for developing and testing advanced control strategies for UAVs with robotic arms, paving the way for practical implementation in complex operational environments. The drone is designed in a harmonious way that suits the process of large manoeuvres and achieving balance by changing the structure of the electric current of the brushless motors, so the tone changes by varying the degrees of the power of the throttle as a result of the harmony of the mechanical design with all its components and loads with the electrical design in its distribution of the battery power and the electronic system in controlling the robotic arms “Fig. 1”

2.1. MECHANICAL SYSTEM

Airframe conventional airframe consists of merely fuselage part of the airframe. This design clarifies the placement of the electrical and electronic components in relation to the mechanical structure so that it copes with the mechanical reactions resulting from the momentum of flight and ensures that it is not affected by mechanical loads during take-off and is covered and

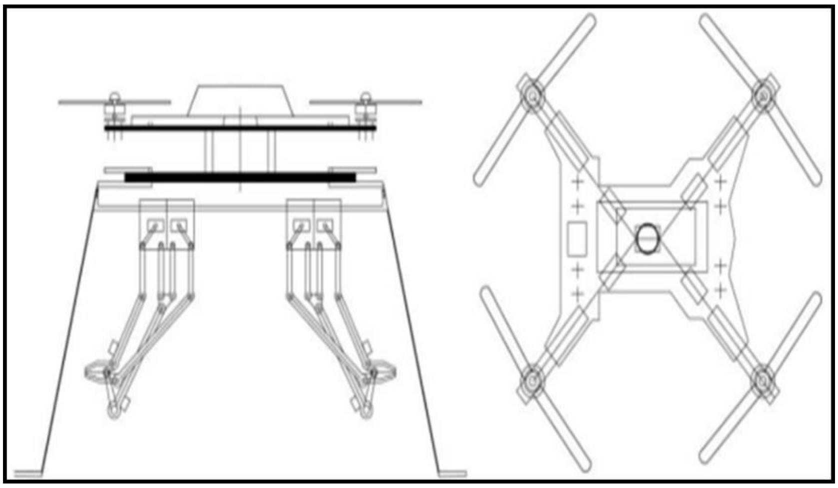


Figure 2. geometry scheme

protected from erosion factors, wind, rain and dust. “Fig 2”, In the geometric graph shown are two sections of the drone , a side plan and a vertical section, which show the placement of non-sprung engines on the ends of the branches to work on the vertical take-off. The mechanical structure is shown as connected to the four legs by fixed and moving mechanical links, which provide flexibility during landfall on the mainland. The aluminium structure of the legs achieves the necessary flexibility and smoothness during flight and protects the arms during work. The work of the structure depends mainly on protecting the components of the drone to achieve the required work with high efficiency[13]“Fig 3”.

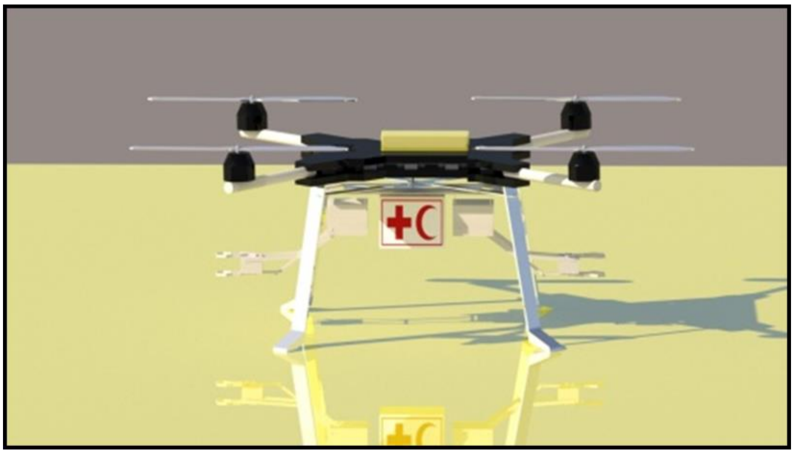


Figure 3. solidwork

2.2. propulsion system

Its consists of motors, propellers, ESCs, and, occasionally, a battery. Since it controls important features like hovering duration, load capacity, and flight speed and distance, this system is the most important part of the multicopter. Additionally, parts of the propulsion system that must be compatible with each other in order for them to function correctly or, in some situations, fail. Unusual situations. The propeller generates the thrust needed to operate a multicopter. Depending on the output torque, which is influenced by the propeller's size, speed. “Fig. 3”

Motors of multicopters are mainly brushless DC motors 800kv for the various advantages such as high efficiency, potential to downsize, and low manufacturing costs. Brushless DC motors are used to convert electrical energy (stored in battery) into mechanical energy for propeller. Concretely, based on the position of rotors, brushless DC motors can be classified into the outer rotor type and inner rotor type. Considering that the motor of a multicopter is supposed to drive larger propellers to improve efficiency, the outer rotor type outperforms the inner rotor type as it can provide larger torques. Besides, compared with the inner rotor type, speed of the outer rotor type is more stable [15].

2.3. **Electrical system**

For brushless ESCs, the most essential parameter is current, which is commonly expressed in Amperes (A), such as 10 A, 20 A, and 30 A. Different ESCs are required for different motors. In particular, the brushless ESC has two critical parameters: maximum continuous current and peak current. The former is the maximum continuous current that the ESC can withstand in normal operation, while the latter is the greatest instantaneous current that it can withstand. Each ESC will be labelled with a rating, such as Hobby wing Rotor 15A, 800kv that shows the maximum continuous current that can be used. When selecting ESCs, pay close attention to the maximum continuous current, which should be verified to see if it includes a safety margin (20 percent, for example) to avoid burning the power tube. Take, for example, a 50A ESC and a 10A ESC [16] “Fig. 4”.

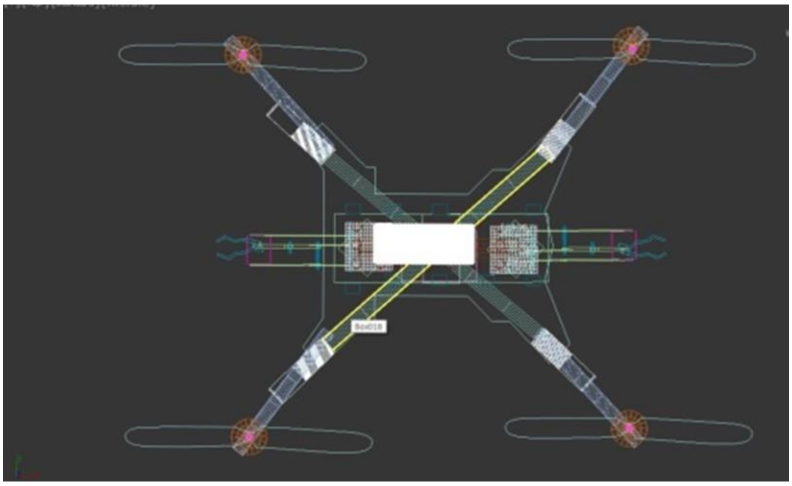


Figure 4. electrical scheme

The Energy is provided via a battery. Figure [5] shows a battery for small multicopters. The period of endurance, which is strongly dependent on battery capacity, is a common worry on today's multicopters. There are many different types of batteries now, including Lithium Polymer (LiPo) capacity within a particular range. However, as the discharge progresses,

Power distribution is Important, influential and highly sensitive modifications have been made to the TDX60 power distribution that allows ensuring stability for the plane controller and accepting more commands from the fligh and its processors, and this is the data sheet of the power distributor after the modifications. PDB-XT60 with BEC 5V and 12V Power Distribution Board shown in “Fig. 5”, have been engineered to provide the highest possible performance and reliability in a 36x50mm, 4-layer PCB. It comes with an XT60 for easy connection to LiPo batteries. Using BECs it distributes power from 3~4S LiPo packs to 6 ESCs, as well as providing synchronized and regulated DC 5V outputs for RC Receivers, Flight controllers, OSD, and Servos. It also provides linear regulated DC 12V for powering Cameras, Servos, RC receiver, Flight Controllers, Video Transmitters, LEDs[17]

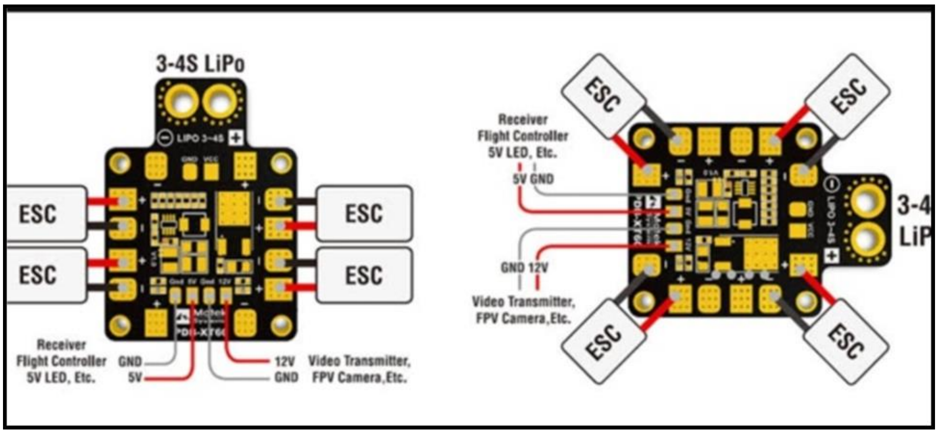


Figure 5. (tx 60) power distribution system[17]

2.4. ESC (electronic speed control)

electronic circuit that controls and regulates the speed of brushless motor. It may also provide reversing of the motor and dynamic braking. Miniature electronic speed controls are used in electrically powered radio controlled models. Full-size electric vehicles also have systems to control the speed of their drive motors. microcontroller that governs power functions of digital platforms. This microchip has many similar components to the average computer, including firmware and software, memory, a CPU, input/output functions, timers to measure intervals of time, and analog to digital converters to measure the voltages of the main battery or power source of the computer. The PMU is one of the few items to remain active even when the computer is completely shut down, powered by the backup battery. [18]. “Fig. 5”.

3. Control System and programming

The microcontroller has 8 inputs, 8 outputs, and a connection point for the power management unit and LED sensors, it depends on the C++ language in its program, and the following is an explanation of the way to connect to the accessory devices and the work mechanics In the 8 entries there are 4 entries marked with letters.

Programming code (C++) was designed with an orientation toward system programming and embedded, resource-constrained software and large systems, with performance, efficiency, and flexibility of use as its design highlights[10]. C++ has also been found useful in many other contexts, with key strengths being software infrastructure and resource-constrained applications, including desktop applications, video games, servers The program is built by using objects and their association with each other and the external program interface using the program structure and user interfaces specific to each object. One of the advantages of object-oriented programming is that it allows reuse of the tested code by calling it in other programs without reprogramming it. [19]

3.1. Control System

To transfer commands from remote pilots to the appropriate receiver, an RC transmitter is employed, After deciphering the commands, the receiver, Fends them to the autopilot. Finally, the multi copter follows the commands and flies. Some flying parameters, such as throttle direction, stick sensitivity, RC servomotor neutral position, channel function definitions, flight time record and reminder, and lever function setting, can be set on the transmitter. Battery voltage and current multi copter flight data are among the advanced functions. There are various open-source transmitters available right now.[20]

- A lot of times. Instead of setting the frequency manually regulating the crystal, the technology uses microcomputers to plan frequencies automatically.
- Co-channel interference is less likely. This method permits frequency-hopping to avoid reciprocal interference when multiple transmitters work together.
- Power usage is low. The power consumption is greatly lowered because no crystals are utilized as frequency control elements.
- The volume is smaller. Since its inception, Since the control wavelength is very short, transmitting and receiving antennas can be shortened greatly.
- Rapid response and high control accuracy. Although the 2.4GHz RC transmitter can deal with the co-channel interference, some problems still exist.[21]

The drone prototype's mass was increased to a point where it produced relatively manoeuvrable flight after additional calculations involving mass. When the same tests were conducted in the air lab at Delta University for Science and Technology, the drone prototype then demonstrated the anticipated slightly free manoeuvrable flying. The prototype's height could be adjusted by 5 meters thanks to the vertical brushless motors without adding any noticeable pitch. This suggests that the vertical brushless motor of the drone prototype is located at the centre of mass. In the still air of the water tanks, the operator of the prototype managed to locate the Drone vehicle and control its Z-axis and rolling. In just a few seconds, the prototype was also able to ascend to the top of the partially full, but still more than five-meter-high, storage windy air. Because the Delta University air lab has a closed ceiling designed to prevent free current surface without any disturbance impacts when utilized for tow testing, it was unable to assess the drone prototype's forward speed here.. The UAVs struggled mightily to get higher than 25 meters then moored. even when the buoy's height above the surface was achieved by lowering the multiphase water level. In the three-rooms air lab at Delta University, the prototype was flaying .Manoeuvring Control: The drone is controlled by a radio controller that can be operated remotely. [22]

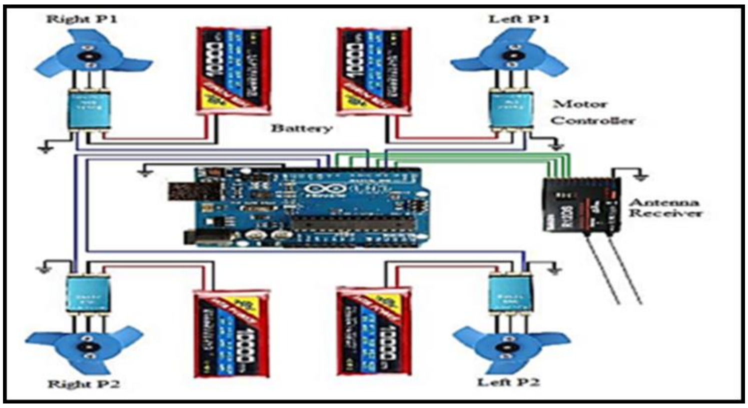


Figure 1. Control System

3.2. Ground Control Station

The software is a crucial component of a GCS. Remote pilots can utilise the mouse, keyboard, buttons, and joystick to interact with the software. As a result, multicopters' way points can be arranged in advance by remote pilots. Remote pilots can also keep an eye on the flight status in real time and launch new missions to intervene in the flight. The software can also record and replay flights for analysis[19]. Radio Telemetry The term "radio telemetry" refers to the use of Digital Signal Processing (DSP) technology, digital modulation and demodulation, and radio technology to transmit data with high accuracy [23]. "Fig7".

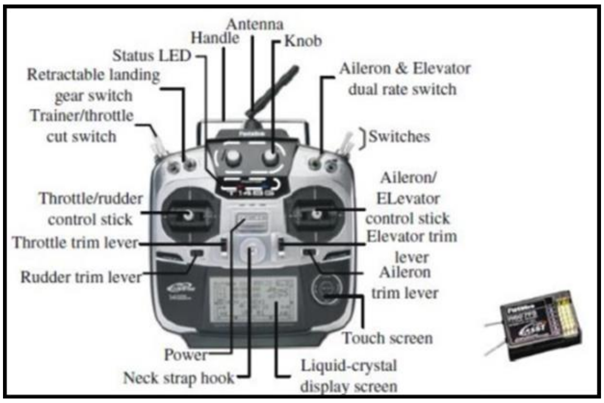


Figure 7. Remote control with 8 channels

4. ROBOTIC ARM

the fixed and mobile mechanical connections that prepare the work of the arm and regulate its movement for the required performance so as to provide stability points that direct the movement to the front handle smoothly, so there will be screws with bevelled ends to provide movement for one of the links and provide stability for the other. Movement after stability or movement, and so forth, and there are screws that fasten the connections to each other and represent the fulcrum of the mechanical movement vectors, and this most likely protects the base of the arm from transferring the reaction from the arm during missions to the structure of the drone, and this is a great mechanical stability and this is important in the designs of the drones “Fig 8”

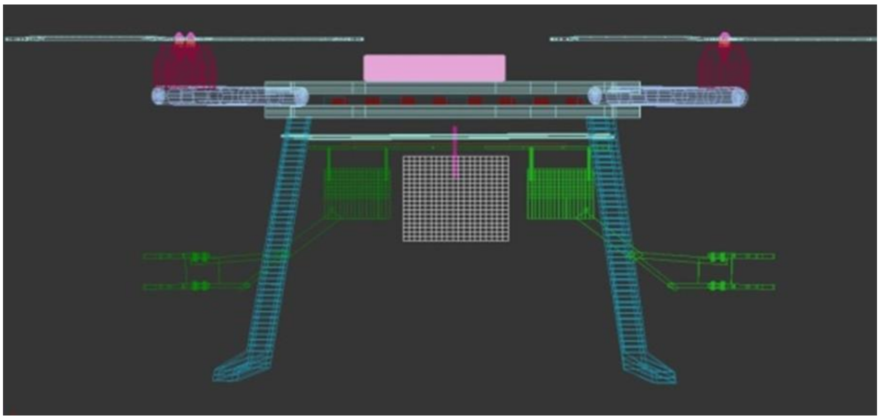


Figure 1. Robotic arm design

In this design, as it is clear, the different mechanical parts and transmissions (gears) from circular to straight and from straight to circular or straight and so forth, so the pieces with their different dimensions form a coherent base for four servo motors and stepper motors that form the source of movement in directing the arm where it connects The axis of each motor has self-extension to its axis, and between the extensions 180degrees for three of the motors, one, two and three, and an angle of 90 degrees between the extensions of the motor, the axis of the fourth motor. Direct steering) for two circular mechanical gears (gears) and this point is located in the fourth motor to form two sharp cutter heads with them.[24].

5. Geometry control

A mathematical method called geometric control describes and regulates the dynamics of systems on nonlinear manifolds using differential geometry. Geometric control directly affects the system's nonlinear dynamics, in contrast to conventional control techniques that linearize system dynamics around an operating point[25].

model. This makes it possible for: Intrinsic Representation: To avoid the singularities and ambiguities typical of linearized representations, control laws are derived on the manifold. Global Stability: Even in the most severe maneuvers, the framework's robust performance is made possible by its inherent accounting for the system's global behavior. Since the blades slope is uncontrollable, the quadrotor helicopter is the perfect way to achieve the straightforward and efficient goal. Compared to traditional helicopters, the quadrotor has certain advantages. In actuality, the displacement is made simpler by using four rotors that provide propeller forces. It gives a better payload since it has more lift thrust. The four rotor speeds, the helicopter's right and left slopes, its forward and rearward rotation, and its own rotation are all controlled by the controller system. Numerous sophisticated[26]. “Fig. 9”.

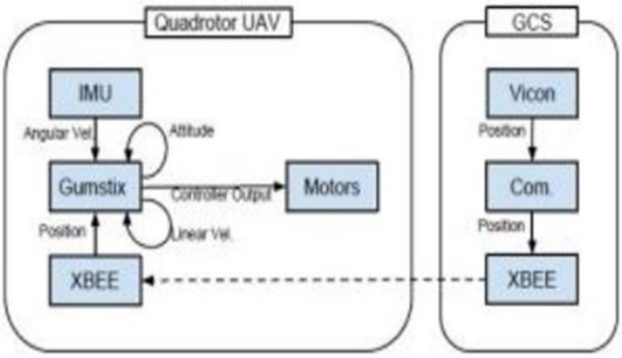
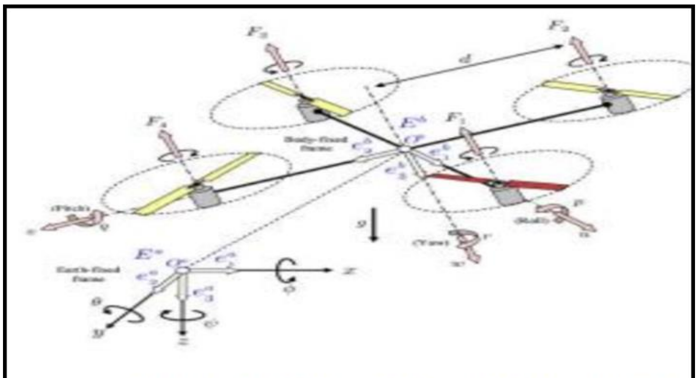


Figure 9. geometry control scheme[27]

Recently, control strategies such accurate linearization sliding mode control and backstopping technique have been used to suit the quad rotor’s performance demands Dynamics of Quad rotors with Disturbances The quad rotor dynamics, including unknown perturbations in the translational and rotational dynamics, are formulated in this section. They might be a representation of the wind disturbance. they are regarded as arbitrary disturbing forces and moments. The location of the center of mass x ∈ R3 in the inertial frame and the orientation of the body-fixed frame with respect to the inertial frame describe the configuration of the quad rotor UAV, which is considered a rigid body [28].

Mathematical Foundations

Differential geometry ideas like Lie Groups and Lie Algebras are the basis of geometric control. The special orthogonal group or the special Euclidean group are frequently used to depict the dynamics of UAV attitude. The formulation of control rules is made easier by exponential and logarithmic maps, which connect the manifold and tangent spaces. Riemannian Metrics: Stability requirements and cost functions are defined using metrics. The equations of motion for UAVs are commonly written as follows: where is the unit vector in the vertical direction, is the mass, is the thrust, is the location, is the angular velocity, and is the rotation matrix. Numerous UAV control issues, such as formation control, trajectory tracking and attitude stabilization, have been addressed with geometric control. Stabilization of Attitude Gimbal lock and singularities plague conventional attitude representations based on Euler angles. By employing rotation matrices or quaternions to directly regulate the attitude, geometric control eliminates these problems. The energy-based Lyapunov function, where is the desired attitude and is a positive gain, is usually used to determine the control law for attitude stabilization.[29]. “Fig. 10”.



$$R(\Theta) = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix}$$

and

$$M(\Theta) = \begin{bmatrix} -S_\theta & 0 & 1 \\ C_\theta S_\phi & C_\phi & 0 \\ C_\theta C_\phi & -S_\phi & 0 \end{bmatrix}$$

Figure 10. Mathematical foundation of eular angels[30]

two sets of rotors (1, 3) and (2, 4) rotate in opposing directions. When necessary, generates yaw motion by balancing the moments. Depending on the desired angle direction, the motors are sped up or slowed down to produce the yaw angle. Euler angles present substantial geometric control issues despite their simplicity, particularly for dynamic and complex systems: Gimbal Lock: When the pitch angle becomes close to ±90 degrees, gimbal lock happens, which results in the loss of one rotational degree of freedom. Unpredictable behaviour and control instability may result from this singularity Nonlinear Coupling: Deriving and implementing control laws is made more difficult by the nonlinear coupling of the angular velocities associated with Euler angles. Limited Global Representation: There are ambiguities and numerical instabilities because Euler angles are unable to accurately depict rotations over the whole manifold. Dynamic Instability: The restrictions of Euler angles can lead to unstable and subpar performance when used in aggressive or high-speed movements. Geometric Control Alternatives to Euler Angles In order to overcome Euler angle constraints, contemporary geometric control frameworks frequently use .Management of the Center of Gravity (CoG) An important determinant of a UAV's stability is its CoG. The CoG of a well-balanced UAV is in line with the thrust vector. In order to compensate for imbalances, geometry control systems can dynamically modify the CoG by shifting payloads, batteries, or other parts. Positioning and Orientation of Rotors The UAV's capacity to produce lift and sustain balance is greatly impacted by the rotor positions and angles. In reaction to outside pressures, the UAV can be stabilized by tilting its rotors or altering their relative lengths. Flexibility in Structure Certain UAVs have folding mechanisms or flexible arms that enable the physical geometry to be changed while in flight. These modifications can increase stability and improve aerodynamics under a variety of circumstances. The distribution of payloads A UAV may become unstable due to uneven payload distribution.[31].

Dynamic model for Robotic Arm

Four rotors with a maximum angular velocity of 4000rpm and a maximum load capacity of 4 kg make up the quad rotor UAV. Together, the four rotors form the vehicle's propulsion system, which can support up to 6 kg of load. For modeling With a total mass of 4 (kg), carbon fiber is chosen for these uses since it is a high-strength material. The manipulation arm is made of the lightweight, highly resistant propylene polymer. To determine the location of the manipulator's end-effector, a kinematic model of a quad rotor unmanned aerial vehicle with a manipulator arm is shown in this section. Three DOFs are defined in the orientation or attitude motion, three more are for the translation motions, and the quad rotor UAV has six DOFs to identify the Euclidean spaces. describes the roll, pitch, and yaw motions of the quad rotor UAV. The quad rotor UAV, where the red rotors on the positive X-axis stand in for the vehicle's front. In the multirotor's top perspective, the green rotors on the positive Y-axis indicate the right side. A downward direction is shown by the positive Z-axis using the right-hand rule. the three degrees of freedom (DOFs) of the manipulator arm in a way that keeps it securely at the bottom of the aerial vehicle. When the arm is retracted and the octorotor UAV lifts off, this position is taken into account for simulation analysis in matlab[32].

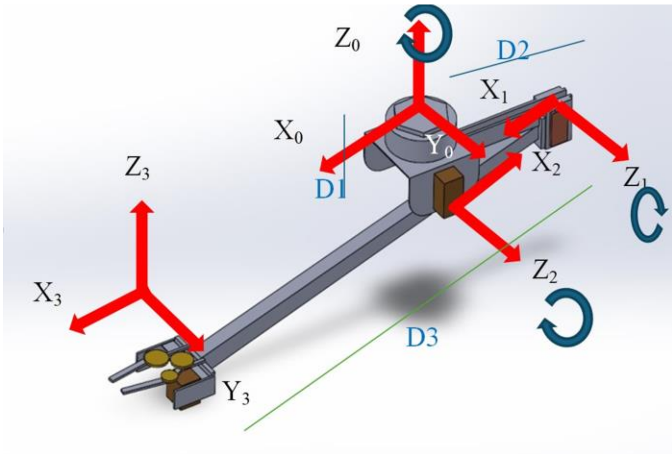


Figure 11. Robotic Arm

The coordinate frame from the Denavit–Hartenberg classical technique is shown in "Fig. 11"., where the right-hand rule is used to depict the coordinate frame. The manipulator arm's base is the frame (∑aB), and the frames ∑a1, ∑a2, and ∑a3 are connected to the joint's prior coordinate frames q1, q2, and q3, respectively. The end-effector frame ∑ee is defined as the coordinate frame ∑a3. The d1, a2, and a3 parameters are each joint's corresponding rotational positions. The following explanation of the circled numbers explains how these variables are utilized to create a transformation matrix: The multirotor vehicle is connected to the base, which is regarded as a stationary base because it lacks joint movement. The first joint is moved by Link 1, which is fastened to the permanent base. There are three servomotors in this link; Link 2 connects to Link 1 and moves the second joint . A servomotor connected between links 2 and 3 drives the motion of the end effector, which is connected to link 3, which is the last link. servomotors move the first two joints [33].

$$R_B{}^1 = \begin{bmatrix} \cos\theta\cos\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix} \tag{1}$$

$$T_B{}^1 = \begin{bmatrix} RB1 & \xi \\ 0 & 1 \end{bmatrix} \quad (2)$$

A homogeneous matrix that characterizes the systems' attitude and translation provides the matrix relationship between the UAV and the manipulator arm. The quad rotor UAV's homogeneous matrix is calculated by taking into account the position vector ξ and the rotation matrix (1).within matrix (2) Euler angles of the quadrotor UAV attitude; (a) Roll angle (φ); (b) Pitch angle (θ); (c) Yaw angle (ψ). The conventional Denavit–Hartenberg convention is utilized to create the kinematic model of the manipulator arm position, TB3.

$$T_3^B = \begin{bmatrix} T^B_{3\,11} & T^B_{3\,12} & T^B_{3\,13} & T^B_{3\,14} \\ T^B_{3\,21} & T^B_{3\,22} & T^B_{3\,23} & T^B_{3\,24} \\ T^B_{3\,31} & T^B_{3\,32} & T^B_{3\,33} & T^B_{3\,34} \\ T^B_{3\,41} & T^B_{3\,42} & T^B_{3\,43} & T^B_{3\,44} \end{bmatrix} \quad (3)$$

With φ = 0 and θ = 0 as known variables, the kinematic link between the quad rotor UAV and the manipulator arm is computed taking into account (2), and (3)

Where :

TB3 11 = cos(q2 + q3) cos q1

TB3 21 = − cos(q2 + q3) sin q1

TB3 31 = sin(q2 + q3)

TB 3 41 = 0

TB3 12 = − sin q1

TB3 22 = − cos q1

TB3 32 = 0

TB3 42 = 0

TB3 13 = sin(q2 + q3) cos q1

TB3 23 = − sin(q2 + q3) sin q1

TB3 33 = − cos(q2 + q3)

TB3 43 = 0

TB3 14 = cos q1(a3 cos(q2 + q3) + a2 cos q2)

TBI3 24 = − sin q1(a3 cos(q2 + q3) + a2 cos q2)

TB3 34 = d1 + a3 sin(q2 + q3) + a2 sin q2

TB3 44 = 1

The quad rotor UAV's dynamic model takes into account ∑I and ∑B. The Newton–Euler formulation to characterize the quad rotor UAV's motion equations

ξ = V (4)

m ˙V = R I (5)

B(−FB) + mge3 (6)

˙η = EΩ (7)

J ˙Ω = −Ω × JΩ + τa (8)

To control the robotic arm's geometry, we use forward kinematics based on the Denavit–Hartenberg (DH) convention to compute the transformation matrix T3B (Eq. 3). The servomotors at the joints receive remote control inputs, updating joint angles q1,q2,q3q_1, q_2, q_3q1,q2,q3, and these angles are used to compute the end-effector's position using trigonometric transformations (Eq. 2). For dynamic integration, the Newton–Euler formulation is applied, where linear velocity ξ\xiξ (Eq. 4) and force balance (Eq. 5, 6) define motion constraints. The arm's rotational state is governed by angular velocity η\etaη (Eq. 7) and torque equations (Eq. 8). In programming, these equations are embedded in functions handling state updates and transformations. The rotation matrix R1B (Eq. 1) is used to transform reference frames, and the homogeneous matrix T1B (Eq. 2) links the quadrotor and manipulator. Integrating these dynamics into code requires defining transformation matrices, updating state

```
    std::vector<std::vector<double>> TB3 = {
        {cos(q2 + q3) * cos(q1), -sin(q1), sin(q2 + q3) * cos(q1),
        {-cos(q2 + q3) * sin(q1), -cos(q1), -sin(q2 + q3) * sin(q1)
        {sin(q2 + q3), 0, -cos(q2 + q3), d1 + a3 * sin(q2 + q3) + a
        {0, 0, 0, 1}
    };
    return TB3;
}

// Function to print transformation matrix
void printMatrix(const std::vector<std::vector<double>>& matrix) {
    for (const auto& row : matrix) {
        for (double value : row) {
            std::cout << value << " \t";
        }
        std::cout << std::endl;
```

Figure 12. C++ controlling the movement of a robotic arm embedded

variables based on input, and implementing motion controllers to stabilize and drive the robotic arm based on computed forces and torques. The dynamic model matrices and equations of the arm are organized into equations and taken into account in the C++ programming code as shown in “Fig. 12”.

6. Testing and validation

Flight tests using a quadrotor unmanned aerial vehicle that is created from the ground up validate the suggested experimental geometric controller. by the writers. Flight tests are conducted with winds produced by an industrial fan and natural wind to show the ability to reject disturbances. We start by outlining the software and hardware setups. Next, we break down the experimental findings into three sections: attitude and flight trajectory monitoring. Hardware content the quadrotor unmanned aerial vehicle (UAV) stage at Delta University's aerodynamics Laboratory (ADL). It is equipped with four 800KV T-Motor brushless DC electrical motors and twelve x 4.2 carbon fiber propellers. Each motor has an electronic speed control (Hoppywing v2) attached to it to regulate its rotational speed. The control receives commands from an onboard computer via Inter-integrated Circuit (I2C) protocols. An naza mv2 TX2 embedded system-on-module running Qubilliasim is used for all calculations. An extension board (Connect Techs Orbitty Carrier), which is connected to a specially made printed circuit board, holds the onboard computer. The experiments were conducted on the drone with three different loads in the robotic arm in one position of the effective end. The transition from the zero equilibrium position to the loading point is done by the lower elbow mechanism according to the Euler angles and appears in the Dunnett-Heitenberg matrices as shown in “Fig. 10”. Three different loads can be loaded on the effective end. The time of rebalancing or not rebalancing is measured in the normal case, the case of using geometric control, and the case of using geometric control, which is enhanced by artificial intelligence.[34]

7. AI OPTIMIZED

To enhance the balance of UAVs with robotic arms through experimental validation, this research integrates artificial intelligence (AI) with arm movement commands using Anaconda-based Python programming. By leveraging machine learning models, the system predicts the position and load variations of the robotic arm in real-time, enabling adaptive control adjustments. AI algorithms analyse sensor data, including IMU readings, force-torque sensors, and visual feedback, to estimate dynamic disturbances caused by arm movements.[35]. Based on these predictions, the UAV's flight controller modifies the thrust and orientation of the aircraft engines, counteracting imbalances and maintaining stability. This AI-driven approach not only improves real-time adaptability but also enhances precision in aerial manipulation tasks, ensuring robustness against environmental disturbances such as wind. Experimental validation through physical UAV tests will assess the effectiveness of this method,[36]. bridging the gap between theoretical models and practical deployment. Anaconda platform to improve the stability of the above-mentioned drone with a robotic arm weighing 4 kg, with 800 kv

```
# PID Controller for Stability
def pid_control(error, prev_error, integral):
    derivative = error - prev_error
    integral += error
    return Kp * error + Ki * integral + Kd * derivative

# Simulation Parameters
state = [0, 0]  # Initial pitch angle and angular velocity
time_span = np.linspace(0, 5, 100)  # 5 seconds simulation
errors, thrusts = [], []
prev_error, integral = 0, 0

# Simulate UAV Stability Adjustment
for t in time_span:
    error = -state[0]  # Error is negative pitch angle
    thrust = pid_control(error, prev_error, integral)
```

Figure 13. Anaconda C++ code

brushless motors, and the arm moves from the zero equilibrium position to a point 20 cm away from the center in the y direction, -10 cm in the z direction, and the movement mechanism is the lower elbow method, and the robotic arm has 3 joints, the first joint is 360 degrees in the x, y direction, the second joint is 180 degrees in the z direction, and the third joint is a universal joint for the head of the arm, and each joint has a 5 v servo motor[37].

Robotic Arm Movement Simulation: The arm moves 20 cm in Y and -10 cm in Z, creating a torque imbalance.

PID Controller: Adjusts thrust dynamically to counteract pitch angle changes.

AI-Based Prediction: Uses a neural network model (TensorFlow) to predict additional thrust needed based on arm position.

Drone Stability Simulation: Runs a 5-second stability test, adjusting thrust in real-time.

Visualization: Plots thrust variations over time to observe balance correction[38]. "Fig. 13",

8. Result

The test was conducted on three main areas inside the aerodynamic simulation laboratory at Delta University for Science and Technology, open air during the day and open air at night. The response time was calculated to balance the drone when moving the head of the effective arm from the zero balance point to the specified point as in Table 1.

When moving the arm, a disturbance occurs for a period of time and then it balances again. There are four response cases:

(n/a) no change in the drone's behaviour,
(D) permanent deviation,
(L) disturbance, then the drone falls,
(time response) disturbance, then balance.

Experiments were conducted and it was noted that the response time varies with the area and weight of the body at the effective end .As in the figure. "Fig. 14", "Fig. 15", "Fig. 16",Therefore, the difference in time changes the weight difference in increasing the loads and changing the effective reaction on brushless motors. The balance is achieved by changing the structure of the current entering the motors based on the movement command of the arm and the weight of the effective head

Table 1. Balance experiment results data.

Load in (KG)	place	Time response Traditional control	Time response Geometry control	Time response Geometry control with AI
400	LAB	n/a	n/a	n/a
400	O A	n/a	n/a	n/a
600	LAB	n/a	n/a	n/a
600	O A	D	1.5	1.5
700	LAB	D	1.85	1.85
700	O A	D	1.9	1.9
800	LAB	D	2.3	2.1
800	O A	L	2.5	2.2
900	LAB	L	3.4	2.3
900	O A	L	D	2.5
1000	LAB	L	L	3.4

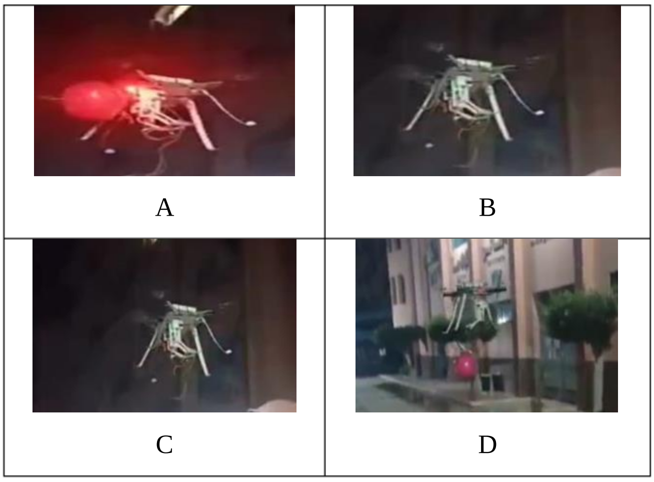


Figure 14. Open air night-time flaying

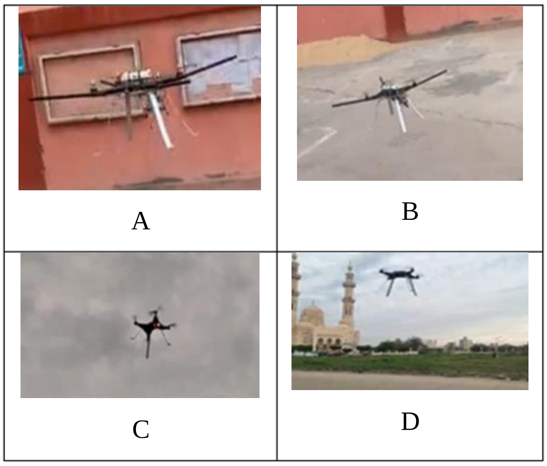


Figure 15. Open air day time flaying

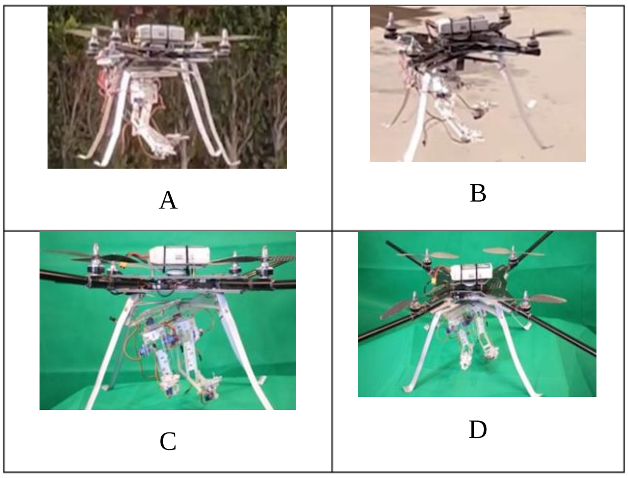


Figure 16. LAB flaying

9. Conclusion

Geometric control to address the stability challenges of robotic arm-equipped UAVs, especially in dealing with high reaction forces and mitigating disturbances caused by the robotic arm motion when manoeuvring. The integration of geometric control principles enables a robust and mathematically sound approach to manage the complex nonlinear dynamics inherent in UAV systems. Through simulation, we demonstrate that the proposed control strategy significantly improves stability, track tracking, and disturbance rejection compared to conventional approaches. The results of this study contribute to the advancement of aerial manipulation by providing a scalable and real-time control solution. Future work will focus on experimental validation using physical UAV prototypes to further improve the proposed framework. Additionally, expanding the methodology to accommodate multi-manipulator UAV systems and adaptive machine learning-based control strategies would enhance the system's autonomy and versatility in dynamic environments. This research paves the way for more reliable and efficient UAV applications in infrastructure inspection, disaster response, and other complex operational scenarios, bringing us closer to fully autonomous aerial robotic systems capable of performing complex manipulation tasks in real-world environments. The effective and advanced use of AI technologies will enhance the stability of UAVs and make them superior task performers.

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