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Design and Development of Drone with a Single Arm 3-DOF Robotic Manipulator

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Abstract: This work proposes the design and development of a drone equipped with a single-arm 3 Degree of Freedom (3DOF) robotic manipulator, aiming to enhance the versatility and functionality of unmanned aerial vehicles (UAVs). The integration of a robotic arm expands the drone's capabilities beyond traditional aerial surveillance, enabling it to perform complex manipulation tasks in various industries and societal domains. The project encompasses several key phases, including the design of the robotic arm using SolidWorks and 3D printing with PLA material, implementation of control algorithms using ROS2 Humble, and integration with a flight controller board for seamless operation. Through a comprehensive methodology, the project aims to achieve optimal design, precise control, and efficient operation of the drone with the attached manipulator. The outcomes of this research hold significant relevance to industries, society, and academic institutions, contributing to technological innovation, societal impact, and advancements in robotics and unmanned systems.

Keywords: Drone; Robot; 3DOF; Manipulator; Arm

INTRODUCTION

In recent years, the field of aerial robotics has witnessed a remarkable surge in innovations, `driven by the escalating demand for drones capable of performing intricate tasks beyond mere surveillance and navigation. This project emerges from the confluence of this technological momentum and a visionary approach to redefine the capabilities of aerial platforms. The core objective was to design and develop a holistic drone system that seamlessly integrates a single-arm three degrees of freedom (3DOF) robotic manipulator, specialized landing gear, and an advanced camera system. Such an integration promises to unlock unprecedented versatility, enabling the drone to undertake a diverse range of missions, from high-precision manipulative tasks to comprehensive aerial inspections. An Unmanned Aerial Vehicle (UAV), also known Drone is an aircraft without a human pilot on board. A UAV’s flight may be controlled remotely by an operator located on the ground or in another vehicle by onboard computers [1].

Unmanned Aerial Vehicles are often preferred for missions that are too dull, dirty or dangerous for manned aircraft. They are mostly found in military and special operation applications, though UAVs are increasingly finding uses in civil and recreational applications, such as policing and surveillance, aerial photography, and drone racing [2-3]. UAVs range from small handheld aircraft with an altitudinal range of up to 600m to large orbital low earth orbit craft. The class of UAVs include fixed wing, single and multirotor craft. A multirotor or multi-copter is a helicopter with multiple rotors and propellers providing uplift, thrust and manoeuvrability [3]. Multi-rotors are classified as rotorcraft, as opposed to fixed-wing aircraft, because their lift is generated by a set of rotors (vertically oriented propellers). Multi-rotors differ from conventional helicopters which use rotors that are able to vary the pitch of their blades dynamically as they move around the rotor hub. They use independent variation of the speed of each rotor to achieve control [1-6].

This project seeks to revolutionize the capabilities of UAVs by integrating a robotic arm, which extends the drone's functionality to include complex manipulation tasks. The integration of a manipulator transforms the drone into a multifunctional platform capable of interacting with its environment, manipulating objects, and executing precise tasks with unprecedented versatility.

By combining expertise in robotics, control systems, and UAV technology, this project aims to push the boundaries of aerial robotics and pave the way for new applications across various industries and societal domains. Through meticulous design, advanced control algorithms, and innovative integration techniques, the project endeavours to create a symbiotic relationship between the drone and its robotic arm, enabling seamless coordination and efficient operation in diverse environments.

With the advent of deep learning technologies, current research efforts have been focused on teaching robots how to perform various tasks autonomously. However, a data driven approach is required to acquire and process the vast amount of data to effectively teach

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a robot how to perform a task which is unfeasible using a real robotic testbed. For this, robot simulation software [7-10] have been used to overcome the shortcomings of data-hungry AI approaches and to allow the developer to obtain a constant environment [11].

In this paper, we propose to carry out a systematic bench mark of current simulation to investigate their performance and suitability to perform different robotic manipulation tasks using the ROS2 (Robot Operating System version 2). We choose ROS2 because it supports a wide array of devices (e.g. micro controllers) which enables the integration of Internet of Things (IoT). The latter is a main requirement for developing a working digital twin system. ROS2 can also be used to bridge the gap between AI-enabled robots and real-world robot control. We choose robotic arms in this paper as they are prevalent in automated manufacturing operations.[7]

MATERIALS AND METHODS

The system developed is made up of two main units; the UAV system and 3DOF robotic arm manipulator underneath the base of the drone.

3D printing of 3DOF Robotic arm manipulator

Utilizing Fused Deposition Modelling (FDM) technique and Polylactic Acid (PLA) material for 3D printing the robotic arm presents a pivotal phase in this project's execution. FDM, a widely adopted additive manufacturing method, offers advantages in terms of cost-effectiveness, rapid prototyping, and material versatility. PLA, a biodegradable thermoplastic derived from renewable resources like corn starch or sugarcane, is chosen for its lightweight properties, ease of printing, and structural durability, making it an ideal candidate for constructing the robotic arm. The selection of PLA aligns with the project's emphasis on achieving a balance between weight optimization and mechanical strength, ensuring the robotic arm remains agile yet robust during operation.

During the printing process, meticulous attention is paid to optimizing parameters such as layer height, infill density, and print speed to achieve superior structural integrity and dimensional accuracy. Fine-tuning these parameters not only ensures the robotic arm's compatibility with the drone's weight limitations but also enhances its performance in executing manipulation tasks with precision. Additionally, iterative testing and validation are conducted to assess the printed components' mechanical properties and structural reliability, guaranteeing that the final product meets the stringent requirements of the project's objectives. Through the strategic utilization of FDM and PLA material, this phase of the project exemplifies a cost-effective and sustainable approach to manufacturing high-performance robotic components, laying a solid foundation for the drone's enhanced capabilities in real-world applications. The specifications are used for 3D printing of the robotic arm as shown in the table 2.1

Table 1: Parameters Used for 3 D Printing

Resolution In mm	Infill Density In %	Support structure In Type	Nozzle temperature In oC	Bed temperature In oC
Fine 0.1mm	40% to 75%	Line type	2100C	600C

The final 3D printed robotic arm, created using FDM with PLA material, epitomizes precision and innovation. Lightweight yet durable, it strikes a perfect balance between agility and strength, ensuring optimal performance. Ready for integration, this model showcases the project's commitment to excellence, promising enhanced UAV capabilities in various scenarios. The below images represent and the slicing of the robotic arm components fig 1.

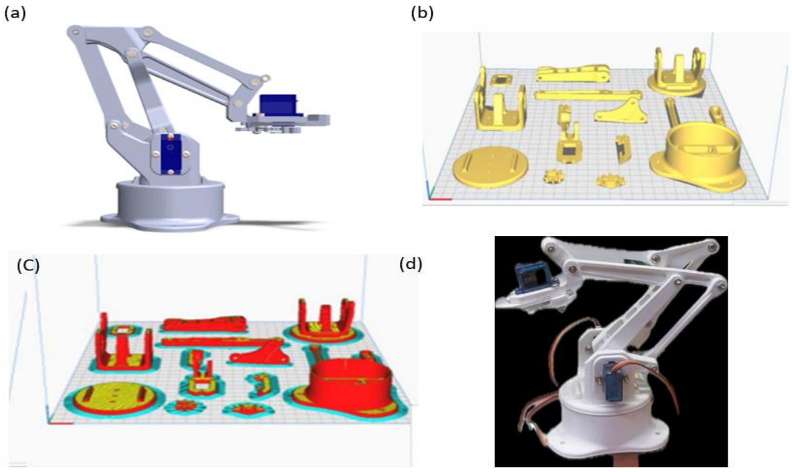


Figure 1: Robotic Arm (a) 3D model (b) STL files (c) Slicing of Components (d) Final product

Quadcopter

A quadcopter, is a type of multirotor helicopter propelled and lifted by four rotors. These aircraft, also known as quadrotor helicopters, possess a symmetrical design that allows for intuitive control of roll (side-to-side tilting), pitch (forward and backward tilting), yaw (rotation around its vertical axis), and overall motion. Each quadcopter typically comprises two pairs of propellers, with one pair spinning clockwise (CW) and the other counter-clockwise (CCW) [12]. This configuration enables the quadcopter to achieve stability and precise control through independent variation of rotor speeds.

Quadcopters offer versatility, being suitable for both indoor and outdoor flight thanks to their compact size and manoeuvrability. Their smaller form factor and mechanical simplicity make them cost-effective and robust compared to traditional helicopters. This simplicity translates into lower maintenance costs and greater durability. Additionally, the smaller blades of quadcopters result in reduced kinetic energy, minimizing the potential for damage in the event of collisions or accidents. This combination of size, simplicity, and reduced energy makes quadcopters an attractive choice for various applications, from recreational flying to professional aerial photography and surveillance.

Moreover, a quadcopter comprises essentially three main systems.

- The Power Conversion System of a quadcopter encompasses the battery, motors, speed controllers, and propellers.
- The Mechanical System of a quadcopter encompasses all its components, as each part possesses mechanical properties crucial to the aircraft's operation.
- The Control System: This system consists of the transmitter/ receiver combinations (both movement) and video, flight controller and various sensors.

Components of a Quadcopter:

The hardware components of each quadcopter vary significantly based on its intended application. These components typically include the frame, motors, electronic speed controller (ESC), flight controller, propellers, and battery.

a) The frame serves as the primary structural support for the quadcopter, akin to the human skeleton, bearing the weight and accommodating the attachment of other components. Typically comprising two to three distinct parts, the quadcopter frame includes a central plate for mounting electronics, four arms extending from the centre plate, and four motor brackets connecting the motors to the arm ends. While quadcopter frames may vary in design and composition, symmetry is essential for balance, necessitating corresponding size and weight distribution on both lateral sides. Frame materials commonly used in quadcopter construction encompass plastic, wood, carbon fiber, fiberglass, aluminium, and even silicon panels.

b) The motor serves as the mechanism responsible for propeller rotation, thereby generating thrust, lift, and manoeuvrability for the quadcopter. Predominantly, quadcopters utilize brushless DC motors due to their efficiency and reliability. Brushless DC electric motors, also referred to as Electronically Commutated Motors (ECMs or EC motors), are synchronous motors powered by a DC electric source through an integrated inverter/switching power supply. This setup produces an AC electric signal to drive the motor. In the context of quadcopters, high pole count motors, commonly referred to as "outrunners," are favoured to eliminate the need for a gearbox. These high pole count motors inherently generate high torque, negating the necessity for torque augmentation through gearbox mechanisms.

c) The Electronic Speed Control (ESC) functions as a vital component in regulating the speed, direction, and potentially serving as a dynamic brake for electric motors. Widely utilized in electrically powered radio-controlled models, ESCs, especially designed for brushless motors, generate a three-phase electric power low voltage source to drive the motor. In the context of quadcopters, ESCs play a pivotal role by providing high-power, high-frequency, and high-resolution 3-phase AC power to the motors in an exceedingly compact miniature package. These quadcopters rely extensively on the ESC's capability to modulate the speed of the motors propelling the propellers, enabling precise control over the aircraft's movement and stability.

d) The flight controller serves as an onboard microcontroller, functioning as a computer that bestows quadcopters with flight control capabilities. It enables autonomous flight and facilitates the integration of sensors, thereby enhancing the aircraft's sensing capabilities. Interfacing with ESCs and the receiver, the flight controller utilizes sensor inputs to optimize flight performance, ensuring smoother and more stable flight operations. Employing sophisticated algorithms such as Proportional, Integral, and Derivative (PID) controllers, flight controllers execute complex control strategies to achieve precise flight control, including attitude stabilization, altitude control, and trajectory tracking.

e) Crucial for lift-off and maneuvering. With four propellers, the quadcopter gains the necessary lift to ascend. By adjusting the thrust of each propeller, the craft can move in various directions and rotate. These propellers are arranged in pairs, with two rotating clockwise and the other two counterclockwise, to prevent unwanted spinning. This setup stabilizes the craft's rotation around its vertical axis, known as yaw. Propellers are specified by their diameter (D) and pitch (P), determining their performance characteristics.

f) The quadcopter's power source, a Lithium Polymer (LiPo) battery, is pivotal for onboard operations. LiPo batteries, with cell voltages of 3.7 volts, are configured in series to produce varying total voltages. The battery's specifications, including capacity and output, vary based on factors such as current draw, motor type, and desired flight duration. Flight time is influenced by motor and propeller types, onboard electronics, pilot technique, environmental conditions, and craft weight. While higher capacity batteries extend flight time, their added weight can reduce efficiency due to increased torque and payload. Achieving an optimal balance between battery capacity and weight is essential for maximizing flight performance.[13]

METHODOLOGY

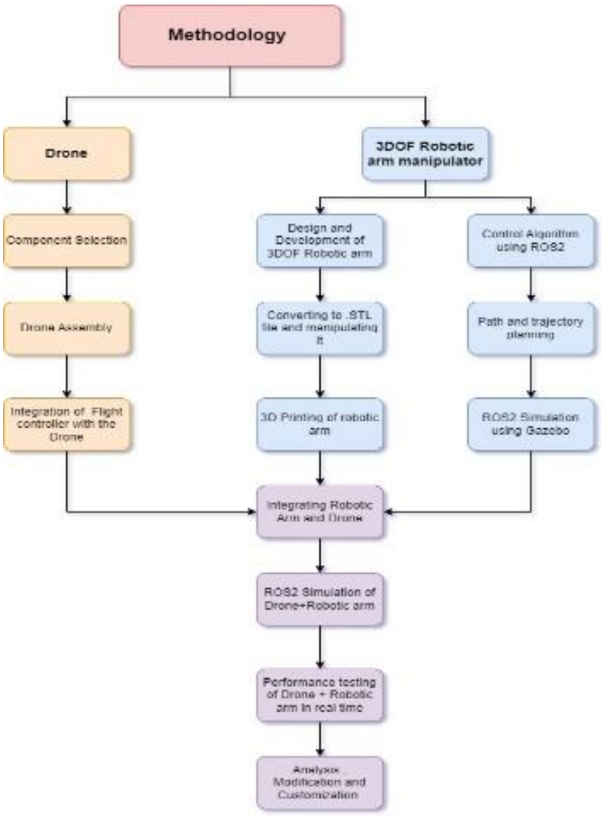
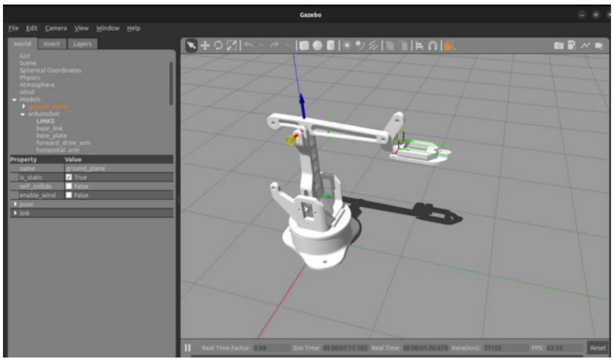


Figure 2: Methodology

The project integrates advanced visualization, motion planning, and simulation techniques to enhance the understanding and performance of the robotic arm manipulator within the UAV system as shown in Fig 2. Leveraging RViz, a sophisticated visualization tool within the Robot Operating System 2 (ROS2) framework, provides real-time visualization of the robotic arm's movement and interactions with the environment. This visualization capability aids in debugging control algorithms, fine-tuning motion planning trajectories, and validating the arm's behaviour before physical implementation, thus contributing to a more comprehensive understanding of its dynamics and operational characteristics.

In tandem with visualization, motion planning algorithms implemented within ROS2, particularly the Rapidly-exploring Random Trees (RRT) Connect algorithm from the Open Motion Planning Library (OMPL), facilitate efficient and collision-free path planning for the robotic arm. These algorithms leverage the arm's kinematic constraints and environmental information to generate optimal trajectories for executing designated tasks. By integrating motion planning into the control system, the project ensures that the robotic arm executes movements smoothly and accurately, while also avoiding obstacles and adhering to specified constraints.

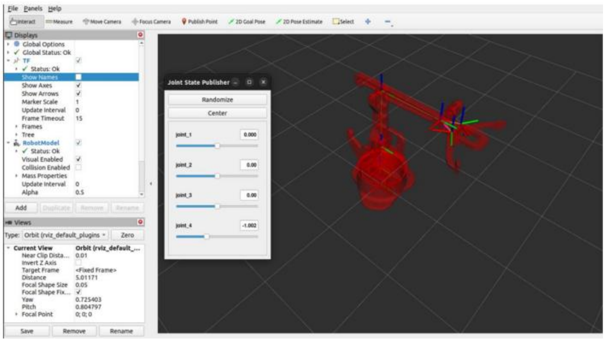
Furthermore, simulation of the robotic arm in Gazebo provides a sophisticated virtual environment for comprehensive testing and validation of its performance under simulated real-world conditions. Gazebo simulates physics-based interactions, allowing for realistic assessments of the arm's dynamics, stability, and response to external forces as shown in fig 3. By immersing the robotic arm in a simulated environment, researchers can systematically evaluate its behaviour across a range of scenarios, identify potential challenges, and iteratively refine its design and control strategies. This simulation-driven approach ensures robustness and reliability in the integration of the arm with the drone system, facilitating its seamless operation in practical applications.



Property	Value
name	ground_plane
is_static	☑ True
self_collide	☐ False
enable_wind	☐ False

Figure 3: ROS2 Simulation in Gazebo

In summary, the integration of RViz visualization as shown in fig 4, motion planning algorithms, and Gazebo simulation enhances the project's capabilities in understanding, optimizing, and validating the performance of the robotic arm manipulator within the UAV system. These integrated tools facilitate a systematic and comprehensive approach to design, control, and simulation, ultimately ensuring the successful integration of the arm with the drone and its efficient operation in real-world scenarios.



Global Options
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TF ☑
Status: Ok
Show Names ☐
Show Axes ☑
Show Arrows ☑
Marker Scale 1
Update Interval 0
Frame Timeout 15
Frames
Tree
RobotModel ☑
Status: Ok
Visual Enabled ☑
Collision Enabled ☐
Mass Properties
Update Interval 0
Alpha 0.5

Type: Orbit (rviz_default_plugins

Current View Orbit (rviz_default_...
Near Clip Dista... 0.01
Invert Z Axis ☐
Target Frame <Fixed Frame>
Distance 5.01171
Focal Shape Size 0.05
Focal Shape Fix... ☑
Yaw 0.725403
Pitch 0.804797
Focal Point 0; 0; 0

joint_1 0.000
joint_2 0.00
joint_3 0.00
joint_4 -1.002

Figure 4: ROS2 Visualization in RVIZ

In a parallel effort, meticulous consideration is given to the selection of the drone and its constituent components, emphasizing compatibility and performance metrics. Following a stringent selection process, the chosen components are methodically assembled, culminating in the integration of the flight controller board to govern flight dynamics effectively. Upon achieving operational status, the project's focus transitions towards the integration of the robotic arm with the drone's base, a critical step necessitating secure attachment and stability to ensure safe flight operations. Leveraging ROS2 simulation capabilities, the drone equipped with the attached robotic arm undergoes comprehensive testing across a spectrum of scenarios, facilitating thorough evaluation of its functionality and performance.

Subsequent to simulation-based testing, a phase of performance assessment, analysis, and iterative refinement ensues, leveraging insights gleaned from simulation results to enhance system performance. This iterative process entails a systematic approach to customization and optimization, aimed at fostering seamless interaction between the drone and robotic arm subsystems, thereby maximizing coordination efficiency and operational effectiveness. Through a meticulously orchestrated integration of design, control, integration, and simulation methodologies, the project endeavours to realize a synergistic and high-performing system, characterized by the cohesive integration of a 3DOF robotic arm manipulator with a drone platform. This systematic pursuit of excellence stands poised to redefine the landscape of aerial robotics, ushering in a new era of capabilities and applications in the field.

RESULTS AND DISCUSSION

The Design and 3D printing of the robotic arm using PLA material have achieved a notable breakthrough in aerial robotics by creating a lightweight and optimized structure. This advancement showcases the potential for leveraging PLA's properties to enhance drones' capabilities, promising diverse applications across industries. Additionally, the successful simulation and integration of the robotic arm with ROS2 represent significant progress in the field. The seamless coordination between the robotic arm and the drone platform, along with pre-emptive issue identification through simulations, ensures optimal performance and reliability during operation.

The integration of a single-arm 3DOF robotic arm as shown in Fig 5 further expands the drone's functionality, enabling wide range of tasks from object manipulation to infrastructure inspection. The flexibility provided by this integration not only improves how efficiently operations are conducted but also sets the stage for ongoing advancements in autonomous systems, effectively tackling practical challenges that arise. Overall, these achievements mark significant milestones in advancing aerial robotics, with far-reaching implications for various industries.

Figure 5: Drone with 3-DOF arm

The successful design and 3D printing of the robotic arm using PLA material mark a significant breakthrough in aerial robotics, showcasing the potential for lightweight and optimized structures to enhance drones' capabilities. By leveraging PLA's properties, such as its strength and low weight, this advancement opens doors to a multitude of applications across industries, promising improved efficiency and manoeuvrability for drone operations. Additionally, the seamless simulation of the robotic arm with ROS 2 represents a substantial leap forward in the field, ensuring precise control and reliable performance during missions. Through pre-emptive issue identification via simulations, this integration enhances operational efficiency and reliability, laying the groundwork for safer and more effective drone deployments.

The incorporation of a single-arm 3DOF robotic arm further extends the functionality of drones, enabling them to undertake a diverse range of tasks, from object manipulation to infrastructure inspection. The adaptability offered by this versatility not only boosts operational efficiency but also nurtures ongoing innovation in autonomous systems. By addressing real-world challenges effectively, these advancements have the potential to revolutionize various industries, including agriculture, construction, and disaster response. Overall, these achievements signify significant milestones in advancing aerial robotics, with far-reaching implications for the future of autonomous systems and their applications in diverse sectors.

CONCLUSION

In conclusion, the successful design, simulation with ROS 2, 3D printing using PLA material, and integration of the robotic arm represent significant strides in the field of aerial robotics. These achievements underscore the possibilities of lightweight and optimized structures to augment drones' capabilities, enabling a wide array of applications across industries. Through the application of advanced technologies and meticulous design methodologies, including pre-emptive issue identification through simulations, these innovations establish a framework for safer, more efficient, and adaptable drone operations. Moreover, the incorporation of a single-arm 3DOF robotic arm further broadens drones' functionalities, promising transformative impacts across diverse sectors. Overall, these milestones signal a pivotal advancement in aerial robotics, with profound implications for the future of autonomous systems and their societal contributions.

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