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Exploring the Concept of Air-runway for Fixed-wing UAVs

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ABSTRACT

The combination of fixed-wing capability for cruising and multi-rotor capability for takeoff and landing has made VTOL UAVs increasingly popular. The runway requirement is eliminated for VTOL UAVs by adding multi-rotor with fixed-wing UAVs, however, this is at the cost of additional weight added to the UAV to carry additional systems for takeoff and landing operations. This additional weight doesn't allow a VTOL to meet the cruise performance of a fixed-wing UAV of similar weight and size. Adding a detachable multi-rotor system to a fixed-wing UAV can provide an in-air virtual runway and enable VTOL capability in a conventional fixed-wing UAV without compromising its cruise performance and without adding any additional weight to it. This study introduces a concept known as the "Air-runway," a virtual landing platform for fixed-wing UAVs designed to operate in mid-air. The Air-runway envisions a flying platform that provides a dynamic and adaptable landing surface, challenging traditional notions of runway infrastructure. This paper delves into the conceptualization of this innovative idea, highlighting the potential advantages and addressing the technical challenges associated with its implementation. This study also presents the development of a guidance law tailored specifically for the Air-runway environment. The proposed guidance law aims to demonstrate approach and landing sequences for fixed-wing aircraft, ensuring a smooth and precise touchdown on the airborne platform. The paper outlines the theoretical foundation of the guidance law and presents simulation results that demonstrate its efficacy in various scenarios.

Keywords: VTOL; UAV; Guidance; Air-runway; aerial runway; flying runway; flying landing pad; detachable lander

Nomenclature

(x_m, y_m, z_m)	=	multirotor coordinates
(x_{fw}, y_{fw}, z_{fw})	=	fixed-wing coordinates
V_m	=	multirotor speed

a_m^h, a_m^v	=	horizontal and vertical acceleration components of the multirotor
θ_m, ψ_m	=	flight path angle and course angles of multirotor
$\dot{\theta}_m, \dot{\psi}_m$	=	rates of pitch and yaw angles of multirotor
V_d	=	desired speed for multirotor
$K_{P_\psi}, K_{I_\psi}, K_{D_\psi}$	=	PID gains for course angle
$K_{P_\theta}, K_{I_\theta}, K_{D_\theta}$	=	PID gains for pitch angle
$K_{P_V}, K_{I_V}, K_{D_V}$	=	PID gains for multirotor speed
T	=	Throttle input

1 Introduction

Vertical Take-Off and Landing Unmanned Aerial Vehicles or VTOL UAVs, are becoming increasingly popular in the aviation industry. VTOL UAVs combine the features of both fixed-wing and multirotor UAVs, making them unique and versatile in their capabilities. Like fixed-wing UAVs, they are capable of high-speed flight over long distances, thanks to their aerodynamic design. At the same time, like multirotor UAVs, they have the ability to take off and land vertically, enabling them to operate in confined spaces and perform tasks that require precision hovering. This joint feature of fixed-wing and multirotor capabilities makes VTOL UAVs ideal for a wide range of applications, from military surveillance to commercial deliveries, even personal transportation, and beyond. One of the main reasons for the growing trend of VTOL UAVs is their versatility. Traditional fixed-wing drones require a runway or launch mechanism, which limits their mobility and accessibility. VTOL UAVs, on the other hand, can take off and land in almost any location, making them ideal for search and rescue missions, monitoring infrastructure, and conducting inspections in hard-to-reach areas. In addition, the ability to hover and maneuver in tight spaces makes them ideal for tasks that require a high degree of precision, such as surveying and mapping. Another reason for the increasing popularity of VTOL UAVs is their ability to carry heavier payloads. Traditional quadcopters and other small drones are limited in the amount of weight they can carry, which restricts them for many applications. VTOL UAVs, however, can be designed to carry much heavier payloads, making them suitable for tasks such as transporting medical supplies or even people. This is particularly useful in areas that are difficult to access, such as remote islands or mountainous terrain. The military has also played a significant role in driving the growth of VTOL UAVs. The ability of these drones to take off and land vertically makes them ideal for military operations, as they can operate in confined spaces and launch quickly without the need for a runway. In addition, the ability to hover and maneuver precisely allows them to provide real-time intelligence, surveillance, and reconnaissance (ISR) capabilities, making them valuable assets on the battlefield. The commercial sector is also taking notice of the potential of VTOL UAVs. Companies such as Amazon and Google are exploring the use of drones for package delivery, and the ability of VTOL UAVs to take off and land in small areas could make them ideal for urban deliveries. In addition, the development of larger VTOL UAVs could potentially revolutionize the air transportation industry, allowing for faster and more efficient travel. The growing trend of VTOL UAVs is driven by their versatility, ability to carry heavier payloads, and potential for military and commercial applications. While there are challenges to be addressed, the benefits of these drones are significant and are likely to lead to continued growth in their use in a variety of industries. As technology continues to evolve, we will likely see even more innovative uses for VTOL UAVs in the years to come.

Adding VTOL ability to a UAV can result in an increase in weight, which can have a negative impact on the UAV's fixed-wing performance. The additional weight required for VTOL capabilities may lead to increased power requirements, which can affect the UAV's endurance, range, and payload capacity. Furthermore, the added weight can impact the UAV's aerodynamic performance, leading to reduced speed and maneuverability. To address these challenges, designers of VTOL UAVs need to carefully balance the trade-offs between the weight of the VTOL system and the UAV's fixed-wing performance.

Facilitating a VTOL launch platform for a fixed-wing UAV can potentially eliminate the need to carry additional weight in the form of VTOL needs. A detachable multirotor platform can perform the launch and recovery operation of a fixed-wing UAV and also will make fixed-wing free from carrying VTOL needs. This novel concept we have named as **Air-runway**. Landing a UAV on a moving platform can be a challenging task that requires precise control and coordination, however, this can benefit from several research conducted on the launching and recovery of UAVs on moving platforms.

There are several approaches to landing a UAV on a moving platform, including visual-based and sensor-based methods. For example, the UAV may use cameras to track the platform's position and orientation, while also using sensors to measure the platform's velocity and acceleration. Visual-based methods typically rely on cameras to track the platform and adjust the UAV's trajectory accordingly. Sensor-based methods can include using accelerometers, gyroscopes, and GPS to track the platform's motion and make adjustments to the UAV's flight path. Several research studies have explored different approaches to land a UAV on a moving platform, including using computer vision techniques, control algorithms, and machine learning. Some notable references on this topic include:

The review papers [1, 2] provide an overview of the different approaches to landing a UAV on a moving platform and discuss the challenges and future research directions in this area. A vision-based control strategy for landing a multirotor UAV on a moving platform is presented in [3]. The authors propose a controller that uses visual feedback from an onboard camera to estimate the relative position and velocity of the vehicle, which is then used to guide the UAV's descent. The system was tested in real-world experiments, demonstrating successful landings on a moving vehicle. Another vision-based approach that enables an aerial robot to autonomously detect, follow, and land on a mobile ground platform is proposed in [4]. The system uses a combination of visual features and motion estimation techniques to track the platform's motion and guide the UAV's descent. A reliable vision-based landing strategy is proposed in [5] for UAV autonomous landing on a multi-level platform mounted on an Unmanned Ground Vehicle (UGV). A model-based and deep learning-based approach for the autonomous landing of a micro aerial vehicle (MAV) on a moving platform immersed in turbulent wind conditions is presented in [6]. For autonomous landing of a UAV on a moving platform based on a model predictive control-based methodology is proposed in [7]. New color-based markers are proposed in [8] for the vision-based landing of UAVs on moving platforms that improves landing performance on both indoor and outdoor applications. An LSTM-based approach for landing a UAV on a moving vehicle is presented in [9]. The proposed approach attempts to predict the mobile platform's future trajectory based on the past states of the mobile platform and combines this with machine learning methods for precise landing on the moving mobile platform. A deep reinforcement learning-based strategy for the autonomous landing of UAVs on moving platforms at different speeds and trajectories is proposed in [10, 11]. The possibility of landing a fixed-wing UAV on a moving platform is explored in [12–14].

These studies highlight the various approaches and techniques being developed to achieve successful landings of UAVs on moving platforms, showing the progress and challenges in this field. Developing a platform for realizing Air-runway can leverage the research conducted for autonomous landing on moving platforms, however, a rigorous study is required to understand the practical challenges associated with it.

An idea has been proposed for release and capture of a fixed wing aircraft in [15] where a multirotor UAV holds a fixed wing aircraft from the top. This can be a possible solution for in-air launch of fixed wing aircraft however recovery in this way is not practical. As a multirotor UAV generated a strong wind field vertically downward [16] where a fixed wing aircraft hardly maintain a flight. Another set of ideas is proposed in [17] where multirotors are approaching to engage with a fixed wing aircraft either from top of the fixed wing aircraft with a sufficient distance maintaining attachment so that multirotor doesn't exert any force on the fixed wing aircraft or from the bottom with a tether cable.

This paper presents a comprehensive analysis of the concept of separating VTOL capabilities from UAVs, building upon pre-existing ideas and figuring out technological gaps for its practical realization.

Further, this paper provides a comprehensive understanding of a novel idea of Air-runway that converts a conventional fixed-wing aircraft into a VTOL aircraft, shedding light on possible challenges in realizing this concept. Operational advantages of Air-runway and their potential applications across various domains, including aerial surveillance, cargo delivery, and emergency response are explored. Furthermore, a simplified guidance law is proposed for landing a fixed-wing UAV on a multirotor UAV.

2 VTOL's Impact on Fixed Wing Performance

Fixed-wing aircraft have the best aerodynamic efficiency among all the categories of aircraft. However, adding VTOL capability to it compromises the overall performance as the aircraft has to carry additional weight for VTOL functionality. The UAV industry has gained momentum toward achieving VTOL capability with different approaches with reduced additional weight. Several configurations have been developed in the recent past. Mainly these configurations can be classified into the following two types,

- Convertiplanes
  - quadplanes
  - tilt-rotor
  - tilt-wing
- Tail-sitter UAVs

Convertiplanes are hybrid air vehicles that combine the features of fixed-wing aircraft and vertical takeoff and landing (VTOL) capabilities. They seamlessly transition between horizontal flight and vertical flight during takeoff and landing. This transition is achieved by either deactivating a set of rotors or adjusting the angle of their proprotors to facilitate forward propulsion while utilizing their fixed wings. Proprotors, on the other hand, refer to specialized propellers designed to fulfill the requirements of both vertical and horizontal flight modes. Broadly, there are three types of convertiplanes as mentioned earlier, which are shown in Fig. 1.

Fig. 1 Typical examples of (a) quadplane, (b) tilt-rotor and (c) tilt-wing aircraft

Quadplanes are designed to perform vertical takeoff and landing using vertical-facing propellers and transition into horizontal flight using fixed wings and horizontal propellers. A typical quadplane carries a multirotor to achieve VTOL operation which is a major part of the total weight fraction of the aircraft. This includes a minimum of four sets of motor, propeller, and ESC, and one additional battery for VTOL operation. Tilt-rotor UAVs are aircraft that have rotors positioned at the tips of fixed wings. These rotors can rotate vertically for vertical takeoff and landing and horizontally for horizontal flight. Using the same propulsion system for fixed-wing as well as VTOL operations eliminates the requirement of additional motors and propellers unlike a quadplane, however, using the same propulsion system for lifting the aircraft vertically requires a large maximum thrust-to-weight ratio (T/W) which results in an additional overall weight. In tilt-rotor UAVs, every motor is attached to a tilting mechanism that adds even more weight to the aircraft. Also, vertical lift draws a large amount of current that results in additional battery and wire weight to the system. In tilt-wing UAVs, the entire wing assembly, including the wings with the propulsion system, is capable of rotating vertically and horizontally during flight to enable vertical takeoff and landing as well as horizontal flight. Like a tilt-rotor aircraft, this type of aircraft also uses the

Table 1 Sources of additional weight in different VTOL configurations

Aircraft configuration	Source of additional weight
Quadplane	VTOL motor, propeller and ESC; VTOL battery and wires; Quad structure
Tilt-rotor	Rotor tilting mechanism; Higher T/W; Larger battery for vertical flight; Electrical systems for large current
Tilt-wing	Wing tilting mechanism; Higher T/W; Larger battery for vertical flight; Electrical systems for large current
Tail-sitter	Higher T/W; Larger battery for vertical flight; Electrical systems for large current

same propulsion system for fixed-wing as well as VTOL operations which eliminates the requirement of additional motors and propellers unlike a quadplane, however, using the same propulsion system for lifting the aircraft vertically requires a large maximum thrust-to-weight ratio which results in additional overall weight. A tilt mechanism is used for tilting the wing assembly which adds some weight to the aircraft. Also, vertical lift draws a large amount of current that results in additional battery and wire weight to the system. Tail-sitter is another way to achieve vertical takeoff and landing that execute vertical takeoff and landing by resting on their tails and then proceeding to rotate their entire body horizontally for flight. This also requires a larger thrust-to-weight ratio which means additional weight for the propulsion system. Further, vertical flight draws a large current that reflects additional weight to the battery and wires. A summary of sources of additional weight in different configurations of VTOL aircraft is presented in Table 1.

2.1 Weight Penalty in VTOL Fixed Wing UAVs: A Quantitative Performance Comparison

Integration of Vertical Takeoff and Landing (VTOL) capabilities into fixed-wing Unmanned Aerial Vehicles (UAVs) introduces a significant trade-off. Specifically, the additional components required for VTOL functionality, such as extra motors, propellers, wires, and structural reinforcements increase the overall weight of the UAV. This added weight, while essential for enabling vertical takeoff and landing, poses a penalty during cruise flight, where these components provide no benefit and instead contribute to inefficiencies.

To quantify the impact of this weight penalty a detailed performance comparison is necessary. This involves identifying and analyzing the additional VTOL components in various commercially available UAVs and determining the extra weight they contribute. The study then explores a hypothetical scenario where this additional weight is substituted with extra battery capacity instead of VTOL components, optimizing the UAV purely for fixed-wing operation.

By comparing the endurance of UAVs with and without VTOL components under these conditions, the research highlights the performance compromise associated with VTOL capability. Essentially, this comparison sheds light on how the weight added by VTOL components affects the UAV's endurance, demonstrating that the potential energy storage and extended flight time sacrificed for VTOL functionality can be significant. This analysis provides a clear picture of the trade-offs involved in designing and deploying VTOL fixed-wing UAVs, offering valuable insights into their operational efficiency and performance limitations.

In the thorough investigation of diverse VTOL UAVs, a detailed performance analysis is conducted. We looked closely at how each drone distributes its weight across different parts. By measuring the weight of these parts and estimating the fractional weight of the battery used for VTOL operations, we

Table 2 Performance compromise in different UAVs for adding VTOL capability

UAV	MTOW (kg)	VTOL system weight (kg)	Fuel/Battery weight (kg)	Endurance (hr)	Payload (kg)	Performance compromise for VTOL system
ASCEND	9.5	2.5	2 (fuel)	4	0.6	125%
Kapetair	6.5	1.4	2.6	1.5	1.0	63%
FDG33	18	4.15	5.12	3	3	101%
HERO2180	7	1.6	2.5	2.26	1	85%
TAVAS	16	3.03	3.7	1	1	110%

compared the drones and found out how much extra weight is needed for them to take off vertically which highlights the incremental load required for achieving vertical takeoff capability. Further, based on a comparative study based on additional weight carried for VTOL requirements and fuel/battery carried for fixed-wing operation the performance compromise is devised. The performance compromise is a percentage estimate of how much more endurance would have been achieved if the additional weight which is used for VTOL needs was used for adding additional energy to the system in terms of battery or fuel. The presentation of findings is summarised in Table 2, the study quantifies not only the added weight for VTOL proficiency but also dissects the corresponding impact on overall UAV performance, providing valuable insights for the advancement of UAV design and technology.

The presented Table 2 offers a comprehensive insight into the impact of incorporating additional equipment to achieve Vertical Takeoff and Landing capability on the performance of a VTOL Unmanned Aerial Vehicle. By examining the data, a noticeable pattern emerges, revealing the extent to which performance is compromised when VTOL capabilities are prioritized over other factors. Notably, the table illustrates that if the VTOL capability were omitted, and the additional weight was instead allocated to extra batteries, the UAV would exhibit a significantly extended endurance. This suggests that there exists a trade-off between VTOL functionality and endurance, with the decision to enhance one aspect resulting in a compromise on the other.

The additional weight of the battery and other systems required to achieve vertical takeoff and landing plays a crucial role in determining the performance of hybrid aircraft. By adjusting the proportion of battery weight to the total weight, it is possible to greatly influence the achievement of various design goals. Air-runway is an idea to achieve vertical takeoff and landing without adding any additional weight to the aircraft which maximizes its performance.

3 Air-runway

Adding VTOL capability in a fixed-wing aircraft involves adding additional weight, which can potentially compromise the overall performance of the aircraft. Air-runway is a proposed solution that aims to address this issue by introducing the concept of an in-air runway, effectively separating the fixed wing from the VTOL system. The idea involves using a separate platform specifically designed for takeoff and landing operations, which can be assembled and disassembled with a standalone fixed-wing unit. Figure 2 is showing a multirotor attached to a fixed-wing aircraft and a separation stage is shown in the Fig. 3.

This approach offers several advantages. By detaching the fixed wing from the VTOL system during vertical takeoff and landing, the added weight of the VTOL components no longer affects the aerodynamic performance of the fixed wing during forward flight. This allows the fixed wing to operate at its optimal performance level, ensuring efficient and effective flight characteristics. The utilization of a separate

Fig. 2 Multirotor attached with fixed-wing UAV

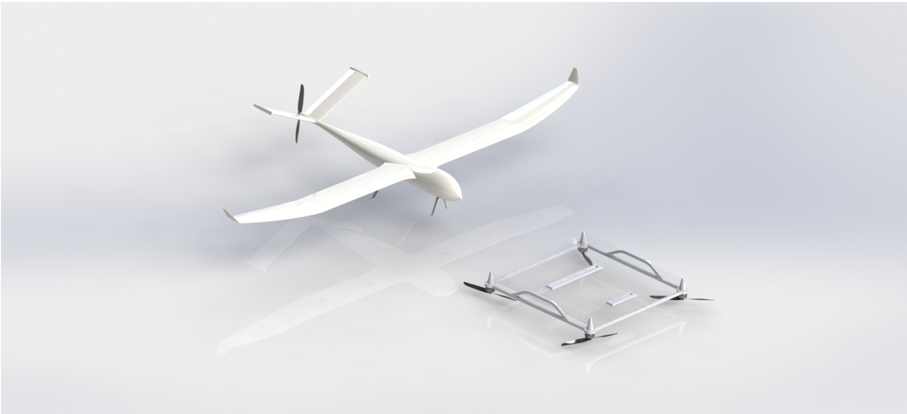

Fig. 3 In-flight separation of a multirotor from a fixed-wing UAV

platform for takeoff and landing operations makes it suitable to be used with multiple aircraft. Traditional VTOL aircraft have their own system for takeoff and landing requirements, whereas the proposed system enables utilizing a common multirotor platform for multiple aircraft. This will potentially reduce operational costs for operating a large number of aircraft. Additionally, the separate development of both systems offers fabrication and maintainability advantages. It simplifies transportation and deployment processes, allowing for the efficient relocation of fixed-wing aircraft as needed.

Overall, by separating the VTOL capability from the fixed wing during forward flight and introducing a separate platform for takeoff and landing operations, this concept addresses the performance compromises associated with adding VTOL capability to a fixed-wing aircraft. It provides enhanced operational flexibility, and improved flight performance, making it a promising approach for certain applications and environments.

The transition process of the proposed Air-runway involves a series of precisely coordinated steps that facilitate the seamless shift between vertical and horizontal flight modes and the safe recovery of both systems. The steps involved in takeoff and landing operations are discussed in the following section.

3.1 Takeoff and Detachment

During takeoff, the multirotor is pre-attached to the fixed-wing and the multirotor activates its rotors for vertical lift-off. Once a suitable altitude is achieved, the fixed-wing gradually activates its motor and transitions to horizontal flight by utilizing its fixed wings for lift and controls, at the same time multirotor gradually deactivates the rotors. Once the transition from vertical to horizontal flight is completed, the multirotor platform is detached from the fixed-wing followed by its landing to the original base. This process involves carefully managing the shift in aerodynamic forces to ensure a stable and controlled transition. The detachment process of a multirotor system to a fixed-wing aircraft typically involves the following steps:

- **Takeoff and Transition to Fixed-wing Mode:** The integrated aircraft takes off and performs a transition from multirotor flight mode to the fixed-wing mode by gradually increasing the speed and once airspeed crosses stall speed, the multirotor system is gradually deactivated.
- **Disengaging the Latching Mechanism:** During the transition from multirotor to fixed-wing flight, when the throttle level of the multirotor reaches a value that is required for a hover flight and also the speed is above the fixed-wing stall speed, the latching mechanism that combines the fixed-wing and multirotor is disengaged. This may involve releasing locking mechanisms, separating connection points, or activating mechanisms that allow for detachment.
- **Gradual Separation:** The multirotor system gradually moves away from the fixed-wing aircraft while maintaining control and stability. This step ensures a safe and controlled separation between the two aircraft.
- **Fixed-wing operation:** Once the separation is complete, the fixed-wing aircraft gains speed for its conventional flight configuration. This involves adjusting the control surfaces to optimize stability and control for fixed-wing flight.
- **Multirotor Operation:** The detached multirotor system operates independently in VTOL mode, allowing for continued vertical hover and landing capabilities. It can perform its intended tasks or return to a designated landing area.

These steps enable the safe and controlled detachment of the multirotor system from the fixed-wing aircraft, allowing both aircraft to operate independently in their respective flight modes. This transition process allows for a seamless transition from the combined configuration to individual operation modes, providing flexibility and adaptability in various mission scenarios.

3.2 Attachment and Landing

During landing, when fixed-wing aircraft reaches a certain distance and altitude, the multirotor takes off from the base location. Now, the multirotor starts to follow the fixed-wing aircraft and align themselves in a formation flight where both systems have the same speed. Gradually the separation between both the systems is reduced and when the multirotor landing platform touches the landing gears of the fixed-wing aircraft, a latching mechanism is activated and both systems are re-attached. At this point, the multirotor starts taking control over the overall system and performs a transition from horizontal to vertical flight, allowing for precise landing and maneuvering. The process of attaching the multirotor system to the fixed-wing aircraft involves the following steps:

- **Trimming the Fixed-wing Aircraft:** The fixed-wing aircraft is trimmed at a lower speed to account for the additional weight and changes in flight characteristics caused by the attached multirotor system. This ensures that the aircraft maintains stable flight during the attachment process.
- **Formation Flight between multirotor and fixed-wing:** The multirotor system is maneuvered and aligned with the fixed-wing aircraft. This alignment is crucial to ensure proper attachment and a secure connection between the two airborne machines.
- **Gradual Approach:** The multirotor gradually approaches the fixed-wing aircraft while maintaining a controlled distance and relative position. This allows for careful alignment and positioning of the attachment points.
- **Latching:** A latching mechanism is utilized to combine both the fixed-wing aircraft and the multirotor system. The latching mechanism securely fastens the two aircraft together, providing structural integrity and stability during operation.
- **Reverse Transition:** Once the attachment is complete, the integrated aircraft transitions from the combined fixed-wing and multirotor configuration to a VTOL mode. This reverse transition involves dominating the multirotor system and gradually reducing the lift generated by the fixed wing. The multirotor takes over the lifting function, enabling vertical flight and landing capabilities.

- **Conventional VTOL Operation:** From this point onward, the integrated aircraft operates in a manner similar to a conventional VTOL aircraft. It can perform vertical maneuvers, hover in a stationary position, landing, and transition back to fixed-wing flight mode when required.

These steps facilitate the attachment and integration of a multirotor system with a fixed-wing aircraft, allowing for combined fixed-wing flight and VTOL capabilities. The reverse transition process enables the aircraft to seamlessly switch between modes, providing increased operational flexibility and versatility.

The concept of in-flight attachment of a multirotor with a fixed-wing aircraft involves the integration of a separate multirotor system onto the fixed-wing platform. This allows the aircraft to transition between fixed-wing flight and vertical takeoff and landing flights during a single mission. This involves several additional considerations as discussed follows:

Design and Integration: The first step is to design the multirotor system that will be attached to the fixed-wing aircraft. This includes determining the appropriate size, weight, and configuration of the multirotor, considering factors such as payload capacity and flight requirements. The integration process involves securely attaching the multirotor system to the fixed-wing airframe, ensuring structural integrity and stability.

Trajectory Planning: A trajectory planning algorithm is required that calculates the desired path for the fixed-wing UAV and an ascending path for the multirotor UAV that considers the relative dynamics of both UAVs and designs a trajectory that ensures a safe and controlled descent onto the multirotor.

Attitude Control and Alignment: For the successful attachment of both the flying bodies, attitude control is crucial. An attitude control algorithm is required where the attitudes of both frames depend on each other. This control algorithm is a distributed control where sensors from both systems play a role in a common operation.

Path Following: For both the airborne systems path-following algorithms will be required that guide them along the planned trajectories. This could involve a proportional navigation controller that continuously adjusts the heading and lateral position based on the deviation from the desired path.

Collision Avoidance: During the landing and takeoff operations it is essential for both the airborne systems to avoid collision due to changes in the environment or each other's disturbances. This could involve using additional sensors such as lidar or cameras.

Control Systems: A control system is required that enables a seamless transition between fixed-wing flight and VTOL modes and facilitates reliable attachment and detachment. This typically involves improved flight control algorithms that are robust enough to handle perturbations that arise due to close formation flight. To accurately control the aircraft's attitude, thrust, and flight path during both flight modes, improved and additional sensors will be required to integrate. The control system should allow for smooth and precise transitions to maintain stability and control throughout the mission.

Power and Propulsion: The multirotor system requires its own power source and propulsion system. As this multirotor may need to match the speed of the fixed wing UAV resulting in a relatively higher speed. This can be achieved by integrating additional horizontal ducted propellers into the multirotor aircraft.

Aerodynamic Considerations: The attachment of the multirotor system may introduce aerodynamic changes to fixed-wing aircraft. These changes can affect the overall flight characteristics and performance. Design considerations should be made to optimize the aerodynamic integration, minimizing any adverse effects on the fixed-wing aircraft's stability, control, and reliability.

Latching Mechanism: A mechanism that allows attachment and detachment of fixed-wing with multirotor. This can involve mechanisms such as hinged latches controlled by servos. The latching mechanism should be robust, reliable, and capable of quick and seamless deployment to ensure safe and efficient operations.

Communication: A robust communication link between the fixed-wing and multirotor UAV is required as both are dependent upon each other's states. This link should allow for real-time data exchange, including position, velocity, and attitude information.

Flight Testing and Validation: Conduct extensive flight testing to validate the integrated system's performance, stability, and control in both fixed-wing and multirotor modes. This step is crucial for identifying and addressing any issues or limitations in the design, control, or integration process. Flight testing should cover a range of flight scenarios and conditions to ensure the system's reliability and suitability for intended missions.

Operational Procedures and Training: Develop operational procedures and training protocols for pilots and ground crew members involved in the operation of the aircraft. This includes familiarizing them with the transition process, flight characteristics, control inputs, and safety considerations specific to the integrated Air-runway system. Proper training ensures the safe and efficient operation of the aircraft during missions.

By following these steps, the process of achieving in-flight attachment of a multirotor with a fixed-wing aircraft can be approached, aiming to enable the aircraft to switch between fixed-wing flight and VTOL capabilities. However, it is important to acknowledge the significant technical challenges involved in this integration, which require careful consideration and precise execution to expand the aircraft's operational flexibility and versatility.

This is a high-level overview, and the actual implementation would require a thorough understanding of the specific UAV platforms, sensors, and control systems involved. Safety should be a top priority, so rigorous testing and simulations are crucial.

Delving into the complexities of landing a fixed-wing UAV on a multirotor platform unveils a multifaceted landscape, with numerous nuances demanding careful consideration. This paper centers its attention predominantly on the guidance aspect, acknowledging its pivotal role in ensuring a successful touchdown on the multirotor platform. While the overall process involves several more tasks, from aerodynamic intricacies to platform compatibility, our present discourse deliberately narrows its focus to a guidance system focused on landing operations.

4 Landing Platform Guidance

For setting up the guidance law, the pure pursuit guidance is considered, we have defined the equations of motion for multirotor as follows:

$$\dot{x}_m = V_m cos\theta_m cos\psi_m \tag{1}$$

$$\dot{y}_m = V_m cos\theta_m sin\psi_m \tag{2}$$

$$\dot{z}_m = -V_m cos\theta_m \tag{3}$$

$$\dot{\psi}_m = \frac{a_m^h}{V_m cos\theta_m} \tag{4}$$

$$\dot{\theta}_m = \frac{a_m^h}{V_m} \tag{5}$$

where, V_m is multirotor speed, a_m^h and a_m^v are horizontal and vertical acceleration components of the multirotor respectively, θ_m and ψ_m are flight path angle and course angles of multirotor respectively, and $\dot{\theta}_m$ and $\dot{\psi}_m$ are rates of pitch and yaw angles respectively.

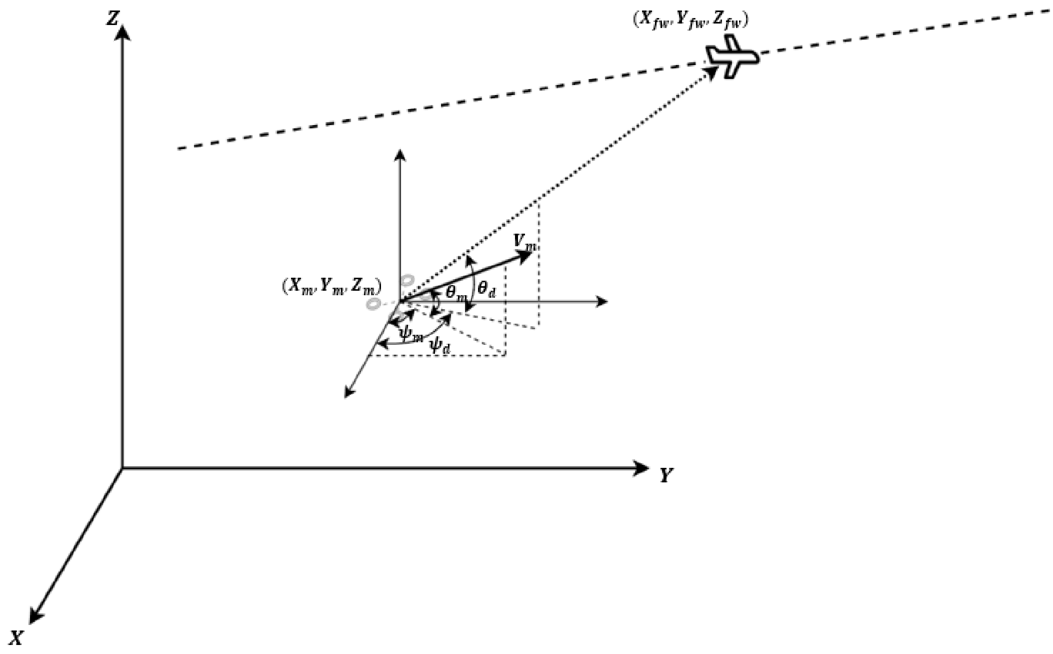

Fig. 4 Geometry of Guidance

4.1 Pure Pursuit Guidance

Each stage of this process requires a dedicated guidance strategy. For simplicity, we are restricting our discussion to landing of the fixed wing on a multirotor platform. The need for a guidance algorithm in landing a fixed-wing UAV on a multirotor platform is paramount for ensuring a smooth and precise touchdown. Unlike traditional fixed-wing landings on runways, the dynamic and confined space of a multirotor platform poses unique challenges. A well-designed guidance algorithm considers factors such as the varying aerodynamics of fixed-wing and multirotor systems, wind conditions, and the limited space available for descent. It provides real-time adjustments to the UAV's trajectory, taking advantage of both the stability of fixed-wing flight and the versatility of multirotor platforms. This algorithm becomes the digital navigator, orchestrating a delicate interaction between the two aerial systems, ensuring a safe and accurate landing even in challenging environments. For simplicity and the scope of this paper, a simplified pure pursuit guidance law is presented. The fixed-wing UAV is the target for the pure pursuit guidance law. The guidance methodology is referred from [18] which is used for virtual target tracking for a fixed-wing UAV. In this, the guidance methodology involves tracking a virtual target through the application of the pure pursuit law, inspired by missile guidance principles.

The objective is to consistently align the quadrotor's heading with the target by minimizing errors in azimuth (ψ) and elevation (θ) angles. The quadrotor avoids intercepting the target by maintaining a minimum distance (L) between itself and the fixed-wing UAV, ensuring the activation of the latching mechanism. Utilizing the vehicle's velocities in the x, y, and z directions, azimuth (ψ_m) and elevation angles (θ_m) as depicted in the Fig. 4 can be given by,

$$\psi_m = \tan^{-1} \frac{y_m}{x_m} \tag{6}$$

$$\theta_m = \tan^{-1} \frac{z_m}{\sqrt{x_m^2 + y_m^2}} \tag{7}$$

This approach requires commanding only two angles, azimuth (ψ_d) and elevation (θ_d) to keep the quadrotor on the desired path. Using the geometry represented in Fig. 4 the commanded azimuth (ψ_d) and elevation (θ_d) angles are given as,

$$\psi_d = \tan^{-1} \frac{y_{fw} - y_m}{x_{fw} - x_m} \tag{8}$$

$$\theta_d = \tan^{-1} \frac{z_{fw} - z_m}{D} \tag{9}$$

where D is the length of the projection of the line joining the fixed-wing and multirotor on the x-y plane and is given by

$$D = \sqrt{(x_m - x_{fw})^2 + (y_m - y_{fw})^2} \tag{10}$$

These control laws are utilized to generate the desired acceleration for the miltirotor body to achieve the desired guidance trajectory. Commanded horizontal, vertical, and forward acceleration laws (a_m^h, a_m^v and a_m^f respectively) are computed by,

$$a_m^h = K_{P_\psi}(\psi_d - \psi_m) + K_{I_\psi} \int (\psi_d - \psi_m) + K_{d_\psi} \frac{d}{dt}(\psi_d - \psi_m) \tag{11}$$

$$a_m^v = K_{P_\theta}(\theta_d - \theta_m) + K_{I_\theta} \int (\theta_d - \theta_m) + K_{d_\theta} \frac{d}{dt}(\theta_d - \theta_m) \tag{12}$$

$$a_m^f = K_{P_V}(V_d - V_m) + K_{I_V} \int (V_d - V_m) + K_{d_V} \frac{d}{dt}(V_d - V_m) \tag{13}$$

where V_d is the desired speed. Further, guidance commands are translated into multirotor commands which are referred from [19], and obtained in a similar way using inverse mapping. Commanded multirotor inputs are throttle (T), roll angle ϕ_c, pitch angle (θ_c), and yaw rate (ψ_c).

5 Results and Discussion

Comparative study of different VTOL UAVs outlining the performance compromise of a VTOL UAV with the incorporation of additional equipment for achieving VTOL capability. The data (Table 2) suggests that opting for the fixed-wing configuration and instead allocating the added weight to supplementary batteries, would result in a noteworthy extension of the UAV's endurance of about 100%.

The fixed wing and a quadcopter which facilitate a landing platform were modelled on the Simulink platform. To simulate the scenario, we focused on a simplified setup: a fixed-wing UAV maintaining a constant speed. The real-time coordinates of this UAV are utilized to generate guidance commands for a quadcopter UAV. In SIMULINK, the quadrotor is modeled with a mass of 15 kg and real inertial data. The implementation involves incorporating the Pure Pursuit algorithm. The Simulink model used is illustrated in Fig. 5.

For simulation, two landing cases are considered, in the first case the fixed-wing UAV is flying at a fixed altitude of 100 m and constant speed of 15 m/s in a straight flight path. The landing platform which is a quadcopter UAV, takes off from 0 m altitude and follows the guidance command. The trajectory of fixed-wing UAV and the quadcopter UAV is presented in Fig. 6. The quadcopter UAV is able to facilitate

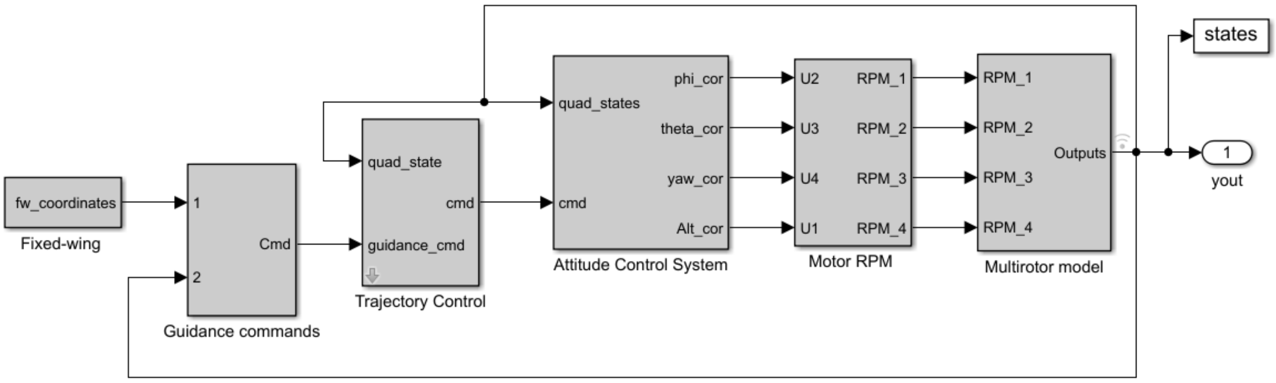

Fig. 5 Simulink model depicting multirotor guidance and control

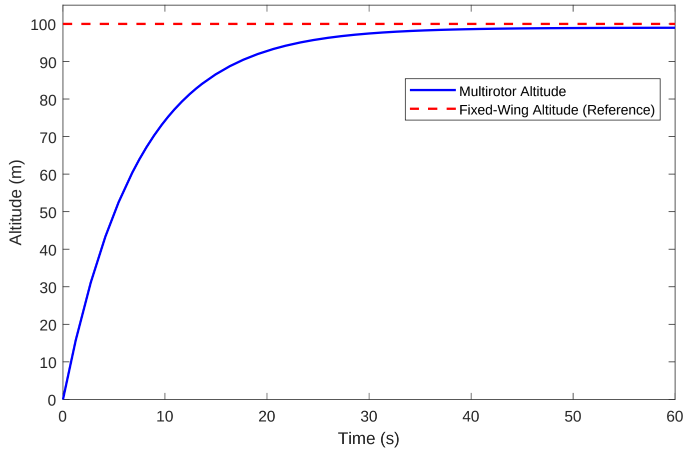

Fig. 6 Air-runway straight line approach

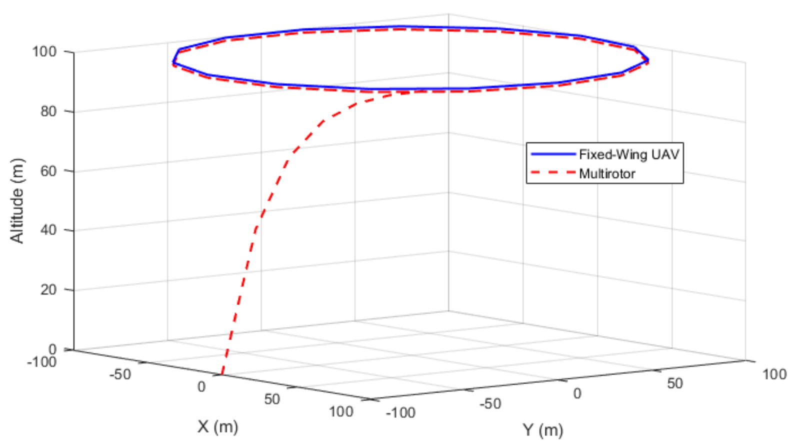

Fig. 7 Air-runway loiter approach

a landing platform for the fixed-wing UAV maintaining a minimum distance of $1\,m$ which is the distance required for engaging the latching mechanism.

In the second case, the fixed-wing UAV is loitering on a circular path of $100\,m$ radius at a fixed altitude of $100\,m$ and a constant speed of $15\,m/s$. The quadcopter UAV takes off from $0\,m$ altitude and follows the guidance command. The trajectory of the fixed-wing UAV and the quadcopter UAV is presented in Fig. 7. The quadcopter UAV is able to facilitate a landing platform for the fixed-wing UAV maintaining a minimum distance of $1\,m$ which is the distance required for engaging the latching mechanism.

The flight controller needs to possess strong resilience in order for the UAV to effectively minimize its susceptibility to various disturbances. Wind, in particular, has a significant impact on the flight of small UAVs, especially during formation flying. Since wind conditions can vary at different positions and the wake of one UAV can affect the stability of the other UAV, it is crucial to enhance the UAV's robustness against wind disturbances to ensure the effectiveness of formation flight.

5.1 Applications of the Air-runway

The "Air-runway" concept can be utilized for a wide range of general scenarios where traditional runway infrastructure is unavailable or impractical. In remote and rugged terrains, such as mountainous regions, dense forests, or isolated islands, the Air-runway enables UAVs to operate efficiently by providing a mid-air landing and refueling platform. This is particularly beneficial for humanitarian aid and disaster relief missions, where rapid deployment and sustained support are critical. Air-runway can be used as a mid-air battery replacement platform which further enhances the endurance for some particular applications. Additionally, the Air-runway can enhance maritime operations by offering a landing solution for UAVs over open water, supporting tasks like marine research, search and rescue, and anti-piracy efforts. In urban environments, the Air-runway can facilitate emergency services, allowing UAVs to deliver medical supplies, conduct surveillance, and support law enforcement without the need for ground-based runways, thus bypassing infrastructure limitations. Overall, the Air-runway's ability to provide a flexible and mobile landing platform expands the operational capabilities of UAVs in diverse and challenging environments. Some of the potential major applications are as follows.

5.1.1 Aerial Surveillance

Extended Operation Time: The Air-runway enables fixed-wing UAVs to remain airborne for longer periods by providing a mid-air refuelling and battery replacement platform. This is crucial for surveillance missions that require extensive coverage over large areas without interruption.

Flexibility in Deployment: With the Air-runway, surveillance UAVs can be deployed in remote or inaccessible areas without the need for ground-based runways. This allows for rapid response and monitoring in diverse environments such as forests, deserts, or oceanic regions.

Increased Range and Coverage: The ability to land, refuel/recharge, and take off from an airborne platform allows surveillance UAVs to extend their operational range, covering more ground and providing more comprehensive data collection for intelligence and reconnaissance missions.

5.1.2 Cargo Delivery

Enhanced Reach in Remote Areas: The Air-runway facilitates cargo delivery to locations lacking traditional runway infrastructure, such as remote islands, mountainous regions, or disaster-stricken areas. This significantly expands the delivery network and ensures essential supplies reach those in need.

Efficient Mid-Air Handoffs: Cargo UAVs can perform mid-air handoffs on the Air-runway, enabling continuous cargo transport without the need for landing. This improves efficiency and reduces downtime which is crucial for time-sensitive deliveries such as medical supplies or perishable goods.

Scalable Operations: The Air-runway concept supports scalable logistics operations where multiple UAVs can utilize the same airborne platform, coordinating their movements to optimize cargo delivery routes and schedules, thus enhancing overall logistics efficiency.

5.1.3 Emergency Response

Rapid Deployment and Mobility: In emergency situations, the Air-runway allows for the swift deployment of UAVs to disaster zones without the need for ground-based runways. This rapid mobilization is critical for timely assessments and delivery of aid at longer distances.

Continuous Support and Supply: Emergency response UAVs can utilize the Air-runway to remain in the air for extended periods, providing continuous surveillance, communication support, and delivery of emergency supplies to affected areas, ensuring sustained support during critical times.

Versatile and Adaptive Operations: The dynamic nature of the Air-runway enables it to adapt to changing conditions in disaster zones, such as shifting debris fields or evolving weather conditions, ensuring that UAVs can operate effectively and safely in unpredictable environments.

A common landing platform can facilitate Air-runway for multiple fixed wing UAVs which potentially will reduce operational costs. Also, as a common multirotor will be used for multiple fixed wing UAVs, this will potentially reduce maintenance time. Overall, the "Air-runway" concept significantly enhances the operational capabilities of fixed-wing UAVs across various use cases, offering unprecedented flexibility, efficiency, and adaptability.

6 Conclusion

There is a trade-off between vertical take-off and landing functionality and performance because the cumulative weight of VTOL components compromises the overall performance of the UAV. Air-runway can enable the best of both VTOL and fixed-wing without compromising fixed-wing flight performance. Air-runway represents a significant advancement in UAV technology, combining the best features of fixed-wing and VTOL aircraft. The transition mechanism employed by this platform enables seamless shifts between vertical and horizontal flight, allowing for efficient aerial operations and expanded mission capabilities. As research and development progress, Air-runways hold significant potential for transforming industries such as logistics, Surveillance, and emergency services, thereby opening up new possibilities for autonomous aerial systems.

Through comprehensive simulations, we explore the performance of the guidance law under different conditions, considering factors such as UAV type, flight path, and platform dynamics. The results not only validate the feasibility of the Air-runway concept but also provide valuable insights into its potential applications and performance considerations.

This study contributes to the ongoing discourse on future aviation technologies by presenting a novel concept that challenges conventional landing infrastructure. The Air Runway has the potential to revolutionize the way UAVs operate, opening up new possibilities for aerial mobility and expanding the horizons of aviation innovation.

References

[1] Long Xin, Zimu Tang, Weiqi Gai, and Haobo Liu. Vision-based autonomous landing for the uav: A review. *Aerospace*, 9(11), 2022. ISSN: 2226-4310. DOI: 10.3390/aerospace9110634.

[2] Weiwei Kong, Dianle Zhou, Daibing Zhang, and Jianwei Zhang. Vision-based autonomous landing system for unmanned aerial vehicle: A survey. In *2014 International Conference on Multisensor Fusion and Information Integration for Intelligent Systems (MFI)*, pages 1–8, 2014. DOI: 10.1109/MFI.2014.6997750.

[3] Davide Falanga, Alessio Zanchettin, Alessandro Simovic, Jeffrey Delmerico, and Davide Scaramuzza. Vision-based autonomous quadrotor landing on a moving platform. In *2017 IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR)*, pages 200–207, 2017. DOI: 10.1109/SSRR.2017.8088164.

[4] Jesús Morales, Isabel Castelo, Rodrigo Serra, Pedro U. Lima, and Meysam Basiri. Vision-based autonomous following of a moving platform and landing for an unmanned aerial vehicle. *Sensors*, 23(2), 2023. ISSN: 1424-8220. DOI: 10.3390/s23020829.

[5] Zijian Ge, Jingjing Jiang, Ewan Pugh, Ben Marshall, Yunda Yan, and Liang Sun. Vision-based uav landing with guaranteed reliability in adverse environment. *Electronics*, 12(4), 2023. ISSN: 2079-9292. DOI: 10.3390/electronics12040967.

[6] Aleix Paris, Andrea Tagliabue, and Jonathan P. How. Autonomous mav landing on a moving platform with estimation of unknown turbulent wind conditions. In *AIAA Scitech 2021 Forum*, pages 1–15, 2020. DOI: 10.2514/6.2021-0378.

[7] Yi Feng, Cong Zhang, Stanley Baek, Samir Rawashdeh, and Alireza Mohammadi. Autonomous landing of a uav on a moving platform using model predictive control. *Drones*, 2(4), 2018. ISSN: 2504-446X. DOI: 10.3390/drones2040034.

[8] Xiaoyun Huang, Qing Xu, and Jianqiang Wang. Vision-based autonomous landing of uav on moving platform using a new marker. *IOP Conference Series: Materials Science and Engineering*, 646(1):012062, oct 2019. DOI: 10.1088/1757-899X/646/1/012062.

[9] Wei Luo, Henrik Ebel, and Peter Eberhard. An lstm-based approach to precise landing of a uav on a moving platform. *International Journal of Mechanical System Dynamics*, 2(1):99–107, 2022. DOI: https://doi.org/10.1002/msd2.12036.

[10] Alejandro Rodriguez-Ramos, Carlos Sampedro, Hriday Bavle, Ignacio Gil Moreno, and Pascual Campoy. A deep reinforcement learning technique for vision-based autonomous multirotor landing on a moving platform. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 1010–1017, 2018. DOI: 10.1109/IROS.2018.8594472.

[11] Jingyi Xie, Xiaodong Peng, Haijiao Wang, Wenlong Niu, and Xiao Zheng. Uav autonomous tracking and landing based on deep reinforcement learning strategy. *Sensors*, 20(19), 2020. ISSN: 1424-8220. DOI: 10.3390/s20195630.

[12] Jintasit Pravitra, John-Paul B. Clarke, and Eric N. Johnson. Landing a fixed-wing uav on a moving platform: A pseudospectral optimal control approach. In *AIAA Aviation 2019 Forum*, pages 1–13, 2020. DOI: 10.2514/6.2019-3257.

[13] Shalini Suresh and Ashwini Ratnoo. Fixed-wing uav guidance for autonomous landing on a translating platform. In *AIAA Scitech 2019 Forum*, pages 1–9, 2019. DOI: 10.2514/6.2019-1170.

[14] Jintasit Pravitra and Eric N. Johnson. Adaptive control for attitude match station-keeping and landing of a fixed-wing uav onto a maneuvering platform. In *AIAA Scitech 2020 Forum*, pages 1–13, 2020. DOI: 10.2514/6.2020-1082.

[15] Dustin Gamble and Matthew Curran. Release and capture of a fixed-wing aircraft, 23 2019. EP 3 127 809 A1. https://patents.google.com/patent/EP3127809A1.

[16] Qiwei Guo, Yaozong Zhu, Yu Tang, Chaojun Hou, Yong He, Jiajun Zhuang, Youliang Zheng, and Shaoming Luo. Cfd simulation and experimental verification of the spatial and temporal distributions of the downwash airflow of a quad-rotor agricultural uav in hover. *Computers and Electronics in Agriculture*, 172:105343, 2020. ISSN: 0168-1699. DOI: https://doi.org/10.1016/j.compag.2020.105343.

[17] Scott G. Carmack, Narasimha R. Lakkakula, and Nima S. Mehr. Using multirotor lifters to deploy fixed wing aircraft, 25 2017. US 9,630,712 B1. https://patents.google.com/patent/US9630712B1/en.

[18] Eran D. B. Medagoda and Peter W. Gibbens. Synthetic-waypoint guidance algorithm for following a desired flight trajectory. *Journal of Guidance, Control, and Dynamics*, 33(2):601–606, 2010. DOI: 10.2514/1.46204.

[19] Jeff Ferrin, Robert Leishman, Randy Beard, and Tim McLain. Differential flatness based control of a rotorcraft for aggressive maneuvers. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2688–2693, 2011. DOI: 10.1109/IROS.2011.6095098.