

Drone Landing Performance in Windy Conditions: Comparing the Vertical and Horizontal Landing Approaches with the EAGLES Port

Iuri Barros, Yoshito Okada, Kenjiro Tadakuma, Masahiro Watanabe, Masashi Konyo, Kazunori Ohno, Yoshiki Yokota, Ranulfo Bezerra, Satoshi Tadokoro

Abstract—Drone docking stations promote efficient operations of drones, but they usually support only one vehicle, and are accessible primarily through vertical landing. These limitations hinder multi-drone operations and result in challenges for fast, precise docking, particularly under severe wind conditions. This study assesses the EAGLES port, which uses a horizontal landing approach to address these challenges, and makes a performance comparison between horizontal and vertical landing through analysis of wind tunnel data with manually controlled drones. Results show that horizontal landing decreases the average landing duration by 35.58%, and can achieve 59.67% faster docking compared to vertical landing in optimal conditions. The system also provides near-zero position error at docking, and supports multiple drones. These advantages stem from improved flight stability, quicker alignment with landing targets, and a 2.8 times higher average velocity compared to vertical landing. These results indicate that vertical landing is better suited for missions with wider landing zones and where delays in landing have mild consequences, whereas horizontal landing excels in scenarios where rapid accurate landings are critical.

Index Terms—Aerial Systems: Mechanics and Control, Field Robots, Aerial Systems: Applications.

I. INTRODUCTION

The integration of Unmanned Aerial Vehicles (UAVs) into various human activities is expected to grow [1] [2], including applications like last-mile delivery [3] [4], entertainment [5] [6], search-and-rescue [7] [8] and military operations [9]. Moreover, many of these activities will rely on the deployment of not one, but multiple UAVs [10], which must complete tasks independent of weather conditions [11] [12]. Given that individual aerial vehicles are commonly required to recharge, be deployed, collect payloads, and perform various application-specific tasks, a central docking station, or drone port, becomes an essential infrastructure element to standardize and accelerate these processes, and assist the vehicles in diverse weather conditions. Therefore, it becomes evident the need to foster the development of drone docking stations, mainly when growing investments in civil unmanned aerial systems are expected to reach billions in the coming decade [13].

Drone docking stations have the potential to enhance the hosted vehicle's performance and reduce costs in a variety of tasks [14] [15], but currently available systems present significant limitations. They are predominantly designed to host and support a single vehicle [16] [17] and are accessible exclusively through vertical landing [18]. These limitations

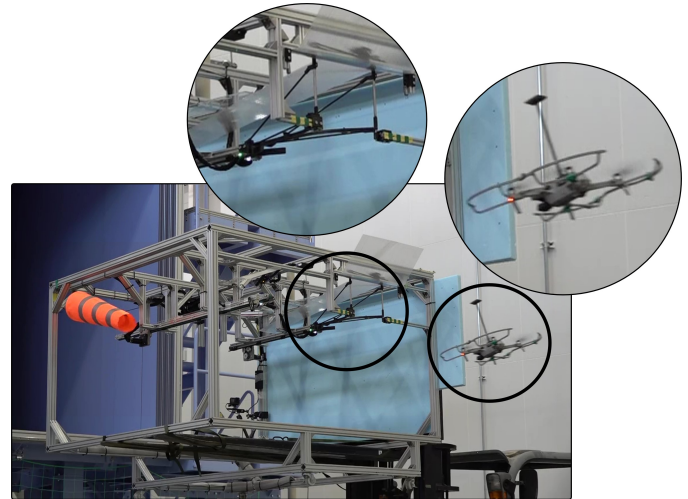


Fig. 1. Experiment overview. Quadrotor landing horizontally in the EAGLES port while facing the wind tunnel, simulating a headwind condition. The EAGLES' entry gate and drone are magnified.

not only hinder multi-drone applications and exclude vehicles incapable of vertical landing, but also causes precision landing challenges, especially in severe wind conditions [19] [20]. Furthermore, these challenges often result in prolonged operational time [21], which rapidly escalate and become critical when dealing with multiple drones, where takeoff and landing become more frequent [22]. A system designed to address these limitations was introduced in our previous work and named EAGLES port [23]. The design emphasized efficient, multi-drone operations using a horizontal landing approach, and that required minimal modifications to UAVs.

The previous study, however, did not investigate the underlying factors behind the EAGLES port performance, nor it assessed the effects of wind conditions on landing, which is the most critical phase of aircraft operations [24]. In addition, the EAGLES port was not evaluated under practical operational circumstances, and a comparison with vertical landing, which is the standard approach employed by drone docking stations, was left for future research. Thus, this study provides a comprehensive evaluation of the EAGLES port, focusing on quadrotor landing performance in diverse wind conditions. Our analysis is particularly relevant for multi-drone

applications, where speed, stability, and precision are critical factors. However, it is important to note that the EAGLES port may not be as advantageous for low-throughput or single-drone applications, as its primary goal is to support high-efficiency, multi-drone operations.

Through controlled wind tunnel experiments (Fig. 1), we demonstrate that the EAGLES port significantly improves landing speed and precision compared to conventional docking stations. Moreover, we show that our port supports multi-drone applications, highlighting its potential for advancing drone docking station solutions. This work represents a large step forward in addressing the challenges of efficient and reliable UAV docking, contributing with novel and practical insights to the field. The key contributions of this study are summarized as follows:

- A robust empirical analysis of docking strategies for multirotor drones, comparing the traditional vertical landing approach with the novel horizontal landing approach. Through comprehensive wind tunnel experiments and exploratory data analyses, we demonstrate that horizontal landing reduces landing duration by 35.58% on average, 59.67% in optimal conditions, and affords ideal landing precision compared to vertical landing.
- A detailed characterization of drone motion during docking maneuvers. By characterizing each landing approach, we identify the key factors driving performance results, and provide valuable information for improving existing docking strategies. We show that horizontal landing leverages greater stability and 2.8 times higher average speed than vertical landing to obtain performance advantages during landing.
- An experimental framework and metrics designed to assess the docking performance of UAVs in stations with windy surroundings. The proposed methodology can be applied to evaluate and obtain insights on different landing strategies for drone docking systems.
- An evaluation of the EAGLES port in a practical UAV landing task, and qualitative evidence demonstrating its ability to enable reliable and safe multiple drone landings in real-world scenarios.

Going forward, this study is organized in the following manner: Section II offers a concise overview of relevant research and commercially available drone station technologies. In Section III, we introduce the EAGLES port, highlighting its key features and the innovative concept enabling multirotors to land horizontally. Sections IV, V and VI detail the wind tunnel experiments, including the materials and experimental setup. In Section VII, we describe the metrics developed for evaluation and their implementation. Sections VIII and IX present the results obtained using the proposed metrics and provide in-depth discussions of the findings. Finally, Section X summarizes the key insights and concludes the paper by discussing the broader implications of our work.

II. THE DRONE STATION LANDSCAPE

In [18], the authors reviewed a decade of UAV docking stations, offering eight classification attributes such as mobility and positioning. However, they did not consider landing methods or the number of supported drones. This highlights how most docking stations have focused on vertical landing and single-drone operations. While this approach is simpler, cheaper and reliable, and most current applications only require a single drone, the popularization of drone technology is leading to multi-drone applications, such as drone light shows and parcel delivery. The examples in the review primarily reflect current commercially available solutions, which we will explore further in this section.

A more unorthodox station was introduced in [25], which proposed an inverted docking station with a gripper mechanism that holds the drone during battery swapping. In [26], a design was proposed that integrates a UAV hangar into a pickup truck. This hangar can accommodate up to four drones and is accessible through vertical landing. UAVs landed in the hangar in about one minute, with landing precision ranging from 0.12 to 0.24 m. Among the studies reviewed, this design was the most compatible with the type of stations that we aim at assessing in this study.

The maturity of drone docking station technology is best assessed by reviewing commercially available products, as companies typically adopt more established solutions. DJI Dock 3 [27] and Hextronics' Universal [28] are relatively small and lightweight (under 100 kg) docking stations meant to house one vehicle and be portable. Drones access these stations through vertical landing. DJI's solution ensures accurate landing positioning using a tapered design on both the drone's airframe and the station's landing zone. Upon touchdown, the drone slides into position using gravity. In contrast, Universal employs an alignment mechanism to center drones, a standard approach shared by other solutions. Universal is compatible with various drones, while Dock 3 requires a specific DJI drone.

Above 100 kg, solutions like Skydio Dock [17], Hextronics' Atlas [29], Percepto Base [30] and J-inspace's DroneSAT [31] are designed to be stationed at fixed locations and are not meant to be moved frequently. These stations house one vehicle, targeting larger drones with higher payload and flight time capabilities. Of the options evaluated in this range, DroneSAT is the only solution that offers battery swap technology, though this comes with a trade-off in weight. From these, Skydio Dock is the only station in this category that requires a proprietary drone.

Skycharge's Skyport [32], Hive M300 [33], and Optimus from Airobotics [34] are fully autonomous solutions weighting over one ton, offering features like battery swapping and payload carrying capacities. These stations are resistant to tampering and withstand a wide range of weather conditions. Optimus is the only solution that requires proprietary UAV, while the others are cross-platform, compatible with different drone brands. For example, drones can be retrofitted for

charging using Skyport’s proprietary wireless charging floor. Access to these stations is through vertical landing on their roofs, with an integrated alignment mechanism for precise positioning.

To the best of our knowledge, Heisha Technology is the only company attempting to manufacture a commercial port capable of managing multiple drones. The DPort [35] is a multi-drone airport roughly the size of a small house, with openings on its roof for vertical landing access. However, limited data is available about the DPort. In addition, a patent was issued for a stackable UAV system and portable hanger by [36], but this system cannot carry payloads, as the top and bottom of the drones are used for stacking.

Current state-of-the-art drone ports are highly limited in managing a fleet of drones and often struggle with landing in severe wind conditions. Our work focuses on analyzing essential attributes for managing drone fleets in a fully autonomous manner. An ideal docking station for multi-drone operations would be able to support the sequential landing of multiple drones with high stability, precision and in minimal time. These criteria form the basis for our comparisons, and they should be considered when evaluating the remainder of this study.

III. THE EAGLES PORT

A. Concept and working principle

The EAGLES port is a drone docking station designed to enable continuous horizontal takeoff and landing (HTOL) of multirotor drones in a small time frame, with improved stability and precision across diverse wind conditions. The key feature of the EAGLES port is its entry gate, a mechanism that compensates for drones’ positional misalignment relative to the target landing location during touchdown. The gate guides the vehicle towards a hanging rail, which transports the drone between the landing and takeoff locations using a belt conveyor. This system allows for greater operational efficiency as drones can be quickly moved aside after landing, making room for subsequent drones to use the EAGLES port. To use both the entry gate and the rail, drones must be equipped with a landing guide, which is attached to the top part of the vehicle. This gate-rod system drastically changes how multirotor drones access docking stations. When using the EAGLES port, drones land horizontally instead of vertically (see Fig. 2a), thus overcoming many limitations of the vertical takeoff and landing (VTOL) approach adopted by state-of-the-art drone stations.

Vertical landing imposes significant limitations at the docking stage, such as reduced speed and precision, potentially leading to slow or inaccurate landings [37] [38]. When a multirotor attempts vertical landing, it reduces the rotors’ speed to approach the landing target, making the vehicle unable to generate propelling forces to overcome external disturbance. This makes the UAV unstable when landing close to the ground, especially under rough weather conditions [39]. Horizontal landing can avoid such instability as the quadrotor can still produce relatively large propelling forces

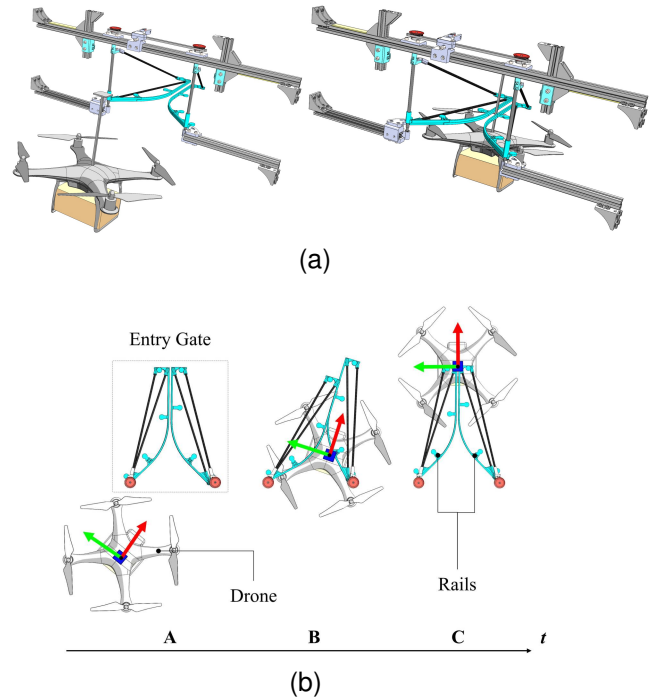


Fig. 2. Motion diagrams of a quadcopter landing in the EAGLES port and using the entry gate (light blue) to correct its trajectory upon touchdown. (a) isometric view. (b) top-down view, emphasizing the gate behavior and the trajectory correction. Chronological order from left to right.

while landing. In fact, the aerial vehicle is encouraged to increase the rotors’ speed when landing horizontally, thus increasing stability. Moreover, fixed axis multirotors can only generate longitudinal and lateral forces when they tilt their bodies. In vertical landing, tilting at the moment of landing is often impractical. This may lead to low positioning accuracy [40] or miss landings. On the other hand, drones are allowed to tilt in the horizontal approach, and thus they can move long and sideways, adjusting their position, increasing precision and stability at the landing stage.

The gate mechanism of the EAGLES port further improves precision and stability. In a typical scenario, the drone approaches the EAGLES’ gate without the need for significant speed reduction. The vehicle can assume different poses relative to the gate, with specific tolerances described in [23]. Illustration A in Fig. 2b displays a drone that is at an arbitrary position relative to the entry gate. Upon reaching the gate mechanism, illustration B, the landing guide meets the gate’s rails. These rails can pivot around shafts and are synchronized by a belt system. Then, springs attached to the shafts passively resist the forces exerted by the drone (through the rod) while attempting to return to its initial state. As a result, the gate redirects the landing guide towards its exit and landing is completed (illustration C in Fig. 2b). These features allow drones to land faster, shortening the time required for landing when compared to common vertical landing strategies.

Patents for the EAGLES port are also available: “Aerial vehicle takeoff and landing system, aerial vehicle takeoff and landing apparatus, and aerial vehicle”,

US11905037B2, EP4011768A4, and CN114206725B. Inventor: Kenjiro TADAKUMA at el, NPO International Rescue System Institute Tohoku University NUC.

B. Landing guide

The landing guide (Fig. 3) is a lightweight attachment that mounts on a drone’s airframe, facilitating landing in the EAGLES port. Positioned on top of the drone, it preserves the vehicle’s ability to land vertically in emergencies. Moreover, once the drone is hanging inside the EAGLES port after landing, its bottom remains accessible, allowing for convenient payload placement in practical use cases.

The landing guide was designed to fit a DJI Mavic Air 2 quadrotor, the drone chosen for the experiments. It consists of three components: mount, rod, and tip. The mount uses a plug and play design, which snap fits to the drone’s battery module. Cutouts in the mount match the battery’s release mechanism, providing a tight fix between the landing guide and the drone. The rod works alongside the gate mechanism to redirect the drone into the EAGLES port, and it should be the only component to interact with it during landing. Lastly, the tip allows the drone to hang on the conveyor, and has enough friction to ensure smooth movement on the belt with minimal slipping.

Both mount and tip were manufactured using Markforged’s Mark Two 3D printers with the Onyx filament [41]. As for the rod, it is a commercially available 6 mm carbon fiber square tube cut to the desired length of 25 cm. The mount and tip are fixed to the rod by two sets of standard M2 bolts and nuts, one for each component. When assembled, the implement weighs approximately 25 g. For comparison, the Mavic Air 2 propeller guards weigh 90 g, as per the official specifications. The implement’s lightweight prevents any harmful effects on drone controllability and avoids significant battery burden, which would otherwise lead to higher energy consumption and reduced flight time. Additionally, as the landing guide is similar to GPS vertical mounts used by drones, its aerodynamic effects would be similar to those of the mounts.

Due to the landing guide’s lightweight design and material choices, it may not be suitable for prolonged use. Alternative designs and materials, like carbon fiber reinforcements, could be applied to the mount, improving its robustness. Nevertheless, no landing guide failed during the wind tunnel experiments.

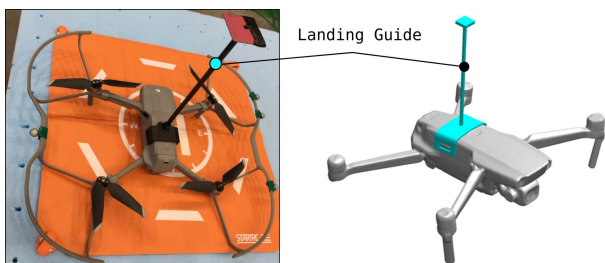


Fig. 3. Photo of the landing guide (left) and corresponding 3D mockup (right).

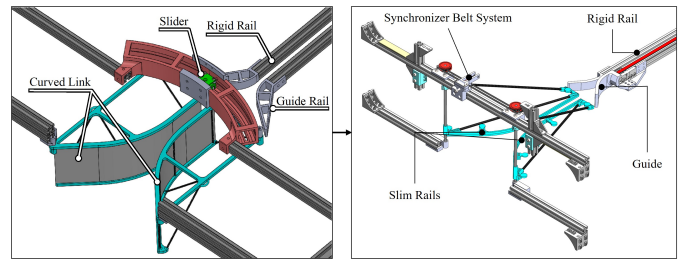


Fig. 4. Comparison between the previous (left, [23]) and current (right) versions of the EAGLES’ gate mechanism.

C. Design modifications for the experiments

Compared to the system proposed by [23], the EAGLES port has undergone changes for the wind tunnel experiments. Even though a comprehensive mathematical analysis of these design changes is out of the scope of this study, we provide a brief assessment of their effects throughout this section.

The original design provided by [23] had tall, curved links that restricted the drone’s ability to tilt and rotate (roll and yaw) upon landing, causing the drone to experience abrupt changes in its attitude. The novel design replaces the curved links with slim rails, which modify how drones interact with the EAGLES port. Before, their interaction was primarily along a surface, where the tip of the rod would meet the curved link’s surface. Now, it occurs almost in point-to-point fashion, where the body of the rod itself meets the slim rail. This change means the drone can rotate about the rails and land in a wider range of orientations.

In the EAGLES port, we also introduced two extension springs with one end placed off-center from the shafts’ rotational axes and the other to the port’s body frame. This off-center placement allows them to act like torsion springs, but with ease of installation and maintenance. These springs ensure the rails always return to their original state. This means drones can find the gate in a consistent location, no matter how many times it has been used. Moreover, having fewer states for the gate should make it easier for an autonomous landing system to learn how to use the EAGLES port. Springs with high stiffness, if implemented, could also help redirect drones towards the gate’s exit, and the rail behavior could be tuned by changing the springs for others with different stiffness. Future research can focus on understanding the effects of high spring stiffness. Finally, we changed the slider into a belt system, but the working principle, synchronization, was maintained. Fig. 4 shows the difference between the previous and current versions of the EAGLES port, where the left-hand side picture of Fig. 6 displays the new gate design.

The effects of these changes on the gate-drone interaction can be assessed in a similar manner to our previous work [23]. This interaction was modeled as a collision between two bodies using the impulse-momentum theorem, which assumes that collision is nearly instantaneous. At the moment of collision, the spring undergoes a very small initial deformation, and according to Hooke’s law, the restoring force provided by

the linear spring is proportional to its deformation from the free length. Given the spring’s low stiffness (0.343 N/mm), its force is negligible compared to the impulse generated during the collision. Hence, the interaction between the gate and the drone remains reasonably consistent with the original model. Nonetheless, the spring will have an effect on the behavior of the gate after the collision. The gate will oscillate around its equilibrium position, being damped only by the friction between moving parts. Over time, the gate returns to (or close to) its initial position, which is the desired function of the spring.

IV. FACILITY AND MATERIALS OVERVIEW

To compare the performance of the EAGLES’ horizontal landing approach with the standard vertical landing strategy, we conducted wind tunnel experiments at the Fukushima Robot Test Field, Japan [42]. The wind tunnel ensures evaluation of the landing phase under different wind conditions, crucial since landing is highly sensitive to wind disturbances. The tunnel (item 3 in Fig. 5) has a cross-sectional area of 3 m x 3 m, large enough to fully enclose both the drone and the port within a wind field. We also used the facility’s 3D motion capture (MOCAP) system to track UAV position, as the performance analysis relies on position information. The MOCAP consisted of five Qualisys QOUS7+ cameras, which tracked 4 reflective markers on the drone at an acquisition rate of 300 Hz. Moreover, the Qualisys Track Manager® was used to treat the measured data. For the tracking, the drone coordinate frame was set to its center of gravity, while that of the port at the front-right corner of the frame structure. Both coordinate frames are depicted as items 1 and 2 in Fig. 5.

We also built a structure with Misumi’s HFS5 aluminum frames (1.7L x 1.6W x 1.3H m) to house the gate mechanism (0.275 m entry width) and emulate the EAGLES port for the

experiments. Similar to the landing guide, the gate rails were 3D printed using the Onyx filament. These rails were then linked together using carbon fiber pipes for improved structural strength. We hired professional drone operators to pilot DJI Mavic Air 2 quadrotors and perform the landings. Notice that the operators had no prior experience with the EAGLES port and its horizontal landing approach. These were the primary elements of the experiments and a diagram of the wind tunnel, the EAGLES port and its frame structure is displayed in Fig. 6.

V. EXPERIMENTAL CONDITIONS

We assessed UAV landing at wind tunnel speeds of 0, 3, 6 and 8 m/s, and changed the port orientation into various angles relative to the tunnel for comprehensive exploration of the wind conditions. These speeds reflect the operational limitations of the drone, as speeds exceeding 8 m/s were posing considerable challenges to landing with any of the strategies, and speed intervals sufficiently large for operators to notice a difference in handling. Port angles included 0°, 45°, 90°, and 180°, which represent four common wind types: headwind, quartering wind, crosswind, and tailwind, respectively. The selected speed and angle settings enable a comprehensive investigation, enhancing the confidence of this study’s findings.

Due to time constraints, our goal was to produce three measurements for each combination of wind tunnel speed and wind type, except for the 0 m/s setting, where angle variations should pose no influence on landing. Following these guidelines, the experiments yielded a collection of 78 samples, 39 for each landing strategy.

VI. ENVIRONMENT SETUP AND TEST INSTRUCTIONS

To ensure consistent experimental conditions, instructions were designed and followed. Positions for drone takeoff and the port were measured and marked on the floor with tape. These positions were primarily driven by the facility’s dimensions and our experimental conditions, such as port angle. A forklift operator was responsible for placing the EAGLES port at predefined positions (relative to the wind tunnel), and heights (relative to the ground). Fig. 6 depicts the forklift holding the port in front of the wind tunnel. Once the port was properly placed, the wind tunnel was set to the target wind speed, and the drone was positioned at the designated takeoff location. After placing the drone in position, the operator ensured he was facing the entry gate. We then started the MOCAP system and measurements followed. After landing, the MOCAP was stopped, and the drone repositioned at the takeoff location so that a new trial could follow.

Given the influence of port position and orientation on the results, we minimized changes to the pose of the EAGLES port during the trials. Initially, drone operators performed horizontal landing for a specific angle and speed combination. After obtaining successful trials on the given combination, the tunnel was set to the next target wind speed. Measurements followed until all wind speeds were investigated for horizontal

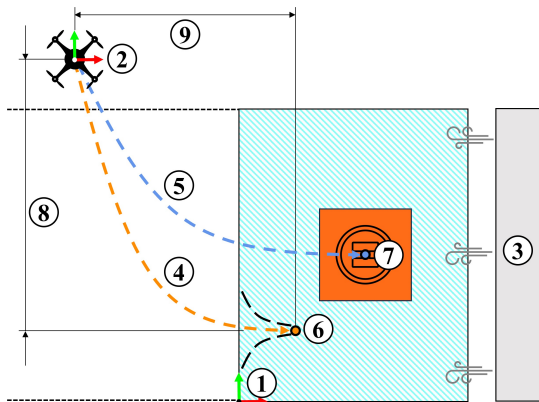


Fig. 5. Experiment diagram and common terminology. 1) EAGLES port 2) drone 3) wind tunnel 4) horizontal landing trajectory 5) vertical landing trajectory 6) target horizontal landing position 7) target vertical landing position 8) y-axis position error relative to the horizontal target 9) x-axis position error relative to the horizontal target. The light-blue patch in 1 represents the landing platform. The coordinate frames of the port and drone are also depicted in items 1 and 2. Green arrows indicate positive y-axis, and red ones, positive x-axis. The positive z-axis is derived by taking the right-hand rule.

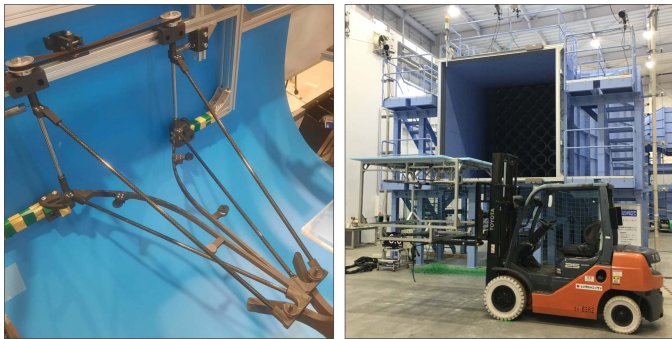


Fig. 6. Photos of the entry gate (left) and the experiment setup (right). The setup photo displays the EAGLES port being lifted by a forklift in front of the wind tunnel.

landing. Upon completion of the horizontal landing trials, the port was lowered to the designated height for vertical landing. This was necessary to make the helipad visible to the operator, and to place the helipad in a similar height to that of the gate, since the helipad was on top of the frame structure. Vertical landing measurements were then performed for the different wind speeds. Only after completing both the horizontal and vertical landing measurements for the predefined wind speeds that changes to the port's position and orientation were made. This procedure sped up the experiment and avoided results variation with respect to the pose of the EAGLES port.

We also designed procedures on how the drone operators should approach the experiments. As mentioned, the quadrotor was initially placed at its takeoff position, and then the MOCAP system was started. Next, the operator would approach the port from either its sides (depending on the port angle) before attempting landing to minimize initial position deviations between trials for the same port angle. After crossing one of the port's sides, the operator attempted landing. When landing was accomplished, we stopped the MOCAP system, and the trial was concluded.

VII. EVALUATION

In this section, we present the most insightful metrics for characterizing the landing methods, though our analysis was not limited to them. For instance, acceleration data exhibited similar behavior to velocity and did not provide additional insights, leading to its exclusion. Likewise, findings from orientation data were less conclusive than the metrics presented here. Including these additional analyses would offer only minor insights while shifting focus from the core observations. Therefore, the authors have chosen to omit these results.

A. Performance analyses

1) *Time for landing*: The time required for drones to land in the port is an effective metric for comparing the performance of landing strategies. We thus estimate the *time for landing* by tracking the drone position with respect to the EAGLES port, and comparing timestamps when tracking starts and when it ends.

Tracking starts when the UAV crosses a line parallel to the port's longitudinal axis. This line must be carefully chosen, and mark the beginning of the critical landing zone, where starting tracking ensures the UAV is fully within the wind field. This line needs to remain fixed for identical wind and angle settings to ensure a consistent reference, making results comparable. In our study, we used either the line formed by the right-hand side of the port (at $y = 0$ m) or the left-hand side (at $y = 1.7$ m) depending on the port angle for convenience. These lines are also depicted in Fig. 5.

Due to the inherent differences in the landing strategies, the criteria for tracking termination varied accordingly. For the horizontal approach, tracking ends when the drone exits the EAGLES' gate. For the vertical method, tracking terminates when the squared error of the UAV position is lower than 0.001 mm^2 for 9 consecutive frames, or 0.03 s. In instances where landing was not detected, an increment of 0.001 mm^2 was given to the threshold and the process repeated until termination was detected.

Time for landing is primarily assessed with exploratory data analysis and statistical testing. The latter determines if there is a noteworthy difference in landing duration between the horizontal and vertical landing approaches when it comes to landing duration. For the test, we adopted the null hypothesis (H_0) that there is no significant difference in time for landing between horizontal and vertical landings. A non-parametric Mann-Whitney U test was chosen due to possible outliers in the distributions and the relatively small sample size per group ($n = 39$).

2) *Precision error*: As UAV applications become increasingly automated tasks [43], precision landing becomes critical for safe and smooth integration of landed drones with various systems. Precision landing is especially crucial in multi-UAV applications, where mispositioning can obstruct subsequent landings, similar to the aircraft landing problem [44]. Therefore, we evaluate the *precision error* associated with each landing strategy.

Precision error is measured by taking the absolute difference between the drone position and the target landing position when landing is deemed completed. Thus, a precision error of zero is considered ideal. Moreover, we assess landing precision along the x and y axes only, given that the z-axis should naturally exhibit zero precision error for both strategies.

B. Motion analysis

1) *Position error*: Assessing the position of drones during docking can help us characterize each landing approach and provide further insights into any advantages revealed in our performance analysis. Through this characterization, we hope to provide detailed information about each landing approach, guiding future research while aiding users select the most suitable approach for their specific applications. The *position error* evaluation relies on calculating the absolute error between the drone position and the target landing position along the x, y and z axes. Fig. 5 depicts the x and y-error for a drone landing horizontally, indicated by items 9 and 8 in the figure,

respectively. The target position of the horizontal approach is located at the exit of the EAGLES’ gate, and the target position for the vertical approach is defined as the center of a helipad. These two natural targets for the evaluated landing techniques are represented in Fig. 5 by items 6 and 7. Furthermore, we discretize the error into 2-second intervals and compute their mean in each interval to uncover any trends within the data, facilitating the analysis.

2) *Velocity*: To obtain valuable insights into the dynamics of the landing process, we make an exploratory analysis of drone velocity. This evaluation is limited to the longitudinal (x-axis) component for horizontal landing drones, and the vertical (z-axis) component for vertical landing drones, as these are the primary landing directions of each approach. We apply the finite difference method to estimate velocity from the time and position measurements, and smooth out the results using a moving average over 31 frames. Also, we discretize the data into intervals of 0.1 s and then compute the mean from all data points associated with each time interval to expose any velocity trends.

3) *Trajectory*: To investigate the paths drones follow to reach their targets and how these impact their stability we conduct a trajectory analysis. A common approach for trajectory analysis is to make use of 2D or 3D line plots like items 4 and 5 in Fig. 5. However, when evaluating multiple trajectories, plots may become cluttered, making it difficult to uncover any patterns within groups. Instead, we make use of trajectory heatmaps on the *xy*, *xz* and *yz* planes. This allows for a qualitative assessment of drone stability by examining the size, shape and density of the heat patterns.

We interpret the heat patterns as indicators of the operator’s control over the drone’s trajectory. High-density, compact shapes suggest that drones followed the desired path without needing corrections, i.e. less operator intervention. Low-density, spread patterns with varying shapes and sizes imply the operator had difficulty maintaining the intended trajectory and needed to adjust the drone’s path due to external disturbances. Therefore, trajectory heatmaps are used as a proxy for evaluating stability in this study.

C. Multiple drone operations

After collecting robust data on individual drone landings, we used part of the final day of experiments to explore scenarios involving multiple drones. For these experiments, we hired five operators, which were responsible to land drones in the EAGLES port. Unfortunately, because of time and resources constraints, we were unable to acquire sufficient data for a thorough quantitative analysis. Therefore, we based our analysis on observations of video recordings and focused on a qualitative assessment of the results. To distinguish between the previous analyses, we present and discuss the multi-drone results in the Discussion section alone.

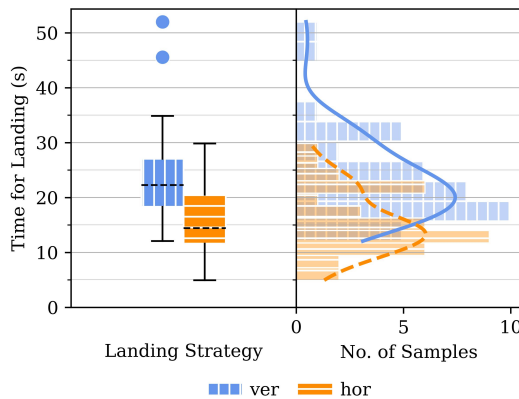


Fig. 7. Summary statistics of *time for landing* for each landing approach through boxplots (left) and histograms (right). $n = 39$ for each distribution.

VIII. RESULTS

A. Performance Analysis of Drone Landing Techniques

1) *Time for Landing*: Fig. 7 displays boxplots and histograms of the time required for landing associated with each landing approach. In this study, boxplots showcase central tendency through the median, a choice made due to its robustness to outliers. From the boxplots, the horizontal and vertical landing strategies yielded average landing durations of 14.40 s and 22.26 s, respectively. Besides, when performing horizontal landing, the operator was able to land in as little as 4.93 s, and with the vertical approach, in 12.05 s. Moreover, the distributions shared similar interquartile ranges (IQRs) of 8.77 s and 8.89 s, with the vertical approach revealing two outliers above the 45-second mark.

The Mann-Whitney U test revealed a statistically significant difference in time for landing between the horizontal and vertical groups, $U = 300.00$ and $p = 0.00000167$ for $n_{\text{ver}} = n_{\text{hor}} = 39$. Results were similar when removing outliers from the vertical landing distribution. Lastly, the histograms indicate that both distributions have two peaks and are right-skewed, with the horizontal approach showing higher distinction between the two peaks and skewness.

2) *The effects of wind speed*: In Fig. 8a, *time for landing* is compared under different wind conditions. The data show that at wind speeds of 0, 3, 6 and 8 m/s, the median landing durations were 16.27 s, 23.12 s, 19.36 s and 25.40 s for vertical landing and 4.93 s, 13.33 s, 14.66 s, 19.25 s for horizontal landing, respectively. Horizontal landing resulted in lower medians across wind conditions, with these values increasing as wind speed increased. In terms of variation, the IQR values for vertical landing were 8.14 s, 6.65 s, 4.38 s and 12.59 s, while those for horizontal landing were 3.11 s, 3.63 s, 6.71 s and 6.99 s. IQR values for horizontal landing were generally lower and more consistent across wind settings, except for the 6 m/s case, where vertical landing resulted in lower variation. This unusual result will later be addressed in the discussions section. Outliers appeared in both landing

strategies, with vertical landing having outliers at 6 m/s and 8 m/s, and horizontal landing at 3 m/s and 6 m/s.

3) *The effects of wind type:* A comparison of *time for landing* for different types of wind is shown in Fig. 8b. For headwind, quartering wind, crosswind and tailwind conditions, the vertical landing method resulted in medians of 18.96 s, 18.50 s, 22.85 s and 24.27 s, respectively, while the horizontal approach had medians of 14.40 s, 15.06 s, 17.23 s and 13.23 s. Once again, horizontal landing resulted in the lowest median values across the investigated conditions, with the values consistently remaining within the 10 to 20-second range. For variation, vertical landing had IQR values of 11.38 s, 5.86 s, 4.69 s and 7.90 s, while horizontal landing had values of 9.16 s, 6.77 s, 8.82 s and 5.72 s. The vertical approach had lower variation for quartering wind and crosswind, whereas the horizontal approach showed lower variation for headwind and tailwind. Moreover, outliers were observed only in vertical landing, appearing in all cases except for the headwind scenario.

4) *Precision:* Precision error results are shown in Fig. 9a. The plot indicates that vertical landing produced average errors of 0.22 m and 0.12 m along the x- and y-axes, respectively, while horizontal landing resulted in medians of 0 m and 0.04 m. Thus, precision error was minimized with horizontal

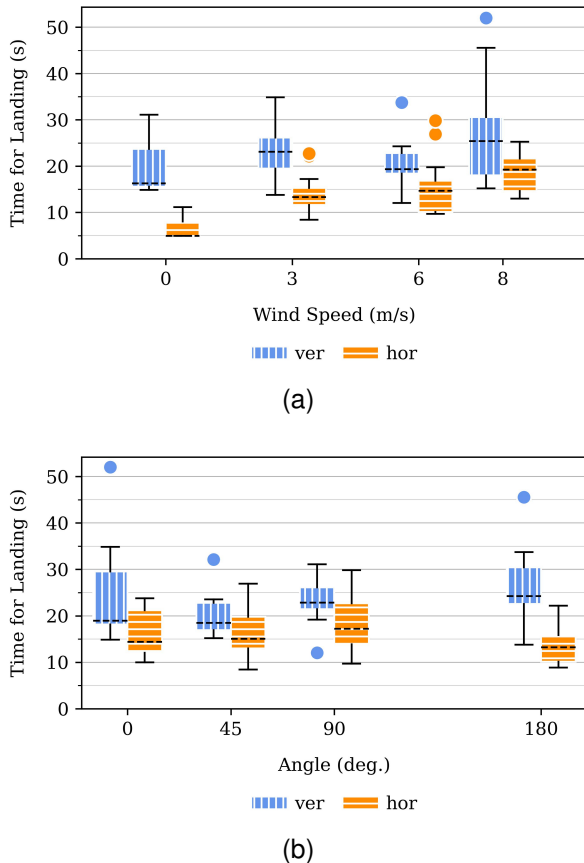


Fig. 8. Summary of the effects of various wind conditions on *time for landing*. (a) effects of wind speed, $n = 3$ for the 0 m/s condition, and $n = 12$ for the others. (b) effects of wind type, $n = 9$.

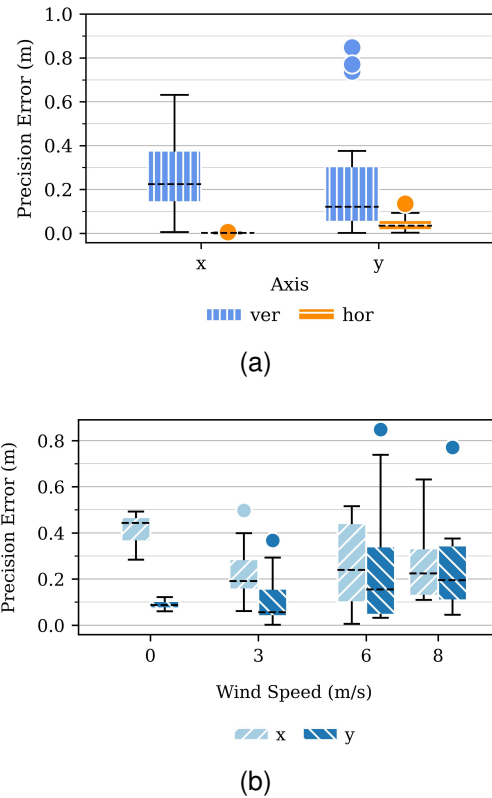


Fig. 9. Landing precision results denoting the error between the final position of the quadrotor and the target landing position. (a) precision error on the xy -plane for both landing strategies, $n = 39$ for each box. (b) effects of wind speed on precision error for vertical landing. $n = 3$ for the 0 m/s condition, and $n = 12$ for the others.

landing compared to vertical landing. Regarding variation, IQR values were 0.23 m and 0.25 m for the vertical landing, and 0.01 m and 0.14 m for the horizontal landing. Overall, the EAGLES port contributed to a lower precision error upon landing.

To further explore the precision error results for vertical landing, the most affected approach, we assess the effects of wind speed on precision (see Fig. 9b). The average errors in the x-axis were 0.44 m, 0.19 m, 0.24 m, and 0.22 m for wind speed settings of 0 m/s, 3 m/s, 6 m/s and 8 m/s, respectively. For the y-axis, they were 0.09 m, 0.06 m, 0.15 m, and 0.20 m. As for variation, the vertical landing approach displayed IQR values of 0.10 m, 0.13 m, 0.34 m, and 0.20 m in the x-axis, and values of 0.03 m, 0.12 m, 0.30 m, and 0.24 m in the y-axis. Investigating the ranges more closely, the 6 m/s condition displayed a broader spread of data in both axes, while the 0 m/s condition showed tightly clustered data, as evidenced by the IQR values.

B. Characterizing the Motion of Landing Drones

1) *Position:* The time-series data of position error in the x, y, and z axes during the drone's landing maneuver is presented in Fig. 10. Time is given in a reverse chronological order to simplify comparison, with $t = 0$ s denoting the instant of touchdown. The plot's starting time, -20 s, was chosen from

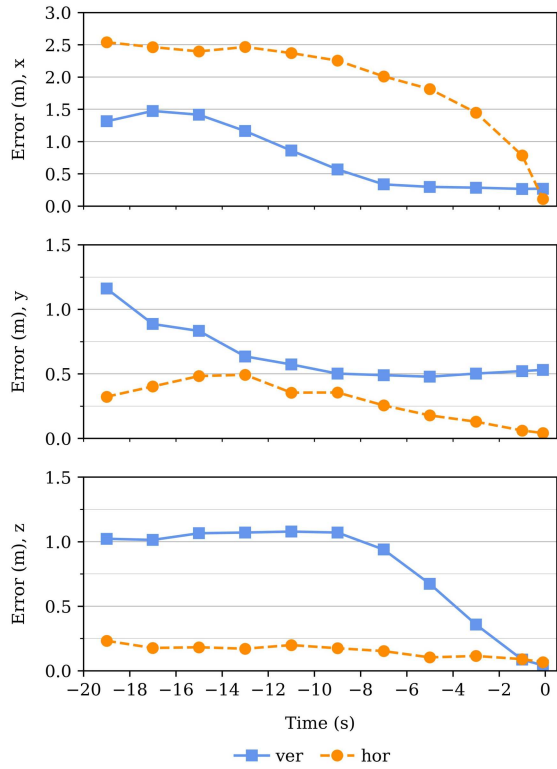


Fig. 10. Position error along the x, y, and z axes. Binned values represent the average error across multiple experiments, highlighting the trends for each landing approach. Axis errors are relative to the target landing positions.

visual inspection of the error plots to ensure that the analysis focuses on the interval where meaningful trends begin.

Assessing the position error in the x-axis, the vertical landing approach begins with an error of approximately 1.31 m at $t = -20$ s. The error decreases gradually over time, stabilizing around 0.27 m at $t = 0$. The initial x-axis error for horizontal landing is higher, starting near 2.54 m at $t = -20$ s and remaining rather constant until $t \approx -8$ s. After this point, the error decreases significantly, reaching near-zero value (0.11 m) at touchdown. As for the y-axis, the vertical approach starts with a higher error of approximately 1.16 m. The error gradually decreases and stabilizes near 0.53 m at $t \approx -10$ s, and remains unchanged until touchdown. The initial y-error resulting from horizontal landing is lower, nearly 0.32 m. The error shows some fluctuations, but eventually starts decreasing over time, reaching a near-zero value (0.04 m) at $t = 0$ s. Along the z-axis, vertical landing begins with an error of about 1.02 m, and it remains steady up to $t \approx -8$ s, from which it decreases almost linearly, converging to roughly zero (0.04 m) at $t = 0$ s. Lastly, starting at about 0.23 m, the z-error for horizontal landing remains consistent throughout landing, approaching a near-zero value (0.07 m) at touchdown.

2) *Velocity*: The average velocity of drones during landing is summarized in Fig. 11a using boxplots. Drones employing the vertical landing approach exhibit an average velocity of 0.13 m/s and an IQR of 0.06 m/s, while those using the

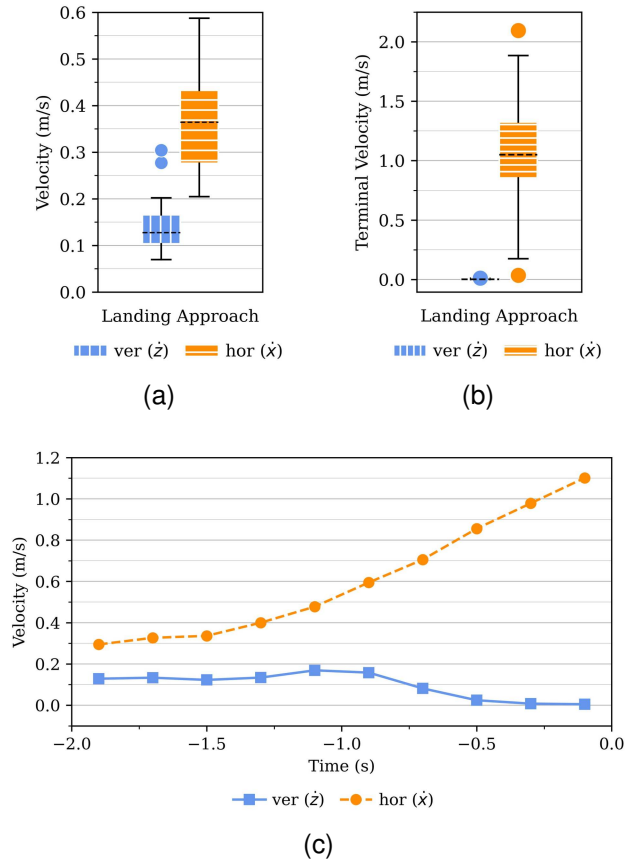


Fig. 11. Velocity statistics. (a) summary of velocities during the whole landing phase. (b) velocity profiles moments prior to touchdown. (c) boxplots of terminal velocities ($t = 0$ s) for each landing approach.

horizontal landing approach demonstrate a higher average velocity of 0.36 m/s with an IQR of 0.16 m/s.

To further analyze the landing process, the velocity profiles of drones are depicted in Fig. 11c for each landing approach. In the figure, time is presented in a reverse chronological order, with $t = 0$ s marking the instant drones landed. Plotting begins at $t = -2$ s because both landing techniques exhibited minor velocity fluctuations prior to this point. In the plot, vertical landing shows an initial velocity of 0.13 m/s, while horizontal landing of 0.29 m/s. From the -2 s mark, the descent velocity of vertically landing drones remains relatively constant up to the -1 s mark, from which it gradually decreases to zero. In contrast, when landing horizontally, drones' longitudinal velocity steadily increases, reaching an average value of 1.10 m/s right before docking.

Fig. 11b provides a summary of the terminal velocities through boxplots. Vertical landing results in zero average velocity and no variation, whereas horizontal landing produces a significantly higher average velocity of 1.05 m/s and a variation of 0.47 m/s. Moreover, both approaches exhibit outliers, indicating occasional deviations from these trends.

3) *Trajectory*: Trajectory heatmaps are displayed in Fig. 12. Assessing the vertical landing heatmaps, we observe that

the patch on the xz -plane has a broad irregular shape, with data points spreading across a larger area and forming a L-shaped pattern. In turn, the patch for horizontal landing has a more compact, elongated (wide but short) shape, with data points densely organized in a smaller region. In the vertical plot, density is mild in the central region of the patch around $(1, 0.5)$, from which it spreads out covering a wider area. The horizontal plot has one high-density cluster located at its center, around the coordinates $(-1.5, -0.5)$, with a strong peak and less spread in comparison. From the peak, density fades quickly as it moves away from the center. Another mild-density cluster is located about $(0.5, -0.5)$, where the gate is located.

On the xy -plane, the heatmap for the vertical method shows that data points are more clustered around the coordinate $(1, 1)$. This region has the highest concentration of points, and it quickly decreases along most directions, taking on a shape that resembles a water drop. The shape of the heat patch from horizontal landing trajectories is similar to that of the xz -plane, but even more compact. Color intensity is more evenly distributed, without any peaks, with data points enclosed in a smaller region compared to the vertical approach.

On the yz -plane, the heat pattern from vertical landing has a slender (tall but thin) shape, with approximately 1.5 m of height and 0.5 m of width, while the pattern from horizontal landing has a circular shape with a diameter of roughly 0.5 m. The density of the slender patch is low, with a lightly-populated cluster at $(1, 1)$. The horizontal cluster, however, features a high-density cluster with a clear gradient. The highest values are located at its center, $(0.5, -0.5)$, which rapidly decreases towards the periphery like a bullseye.

IX. DISCUSSIONS

A. Comparing the Performance of Docking Strategies

1) *Time for landing*: The EAGLES port is designed to consistently reduce UAV landing duration, and it effectively achieves this goal. Comparing the *time for landing* results in Fig. 7, it becomes apparent that the horizontal approach enables faster landings than the vertical approach. Numerically, the horizontal approach displayed a 35.58% decrease in the average landing duration of drones while maintaining a similar variation to that of the vertical approach. Moreover, with $p < 0.05$, the Mann-Whitney U test allows us to reject the null hypothesis (H_0), indicating a statistically significant difference in *time for landing* between the horizontal and vertical landing techniques.

The results also show that the EAGLES port has a margin to substantially increase the number of drone landings within a comparable time frame. In our experiments, the operators piloted drones with an off-the-shelf controller, and when using the EAGLES port, they were able to perform landing in a time as short as 4.86 s. This result is 59.67% faster than the shortest obtained through the vertical approach, which was 12.05 s. Assuming an autonomous navigation system that can consistently perform 4.86-second horizontal landings, and that drones only start docking after the preceding vehicle has

landed, we can estimate that the EAGLES port would enable approximately 12 landings in the time span of a minute. In the same scenario, the vertical approach would allow for only 4 landings.

Moreover, the histograms show that both strategies exhibited bimodal distributions, suggesting that each set of data likely represents two distinct subgroups. One subgroup might correspond to successful landings in which the operator performed the task with precise drone control, while the other subgroup could represent cases where the operator faced challenges when trying to land the drone. As the peaks are more evident in the horizontal distribution, it suggests that this approach has the potential to cater more consistent and faster landings if operators are provided with training or if an autonomous landing system is in charge of docking the vehicles. Nonetheless, further investigation is required to confirm these assumptions and understand their implications on landing duration.

Lastly, outliers suggest that touchdown dynamics is less affected by wind conditions when landing in the EAGLES port. Outliers in the vertical landing data, depicted in Fig. 7, correspond to events where the operator had to regain control of the drone after a missed landing due to strong winds. These outliers occurred under 8 m/s settings, specifically in the headwind and tailwind conditions. When the drone approached the landing platform, the operator had to reduce the vehicle speed to fine-tune its position. This reduction in speed potentially made drones more vulnerable to wind disturbances, driving them away from the landing zone. As the horizontal approach eliminates the need for deceleration at touchdown, drones stayed near the gate even after a missed attempt, enabling prompt retries.

2) *The effects of wind speed*: Horizontal landing allowed operators to dock drones faster than the traditional method through varying wind speed conditions. As shown in Fig. 8a, the average time required for landing drones using the horizontal approach was shorter than that of the vertical approach across all wind speeds. In addition, the average time for horizontal landing increased steadily with stronger speed conditions, suggesting predictable behavior aligned with environmental changes. Differently, vertical landing did not exhibit a consistent trend, indicating its response to varying wind conditions is more irregular. Furthermore, a similar trend was observed in the variation, which was also predominantly lower for the horizontal approach. This consistent behavior suggests that the EAGLES port, with its horizontal landing approach, enables more standardized and predictable landings across various wind speed conditions, potentially simplifying the design of autonomous flight systems.

Despite providing shorter landing duration, the EAGLES gate mechanism requires further design improvements. The outliers manifested when landing horizontally were usually a result of the operator's struggle to properly guide the drone into the entry gate, leading to miss landings. The operator would then try to remedy the situation by moving the drone away from the EAGLES port, regaining control, and making other landing attempts until it was successful. Still, the faster

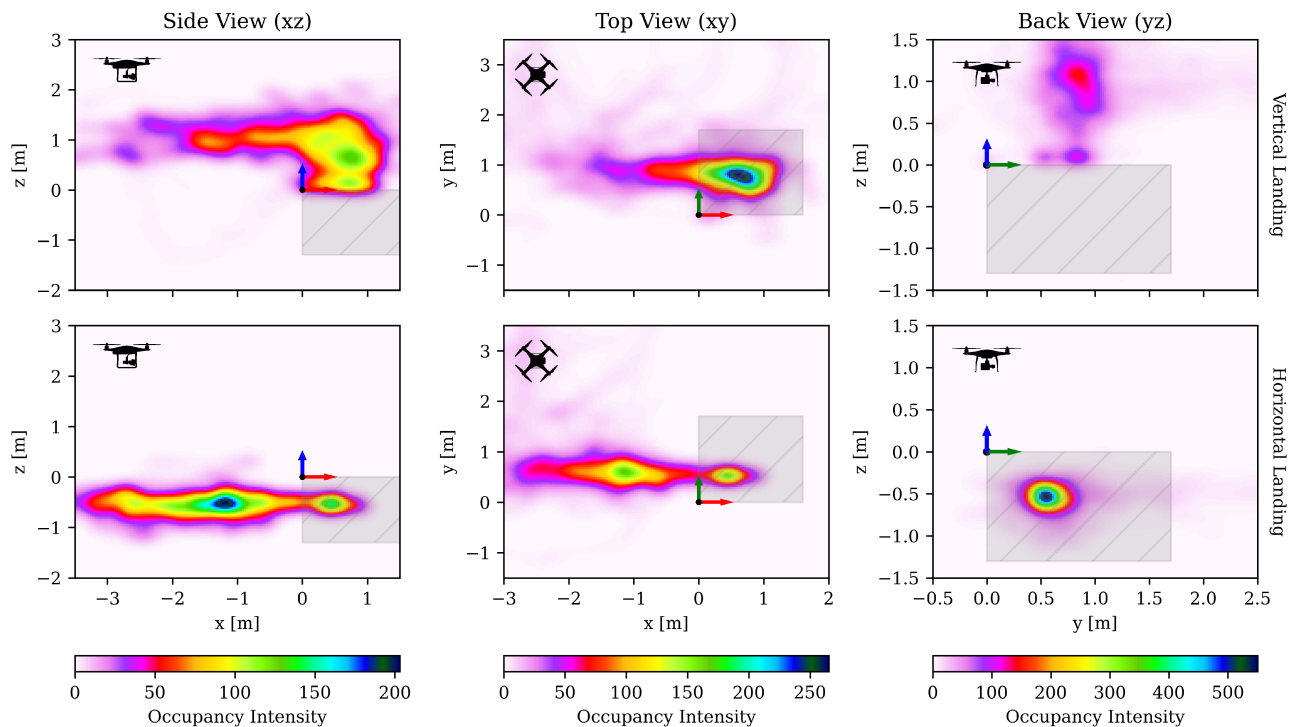


Fig. 12. Occupancy heatmaps from trajectory data projected on three different planes. Occupancy intensity was kept the same for similar planes to allow comparisons. The hatched, gray rectangles represent the EAGLES port and drone icons are visual cues to ease interpretation of each projection.

landing and lower variation provided by the EAGLES port can reduce drone downtime, allowing for more frequent missions. This efficiency can be particularly valuable in high-demand scenarios, such as package delivery and drone light shows.

3) *The effects of wind type:* When challenged with different types of wind, operators were able to land drones quicker with horizontal landing. The boxplots in Fig. 8b showed that, regardless of wind type, average landing duration was systematically lower with horizontal landing. Moreover, these averages remained consistent, indicating that the time required for landing drones is not significantly affected by wind type when employing the horizontal approach. When operators landed drones vertically, crosswind and tailwind conditions had a greater impact on vertical landing duration. This suggests that vertical landing is more influenced by wind type, potentially affecting its reliability in varying environmental conditions.

Furthermore, the lower variation in the data indicates that vertical landing is more time-consistent in quartering wind and crosswind scenarios, while horizontal landing performs better in headwind and tailwind conditions. However, the presence of outliers in the vertical landing distributions implies that the achieved consistency may not be as robust as it seems. In contrast, horizontal landing displayed no outliers, and variation was generally similar between the distributions, except for the tailwind condition. Under this condition, the horizontal approach showed lower variation, likely because the wind aligned with the landing direction, helping operators focus on

lateral alignment while the wind assisted forward motion. Nevertheless, further investigation would be needed to determine the specific factors contributing to these results and to assess the practical reliability of vertical landing subject to varying types of wind. Overall, the reduced and consistent landing duration provided by horizontal landing can enable better fleet coordination, especially in situations where multiple drones share one, or a limited number of docking stations in varying environmental conditions.

4) *Precision:* Docking precision is nearly optimal with horizontal landing but remains a challenge with vertical landing. When comparing the precision results in Fig. 9a, drones performing horizontal landing consistently exhibited better alignment with the target at touchdown, as evidenced by the lower average error and variation in precision compared to vertical landing. These finds indicate that the horizontal approach outperforms the traditional method in landing accuracy, and improves precision landing capabilities of multirotors. Such advantages ease the integration of landed drones with other systems, and reduce downtime by eliminating the need for realignment mechanisms, which are required by many stations. Results also showed that, even with a large landing area available (1.7 m x 1.6 m), the operators would occasionally land drones far from the target position. This resulted in outliers, suggesting that precision landing for the vertical approach can be challenging, and lead to uncertainty about the position of landed drones. In general, applications requiring drones to land in small, restricted entryways, such as building

and car windows, or with strict alignment requirements, would benefit from the more precise horizontal approach. In contrast, applications that do not require precision landing, or have a large landing area benefit from the significantly cheaper vertical landing approach.

When performing vertical landing, a trade-off emerges between landing duration and accuracy, which can hinder stations from handling multiple drones. Assessing the effects of wind speed on precision error for vertical landing (Fig. 9b), we are able to understand some unusual *time for landing* results. When discussing the effects of wind speed on *time for landing* (Fig. 8a), the 6 m/s condition led to quicker landings compared to the 3 m/s condition, which is counter intuitive. However, examining the precision results for the 6 m/s setting, we observed higher error and variation in the data compared to the 8 m/s setting, a rougher wind condition. This suggests that faster landing might be associated with lower precision when docking vertically. Since the EAGLES port improves accuracy, the promotion of faster landing is one of the few concerns of operators. This is likely a factor that contributed to the lower *time for landing* results from the horizontal approach in nearly all experimental conditions.

B. Motion Characteristics Underlying Landing Performance

1) *Position*: The position error results show that the horizontal approach simplifies the operator's landing task, making docking more efficient and reliable. At the beginning of the plots in Fig. 10, drones are generally misaligned with the target when using vertical landing, with the x, y and z errors being slightly large. Then, throughout the first-half of the evaluated interval, drone altitude (z-error) remains practically unchanged while the operator adjusts the drone's position on the *xy*-plane, as indicated by the fluctuations in the x and y errors. When these two converge, usually to non-zero values, the operator lowers the drone's altitude, decreasing the z-error. At the end, the operator levels the drone with the target, reaching a near-zero error along the z-axis. This behavior suggests that alignment on the *xy*-plane is carried out while keeping a vertical distance from the target. Therefore, vertical landing involves aligning the drone's position on the *xy*-plane, followed by alignment along the z-axis, with guaranteed precision limited to the z-axis.

In comparison, the operator achieves better lateral and vertical alignment sooner with the horizontal approach, as evidenced by the initially small errors in the y and z axes. The longitudinal distance between the drone and the target (x-error) starts high, and stays relatively the same while the operator makes small adjustments to the drone's lateral position, as indicated by the small fluctuations in the y-error. When the lateral position is fairly aligned, the operator lands the drone by moving it forward, decreasing the x-error. In the evaluated interval, no major changes are made to the drone's altitude (z-error), as it is generally low. Unlike the vertical approach, position errors converge to near-zero values along all axes, indicating that drones successfully reach the target location. Therefore, horizontal landing mostly involves aligning the

drone's position in the y-axis, followed by alignment along the x-axis, with guaranteed precision in all three axes, and better alignment sooner.

These motion characteristics suggest that horizontal landing simplifies the operator's task compared to vertical landing. Horizontal landing focuses primarily on handling the lateral position of the UAV, whereas vertical landing demands simultaneous handling of multiple axes. This makes horizontal landing more efficient and potentially less prone to error during manual control, an advantage that is likely transferable to autonomous operations. Moreover, these characteristics demonstrate that horizontal landing induces better alignment throughout the entire landing phase. The vertical approach, however, often shows larger errors and more fluctuations, continuously requiring major handling as the drone nears the target. In summary, horizontal landing may be more reliable for high-precision applications, while vertical landing remains suitable for operations where larger landing areas are available.

2) *Trajectory*: Horizontal landing offers greater flight stability than vertical landing while docking. In Fig. 12, we compared drone trajectories using heatmaps with projections on different planes. Vertical landing usually formed broader and less-dense clusters, indicating more instability in the position of the drone. This can be interpreted as the UAV often drifting from the operator's intended path, likely due to wind disturbances, and the operator intervening to adjust the UAV position. In contrast, clusters from horizontal landing drones were generally compact and dense, indicating a narrower range of movement compared to the vertical case. This lower variability in the drone's trajectory suggests a more stable or consistent flight, highlighting the benefits of horizontal over vertical landing when it comes to landing stability. The higher stability provided by the horizontal method may have allowed the operator to land drones more quickly, resulting in the shorter landing durations observed in the performance analysis section.

As the heatmaps incorporate data from different wind conditions, it indicates that horizontal landing is more stable across various wind conditions compared to vertical landing. Moreover, we acknowledge that the high-density cluster in the *xz*-plane for horizontal landing can be a bottleneck of this approach, and optimization around this region could be the focus of future studies to promote even faster landings.

3) *Velocity*: The horizontal approach enables drones to maintain higher velocity throughout the landing phase. The boxplots in Fig. 11a summarized the overall velocity of drones during landing, and they suggest that the vertical approach typically leads to slower docking, as evidenced by its low average velocity. Besides, the lower variability indicates that vertical landing is naturally bounded to lower speeds, potentially a consequence of the required controlled descent. Horizontal landing, on the other hand, induces higher velocities throughout landing, being on average 2.8 times faster than vertical landing, and displays higher variability. This suggests that the horizontal approach is less constrained in terms of velocity, allowing drones to assume higher velocities during

landing. We can thus infer that vertical landing is better suited for applications where speed is less critical, while horizontal landing is more appropriate for operations requiring high-speed performance.

Another critical difference from vertical landing is that horizontal landing drones can assume a wide variety of terminal velocities at touchdown. As shown in Fig. 11b, horizontal landing results in higher average velocities and greater variation, while vertical landing leads to next-to-zero terminal velocities. This aligns with expectations and highlights the inherent property of the vertical approach: the relative velocity between the UAV and its target is minimized at touchdown. This inherent property makes vertical landing more suitable for applications involving direct human interaction, where lower terminal speeds make the drone's behavior more predictable, enhancing user safety. In contrast, the flexibility of horizontal landing allows the EAGLES port to accommodate drones arriving at different speeds, making it particularly advantageous for industrial applications.

The velocity profile results suggest that the key difference between the two landing approaches lies in how the velocity of drones evolves over time. As shown in Fig. 11c, vertical landing features a gradual decrease in descent velocity, which stabilizes at zero upon landing. In contrast, horizontal landing is characterized by a steady increase in longitudinal velocity, stabilizing at a non-zero terminal value. These profiles reflect the more dynamic nature of horizontal landing and highlight the contrasting objectives of the two approaches. Vertical landing prioritizes safety, achieving minimal relative motion at the moment of landing. On the other hand, horizontal landing focuses on speed and throughput, which can translate into faster docking and better integration with dynamic systems, such as moving platforms. The data thus reinforce the efficiency advantage of horizontal landing in scenarios where speed and adaptability are critical.

In general, these findings emphasize why vertical landing is often the go-to approach for the general public and why horizontal landing should be the go-to approach for many industrial applications. Moreover, these results stress the importance of the EAGLES gate mechanism in compensating for the more dynamic behavior of horizontal landing.

C. Qualitative observations from multi-drone experiments

Unlike conventional drone docking stations, the EAGLES port allows sequential landing of multiple drones at a single target location. In the experiments, operators were able to land three to five drones in the EAGLES port several times, performing 25 trials, from which 21 were successful. Three-drone trials would often end within a minute, while five-drone trials would often end within two minutes. As shown in Fig. 13, a video frame from the multi-drone experiments illustrates the five-drone trial. In addition, when further assessing the recordings, intervals lower than 10 s were observed in between drone landings. Considering that three out of five operators were new to horizontal landing, these intervals and the total

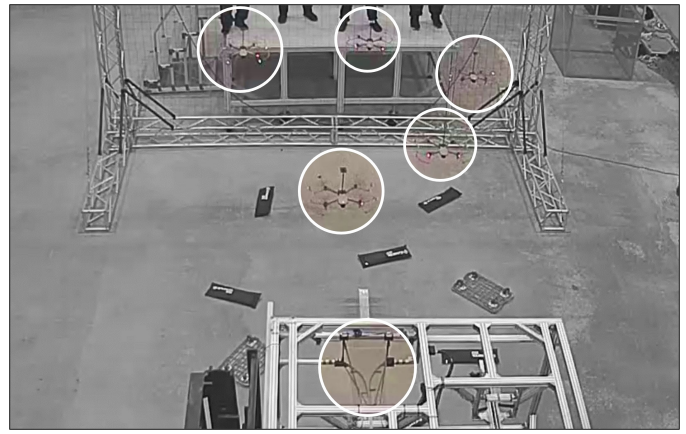


Fig. 13. Video frame from a multi-drone experiment showcasing five different drones hovering in front of the EAGLES port preparing for landing.

landing duration could likely be reduced further with experience or automation.

While these results confirm the EAGLES port's ability to handle several multirotors efficiently and guide them to the hanging rail system, they lack robust quantitative data for a detailed comparison between landing strategies (as performed for the single-drone case). To perform a comprehensive evaluation, additional data from multi-drone experiments are required. This data should then be thoroughly assessed using similar tools and methods described in this study. Still, these observations demonstrate that the EAGLES port effectively fulfills its design purpose for sequential drone landings.

D. Considerations on energy consumption

Energy consumption is a key factor limiting the widespread adoption of drones, primarily due to constraints in current battery technologies. Understanding how vertical and horizontal landing affects energy use is crucial for validating the EAGLES port as an efficient solution for multi-drone operations. While a thorough energy analysis is left for future research, this study initiates the discussion with the following considerations.

When studies evaluate the energy consumption of multirotor drones, flight is usually categorized into four stages: take-off, (vertical) landing, cruising and hovering. While vertical landing is usually modeled as a continuous smooth descent, in practice, it often involves brief hovering, especially for precision landing [26]. Studies commonly conclude that even short hovering periods during landing can have a significant toll on battery life [22], and that low-speed cruising is more energy efficient than hovering [45]. Based on the previous trajectory and velocity analyses, it is reasonable to assume that horizontal landing shares more characteristics with low-speed cruising than with hovering or vertical landing. This suggests that horizontal landing could provide a modest improvement in battery life, as it benefits from the higher efficiency of low-speed cruising while relying less on hovering. Therefore, any time saved during landing would directly extend flight time.

IEEE Robotics & Automation Magazine (RAM) paper, presented at ICRA 2026, Vienna, Austria. Cite as RAM paper.

Energy savings from horizontal landing could be even greater, as it reduces challenges associated with the aircraft landing problem. Drones can land in the EAGLES port at the same spot with shorter intervals than vertical landing ports, minimizing hover time. Naturally, this disadvantage of vertical landing ports could be addressed by either increasing the number of landing pads or implementing a mechanism to clear drones from the landing zone. However, the former would enlarge the station's footprint, while the latter might increase hover time for incoming drones. While this remains to be proven, future research should focus on quantitatively assessing this claim to provide a clear understanding of energy consumption between landing methods.

X. CONCLUSIONS

Traditional drone docking stations with their vertical landing approach lack the flexibility to enable rapid and accurate landing of multiple drones, especially in varying weather conditions. This work introduces the EAGLES port, and its novel horizontal landing approach for multirotor UAVs. Then, by testing the effects of wind speed and wind type on drone landing performance, this study provides a robust empirical analysis comparing the standard vertical landing approach, employed by most docking stations, and the horizontal approach from the EAGLES port.

Our findings reveal that horizontal landing drones require, on average, 35.58% less time for docking than vertical landing drones. Moreover, operators consistently landed drones faster with the horizontal approach across all experimental wind conditions. In ideal circumstances, horizontal landing was up to 59.67% faster than vertical landing, highlighting the system's potential for further performance improvements. Additionally, docking precision with horizontal landing was nearly optimal, whereas precision remained a challenge with the vertical approach. Precision results also suggest a trade-off between speed and precision for vertical landing, making it difficult to achieve both simultaneously. Furthermore, we demonstrated the system's ability to support sequential landings of multiple aerial vehicles. These findings stress the potential of the EAGLES port as a robust solution for enhancing precision, stability, and efficiency of UAV landings in diverse wind conditions, reinforcing its viability for practical single and multiple UAV operations.

The main drivers of these performance results are identified as follows: First, the horizontal approach ensures landing precision along all three axes at touchdown and results in quicker alignment with the target landing position. Second, this approach provides greater flight stability, making the docking process more efficient and reliable. Lastly, horizontal landing drones sustain on average 2.8 times the velocity of vertical landing drones throughout the landing phase, and accommodate a wider range of terminal velocities at touchdown. Together, these factors simplify and speed up the operator's task, leading to faster landings and optimal precision.

In general, our findings offer several practical recommendations. Vertical landing is better suited for environments with

wider landing zones and missions where delays in landing will not cause major consequences. Also, its simpler setup makes it a more cost-effective option for a wide range of applications. In contrast, horizontal landing prioritizes speed, throughput and precision, enabling faster docking and seamless integration with dynamic systems, such as moving platforms. Additionally, the faster docking capabilities of horizontal landing can reduce fleet downtime, improving throughput of drone ports, and making it ideal for large-scale logistics operations.

As for future work, we aim at optimizing the entry gate's design to ease drone access into the EAGLES port and develop an autonomous horizontal landing system. This system will be used to assess the EAGLES port when drones are operated by state-of-the-art landing algorithms. We also aim at performing more robust multi-drone experiments to assess the concrete advantages of the EAGLES port for multi-drone applications in a quantitative fashion.

ACKNOWLEDGMENTS

This research was supported by METI FY 2022 International Research and Education Hub Promotion Project - Exploratory Research on Robots and Drones Aligned with the Basic R&D Plan for New Industries (No.20221025).

REFERENCES

- [1] H. Eskandaripour and E. Boldsaihan, "Last-mile drone delivery: Past, present, and future," *Drones*, vol. 7, no. 2, p. 77, 2023.
- [2] M. Ayamga, S. Akaba, and A. A. Nyaaba, "Multifaceted applicability of drones: A review," *Technological Forecasting and Social Change*, vol. 167, p. 120677, 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0040162521001098>
- [3] J.-P. Aurbout, K. Gkoumas, and B. Ciuffo, "Last mile delivery by drones: An estimation of viable market potential and access to citizens across european cities," *European Transport Research Review*, vol. 11, no. 1, pp. 1–21, 2019.
- [4] Amazon. (2023) Amazon is launching ultra-fast drone deliveries in Italy, the UK, and a third location in the U.S. [Online]. Available: <https://www.aboutamazon.com/news/operations/amazon-prime-air-drone-delivery-updates>
- [5] K.-C. Weng, S.-T. Lin, C.-C. Hu, R.-T. Soong, and M.-T. Chi, "Multi-view approach for drone light show," *The Visual Computer*, pp. 1–12, 2022.
- [6] S. J. Kim, Y. Jeong, S. Park, K. Ryu, and G. Oh, *A Survey of Drone use for Entertainment and AVR (Augmented and Virtual Reality)*. Cham: Springer International Publishing, 2018, pp. 339–352. [Online]. Available: https://doi.org/10.1007/978-3-319-64027-3_23
- [7] B. Mishra, D. Garg, P. Narang, and V. Mishra, "Drone-surveillance for search and rescue in natural disaster," *Computer Communications*, vol. 156, pp. 1–10, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0140366419318602>
- [8] R. Tariq, M. Rahim, N. Aslam, N. Bawany, and U. Faseeha, "Dronaid : A smart human detection drone for rescue," in *2018 15th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT (HONET-ICT)*, 2018, pp. 33–37.
- [9] D. H. Lyon, "A military perspective on small unmanned aerial vehicles," *IEEE Instrumentation & Measurement Magazine*, vol. 7, no. 3, pp. 27–31, 2004.
- [10] K. Kuru, D. Ansell, W. Khan, and H. Yetgin, "Analysis and optimization of unmanned aerial vehicle swarms in logistics: An intelligent delivery platform," *IEEE Access*, vol. 7, pp. 15 804–15 831, 2019.
- [11] M. Abdelkader, S. Güler, H. Jaleel, and J. S. Shamma, "Aerial swarms: Recent applications and challenges," *Current robotics reports*, vol. 2, pp. 309–320, 2021.
- [12] C. Ju and H. I. Son, "Multiple uav systems for agricultural applications: Control, implementation, and evaluation," *Electronics*, vol. 7, no. 9, p. 162, 2018.

IEEE Robotics & Automation Magazine (RAM) paper, presented at ICRA 2026, Vienna, Austria. Cite as RAM paper.

- [13] G. Jeremiah, J. Z. Thomas, and C. Doug, "Teal group predicts worldwide civil uav spending of \$139 billion over the next decade in its 2022/2023 uav market profile and forecast - teal group," Nov 2022, retrieved August 19, 2023, from <https://tealgroup.com/index.php/pages/press-releases/75-teal-group-predicts-worldwide-civil-uav-spending-of-139-billion-over-the-next-decade-in-its-2022-2023-uav-market-profile-and-forecast>.
- [14] C. H. Choi, H. J. Jang, S. G. Lim, H. C. Lim, S. H. Cho, and I. Gaponov, "Automatic wireless drone charging station creating essential environment for continuous drone operation," in *2016 International Conference on Control, Automation and Information Sciences (ICCAIS)*, 2016, pp. 132–136.
- [15] Y. Yu, S. Lee, J. Lee, K. Cho, and S. Park, "Design and implementation of wired drone docking system for cost-effective security system in iot environment," in *2016 IEEE International Conference on Consumer Electronics (ICCE)*, 2016, pp. 369–370.
- [16] DJI. (2023) DJI Dock: Automated drone hangars. [Online]. Available: <https://enterprise.dji.com/jp/dock>
- [17] Skydio. (2023) Skydio dock and remote OPS. [Online]. Available: <https://www.skydio.com/skydio-dock/>
- [18] C. G. Grlj, N. Krznar, and M. Pranjic, "A decade of uav docking stations: A brief overview of mobile and fixed landing platforms," *Drones*, vol. 6, no. 1, p. 17, 2022.
- [19] D. Aláez, X. Olaz, M. Prieto, J. Villadangos, and J. Astrain, "Vtol uav digital twin for take-off, hovering and landing in different wind conditions," *Simulation Modelling Practice and Theory*, vol. 123, p. 102703, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1569190X22001721>
- [20] E. Ranquist, M. Steiner, and B. Argrow, "Exploring the range of weather impacts on uas operations," in *18th Conference on Aviation, Range and Aerospace Meteorology*, Seattle, WA, 2017.
- [21] T. K. Venugopalan, T. Taher, and G. Barbastathis, "Autonomous landing of an unmanned aerial vehicle on an autonomous marine vehicle," in *2012 Oceans*, 2012, pp. 1–9.
- [22] T. Kirschstein, "Comparison of energy demands of drone-based and ground-based parcel delivery services," *Transportation Research Part D: Transport and Environment*, vol. 78, p. 102209, 2020.
- [23] D. Fujikura, K. Tadakuma, M. Watanabe, Y. Okada, K. Ohno, and S. Tadokoro, "Toward enabling a hundred drones to land in a minute," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020, pp. 1238–1245.
- [24] J. K. Luers and J. B. Reeves, "Effect of shear on aircraft landing," NASA, Tech. Rep., 1973.
- [25] S. C. De Silva, M. Phlernjai, S. Rianmora, and P. Ratsamee, "Inverted docking station: A conceptual design for a battery-swapping platform for quadrotor uavs," *Drones*, vol. 6, no. 3, p. 56, 2022.
- [26] X. Sun, M. Zhang, D. Li, and M. Li, "A mobile uav hangar design for transmission line inspection," in *2024 3rd International Conference on Smart Grids and Energy Systems (SGES)*, 2024, pp. 234–238.
- [27] DJI. (2025) DJI Dock 3: Taking on a Tough Challenge. [Online]. Available: <https://enterprise.dji.com/jp/dock-3>
- [28] Hextronics. (2025) Universal: World's most compact and efficient drone nest. [Online]. Available: <https://hextronics.com/universal>
- [29] Hextronics. (2025) Atlas: Industrial grade, battery swapping drone nest for high performance payload UAS. [Online]. Available: <https://hextronics.com/atlas>
- [30] Percepto. (2025) Industrial-grade, weatherproof, and robust drone docking station. [Online]. Available: <https://percepto.co/drone-in-a-box/percepto-base/>
- [31] J-inSPACE. (2025) DroneSAT now fully operational (translated). [Online]. Available: <https://j-inspace.com/jp/product/dronesat.html>
- [32] Skycharge. (2025) Fly any drone. Anywhere. Anytime. [Online]. Available: <https://www.skycharge.de/drone-box-hangar>
- [33] Hive. (2022) Autonomous drone solutions: fully automated droneport for regular monitoring. [Online]. Available: <https://hive.aero/>
- [34] Airobotics. (2024) Optimus: fully automated drone system. [Online]. Available: <https://www.airoboticsdrones.com/optimus/>
- [35] Heishatech. (2025) DPort multi-drone docking airport. [Online]. Available: <https://www.heishatech.com/dport-multi-drone-docking-airport/>
- [36] S. M. A. Husain and J. R. Allen. (2017) Stackable unmanned aerial vehicle (UAV) system and portable hangar system. [Online]. Available: <https://patents.google.com/patent/US10322820B2/en>
- [37] V. M. Gonçalves, R. McLaughlin, and G. A. S. Pereira, "Precise landing of autonomous aerial vehicles using vector fields," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4337–4344, 2020.
- [38] J. Janousek and P. Marcon, "Precision landing options in unmanned aerial vehicles," in *2018 International Interdisciplinary PhD Workshop (IIPhDW)*, 2018, pp. 58–60.
- [39] M. R. Cacan, E. Scheuermann, M. Ward, M. Costello, and N. Slegers, "Autonomous airdrop systems employing ground wind measurements for improved landing accuracy," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 6, pp. 3060–3070, 2015.
- [40] J. Wubben, F. Fabra, C. T. Calafate, T. Krzeszowski, J. M. Marquez-Barja, J.-C. Cano, and P. Manzoni, "Accurate landing of unmanned aerial vehicles using ground pattern recognition," *Electronics*, vol. 8, no. 12, p. 1532, 2019.
- [41] Markforged. (2025) Onyx. [Online]. Available: <https://markforged.com/materials/plastics/onyx>
- [42] Fukushima Robot Test Field. (2024) Unmanned aircraft facilities. [Online]. Available: https://www.fipo.or.jp/robot/en/facility-en/aerial_vehicle
- [43] A. Paris, B. T. Lopez, and J. P. How, "Dynamic landing of an autonomous quadrotor on a moving platform in turbulent wind conditions," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 9577–9583.
- [44] D. Briskorn and R. Stolletz, "Aircraft landing problems with aircraft classes," *Journal of Scheduling*, vol. 17, pp. 31–45, 2014.
- [45] M. Rahmani, F. Delavernhe, S. Mohammed Senouci, and M. Berbineau, "Toward sustainable last-mile deliveries: A comparative study of energy consumption and delivery time for drone-only and drone-aided public transport approaches in urban areas," *IEEE Transactions on Intelligent Transportation Systems*, vol. 25, no. 11, pp. 17520–17532, 2024.