

BIOINSPIRED VERTIPORT SYSTEM DESIGN FOR SUPPORTING DRONE SWARMS IN METHANE GAS DETECTION FROM ORPHANED WELLS

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ABSTRACT

The aim of this paper is to explore bioinspired vertiport designs—a hub for drones' vertical takeoff and landing (VTOL) and servicing, also referred to as a nesting station, docking station, hangar, or landing station—for drone swarms tasked with specific missions. The vertiport system design is inspired by tree structures, with branches represented by capsules that house drones. Solar panels mounted on actuators at the top of the vertiport adjust their orientation to maximize sun exposure, supplying power to the vertiport's isolated grid for continuous energy day and night. A weather station located at the top transmits data to a computing system, ensuring environmental safety for drone operations. The vertiport's key components include capsules that open and close during drone launch and landing. Each capsule is equipped with charging contacts for the drones, AprilTags to facilitate precise landing, and a mechanism to center the drone within the capsule upon closure. Designed to protect the drones from environmental conditions, these capsules feature robust structures capable of withstanding harsh weather, ensuring the drones are safeguarded inside. This design highlights the potential of bioinspired approaches in creating efficient vertiport systems.

KEYWORDS: AprilTags, bioinspiration, drones, vertiports, precision landing

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1. Introduction

Orphaned, abandoned, or inactive wells are natural oil and gas wells that have been decommissioned or left unmanaged by fossil fuel extraction companies due to low production capacity or lack of economic viability. Once a well is declared abandoned, the extraction company deactivates it. While these wells no longer produce oil or gas, they continue to emit methane into the environment. Methane, a flammable natural gas, is harmful to both the environment and human health and is a significant contributor to global warming due to its impact on the ozone layer [1].

Methane emissions from orphaned wells occur because many of these wells are left unplugged after being abandoned; plugging wells is an expensive process. It is estimated that across the United States, there are approximately 2.15 million unplugged orphaned wells still releasing methane and carbon dioxide, with an annual emission rate equivalent to 7.11 million metric tons. This amount of greenhouse gas is comparable to the emissions produced by 1.54 million vehicles running for a year [2]. To address this issue, the US Department of the Interior allocated US\$4.7 billion in January 2022 to plug orphaned wells across the country [3]. However, climate-focused think tanks estimate that fully plugging all documented orphaned wells in the US could cost around US\$280 billion [4]. Given the high cost of the plugging process, it would be more efficient to prioritize wells that are emitting methane at the highest rates. To do this effectively, we must first identify which wells are the largest emitters at each site. This task is challenging because many orphaned wells are located in remote areas that are difficult for humans to access and can be hazardous to their health. Therefore, developing an automated process that can autonomously survey these sites and detect wells with high methane emission rates without human intervention would be highly effective. In this paper, we propose a method to identify orphaned wells with high methane emissions using a drone vertiport concept. Inspired by nature, this concept combines an autonomous vertiport system with a drone swarm [5].

The drone vertiport system supports the detection of methane emissions from orphaned wells by serving as a storage, charging, and landing hub for drones equipped with sensing tools. It also offers a valuable solution for enabling maintenance tasks in smart cities, towns, and villages [6–11]. While the emphasis of this work is on the design and functionality of the bioinspired vertiport system, the methane detection

task itself is carried out by drones equipped with appropriate sensing technologies. The vertiport facilitates these missions by providing a reliable infrastructure for drone storage, charging, and precise landing in remote or challenging environments. The concepts of smart cities and drone vertiports are closely related, as various maintenance operations in smart cities can be carried out using the autonomous drone vertiport system, reducing the need for human involvement, saving time, and lowering costs. This system is fully autonomous and powered by solar energy. The vertiports are designed to resemble tree-like structures, inspired by nature, where the drones are housed in capsules that function like tree branches, providing protection and maintenance for the drones [12].

The rest of the paper is organized as follows: Section 2 explores the role of drones in smart cities and their potential applications. Section 3 discusses the design of drone vertiports, including considerations for support systems. Section 4 focuses on the structural analysis of the drone vertiport. Section 5 examines power supply solutions for the drone vertiport. Section 6 delves into the integration of drones with vertiports, including precision landing techniques. Section 7 outlines future work and development areas. Finally, Section 8 presents the conclusions.

2. Smart Cities and Drones

The rising interest in drones for urban operations has led to significant investments due to their versatility and efficiency in tasks like traffic monitoring, parcel delivery, and farmland irrigation [13–22]. In smart cities, drones assist with surveillance, emergency responses, and firefighting, while in towns and villages, they are used for crop irrigation and livestock monitoring, showcasing their adaptability to diverse environments [6].

Beyond agriculture and recreational markets, drones are now employed in industrial site evaluations, hazard identification, structural health monitoring, wildlife surveys, and atmospheric analysis, emphasizing their role in environmental monitoring [23–27]. Additionally, drones carrying emergency equipment, such as defibrillators and fire-extinguishing canisters, have proven effective in lifesaving and first-responder operations [28, 29].

Drones are increasingly being integrated into goods delivery systems, with companies like Alphabet and Amazon leading the way. Regulatory frameworks such as the US FAA's Part 135 Air Carrier Certification and UTM (Unmanned Aircraft System Traffic Management) framework are critical for ensuring safe and efficient operations in urban airspaces [30–36]. While these regulations primarily focus on drone operations in populated areas, they also emphasize the importance of reliable infrastructure, such as vertiports, to support autonomous drone missions. Our vertiport design aligns with these regulatory requirements by providing a robust and safe system for drone storage, charging, and precise landing, enabling compliance with emerging urban airspace management standards.

2.1. Drone Support and Vertiports

Recent advancements in wired and wireless charging systems have enabled drones to recharge autonomously. Wired systems, such as contact-based charging pads, and wireless methods, including inductive power transfer and resonant coupling, eliminate the need for manual intervention [37–39]. Nesting stations like SkyX's xStation and Volatus Aerospace's AeriePort extend drone range by providing temporary housing, charging, and telemetry for operations spanning hundreds of miles. These stations also mitigate the impact of adverse weather and GPS limitations by guiding drones to safe locations [40, 41].

The current state of drone infrastructure is largely focused on singular hangars, which are designed to support individual drones. While effective for limited operations, these designs lack scalability and efficiency, especially in high-traffic environments such as smart cities or remote locations requiring large-scale drone deployments. In this paper, we aim to address this limitation by developing a bioinspired vertiport system capable of supporting multiple drones simultaneously. This approach not only optimizes space utilization but also enhances the operational efficiency of autonomous drone systems. Urban environments, however, require innovative solutions due to limited real estate and high drone traffic. Approaches like resonant wireless power systems and high-powered lasers have shown potential but are still in developmental stages [42, 43]. Companies like Amazon and DJI have proposed using existing urban infrastructure, such as lampposts and rooftops, for drone docking and charging, enabling scalable operations in densely populated areas [44–45]. Independent companies like SkyX, Volatus Aerospace, Matternet, Heisha, Hextronics, and Skycharge are also developing autonomous charging stations that serve both housing and communication purposes. Additionally, the development of larger, multi-drone hubs could provide significant benefits in smart cities by optimizing space and supporting high-volume operations [46–50].

2.2. Bioinspired Drone Vertiports

Nature offers innovative inspirations for drone vertiport designs, such as blooming flowers, bird nests, and paper wasp nests, to address challenges like environmental protection, modularity, and scalability [12]. Flower-inspired designs use petal-like capsules to encapsulate drones, providing protection from the elements and interference. Similarly, water lilies inspire floating vertiports like FlyOnE's Lilypad Elevate™, which could serve coastal or aquatic operations, although these open-top designs may be less effective at protecting drones from harsh weather conditions [51, 52]. Mobile stations inspired by carrion beetles can combine drones with unmanned ground vehicles (UGVs) for tasks like delivering packages or accessing challenging terrains, but their open structure may also expose drones to environmental elements [53]. Bird nest-inspired designs elevate drones above ground-level activity, making them ideal for urban recharging hubs while providing some degree of weather protection. In contrast, paper

wasp-inspired designs feature compact, multi-cell configurations for vertical takeoff and landing (VTOL) drones, enabling simultaneous operations and efficient cargo storage, while also offering better environmental shielding [8, 29, 54].

3. Drone Vertiport Design

Building on insights from previous designs, a novel vertiport system was developed inspired by the natural architecture of trees, with “branches” serving as suspension mechanisms for drone capsules, similar to bird nests. Solar panels mounted on actuators at the top of the structure track the sun to maximize energy capture, ensuring efficient and sustainable operations. Elevated placement protects against environmental challenges such as flooding and snow, making the design resilient in rugged conditions like the San Juan Basin (testing site), which experiences high winds, moisture, extreme heat, and dust.

To enable autonomous drone operations, the vertiport integrates contact-based charging, weather prediction systems, and a central computing unit connected to a monitoring hub. Solar panels and weather stations are positioned for optimal functionality, while power banks and computing units at the base ensure stability. The modular and portable design allows deployment at multiple sites, meeting the demands of diverse environments.

The initial test site, the San Juan Basin, required a robust structure capable of withstanding wind speeds of up to 75 mph (33.5 m/s) and harsh desert conditions. The system combines lightweight, modular construction with durability, ensuring long-term performance. The conceptual phase focused on creating a design adaptable to severe environments while maintaining functionality and portability. This resulted in a versatile solution for autonomous drone operations.

To ensure portability, the vertiport incorporates folding telescopic features, reducing its size for transport and enabling deployment by just two people. Leveraging existing solutions, a satellite tower was selected as the base for its compact storage and stable, elevated platform when deployed. This approach minimized design and fabrication time while providing a reliable foundation for integrating system components.

The system is designed and selected with a focus on simplicity and portability, employing straightforward deployment mechanisms and a lightweight yet sturdy aluminum framework. The telescopic features of the structure enable easy adjustments to both the trunk height and the base, enhancing adaptability in various environments. Initially, the design included cable winches attached to the legs, anchoring them to the top of the structure to minimize oscillation at the maximum deployment height of approximately 27 ft (8.23 m). However, to mitigate the risk of structural failure, the operational height was reduced to 20 ft (6.1 m). This adjustment not only eliminates the need for a cable system, providing clearer flight paths for the drones, but also reduces the moment arm, improving resistance to higher wind speeds.

This structure serves as an ideal foundation for integrating additional components of the design, most notably the capsule

system. The initial capsule design drew inspiration from the natural world, particularly from plants known for their endurance and adaptability.

Each design concept aimed to create a secure landing zone and sheltered housing for drones, enabling charging and protection from environmental conditions. Two concepts—the pitcher plant and fungi capsules—were prioritized for further development. The pitcher plant capsule was the first to undergo detailed design due to its straightforward fabrication and lid actuation approach. Multiple iterations led to the final version, depicted in Figure 1a, which became the first to be manufactured.

The capsule’s key feature is a dynamic platform mechanism that extends when the lids open, more than doubling the landing and takeoff areas. This design improves error tolerance for autonomous drone landings, guiding drones to the center as the lids close. The expandable platform also acts as the primary actuation mechanism for the lids, using the rigidity of the capsule shell. Figure 1b shows the CAD model and manufactured version of the expanding base mechanism.

The design features a lightweight aluminum 5052 H-32 shell, weighing 11.3 kg, with natural weather resistance. A single-motor actuation system powers the capsule, using a scissor jack mechanism to convert rotational motion from a lead screw into vertical displacement. The stepper motor and lead screw achieve a thrust capacity of 890 N, while custom components enable precise movement of the scissor jack arms. Figure 1c illustrates the actuation mechanism in open and closed states, highlighting a high-precision track that ensures level drone landings and reduces tilt risk.

Experimental trials highlighted challenges specific to this design’s actuation mechanism, particularly friction along the high-tolerance tracks used to ensure precise movement of the platform. This friction is attributed to the unique requirements of the capsule’s expanding base mechanism, which demands precise alignment and structural rigidity to function effectively. While friction is a common challenge in systems requiring high precision, the combination of dynamic loading during lid operation and the compact, lightweight construction of this design intensified the issue. To mitigate these challenges, 3D-printed adapters and graphite were applied to reduce friction, while adjustments were made to address mechanical strain and motor overload during lid descent. These observations informed the development of a second capsule concept aimed at overcoming these limitations and improving overall performance.

Despite these complexities, the fungi design also offered several potential advantages over the initial concept. These benefits theoretically included a lower drag coefficient due to its hemispherical shape, more reliable actuation, a smaller overall footprint, reduced lid volatility, enhanced weather-proofing, direct lid actuation, and optimal zones for heat sink placement. Similar to the previous design, this concept also utilized single-motor actuation.

The dynamic platform within the capsule, as depicted earlier, utilizes a tensioned sheet stretched across its “arms” to

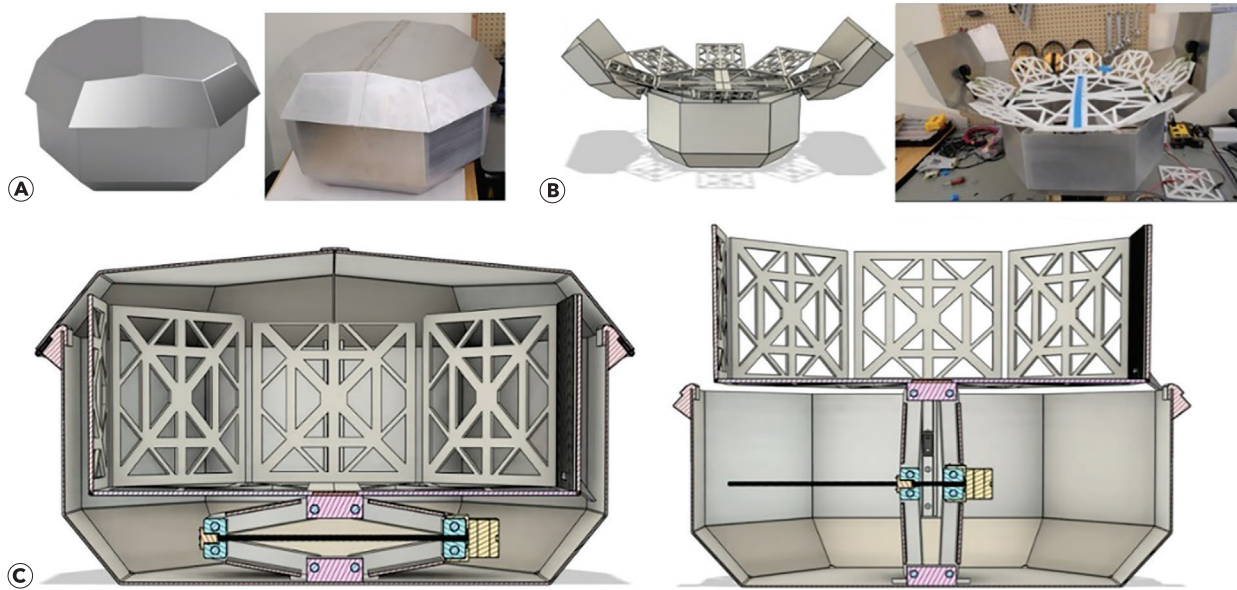


Figure 1. Views of (a) CAD model and manufactured pitcher plant capsule, (b) open state of the capsule (CAD model and manufactured), and (c) closed and open states of the capsule.

provide a landing surface surrounding the drone. This sheet, along with the walls, functions as a self-centering mechanism, similar to the previous design but with more flexible walls. The closing actuation of the capsule is particularly critical for the closing dynamic platform. Because the two opposing “Arms 1” are positioned directly within the “jaw” of the capsule lids, there is a risk of pinching during closure. Figure 2b provides a detailed overview of the capsule’s components and terminology.

To ensure precise movement of the arms, a carefully calibrated spring tension system is implemented. “Arm 1” is spring-loaded to naturally return to the closed position, as shown in Figure 2a. In contrast, “Arm 2” is tensioned to remain in the fully open position. The spring tension on “Arm 2” exceeds that of “Arm 1,” causing them to flatten, holding this

position until the capsule starts to close. During the closing process, the capsule counteracts the downward force on “Arm 2,” releasing the tension and allowing “Arm 1” to return to its closed position, causing “Arm 2” to collapse into the capsule with its adjacent arms. These arms, which are the walls, lie on the same plane as the red base acrylic. When fully open, the drone can rest anywhere and slide from one side to another without interruption. This creates a smooth, flat surface for the drone and will slant the walls upon closing, causing the drone to slide to the center.

The integration of these capsule systems into the base design is achieved through a branch system. The main telescoping trunk of the structure is equipped with four mounting brackets specifically engineered for this application. These brackets are secured to the trunk using simple fasteners, which

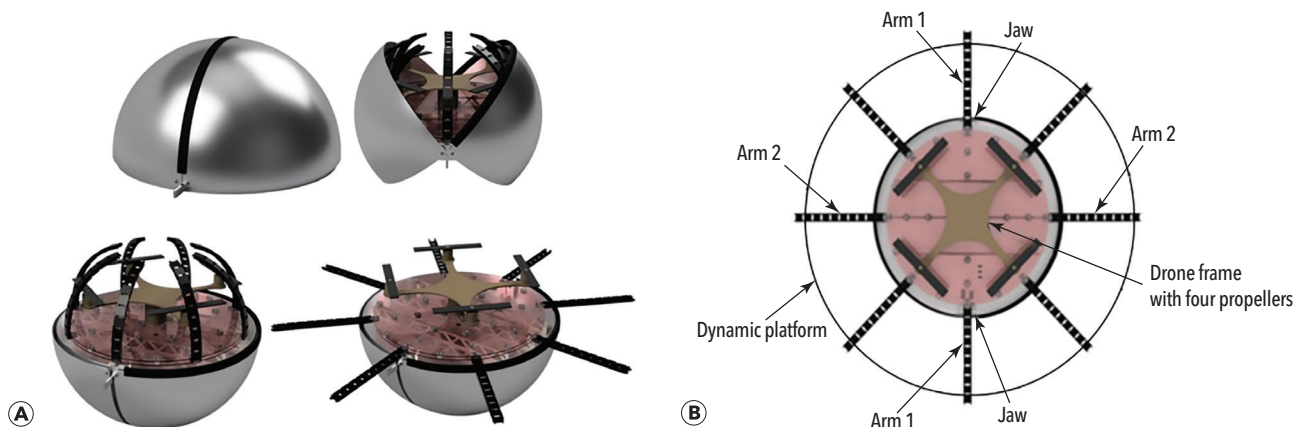


Figure 2. Views of (a) the opening cycle of the fungi capsule, and (b) the dynamic platform of the capsule.

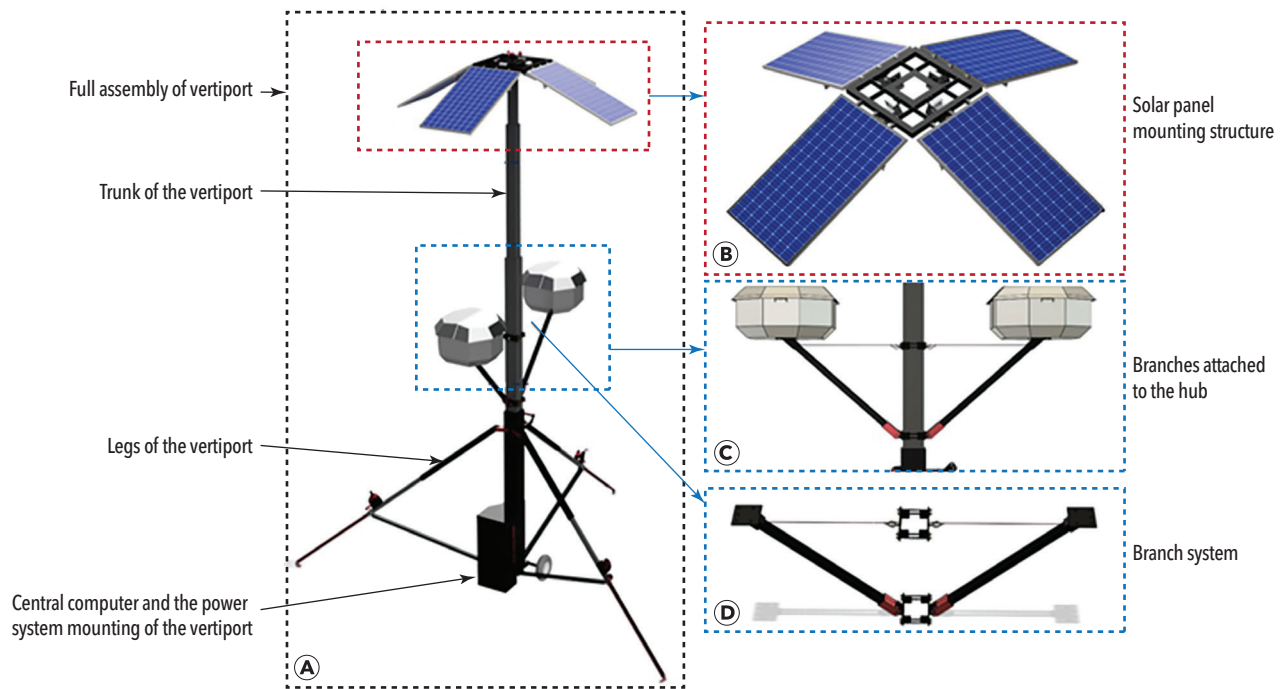


Figure 3. Views of (a) full assembly of the vertiport, (b) solar panel mounting structure, (c) branches attached to the hub, and (d) branch system.

apply clamping force to hold them in place. A combination of slotted channel struts and custom-machined hinges provides an affordable, temporary, yet robust solution for mounting the capsules. The current configuration of the branch system, with pitcher plant capsule mounts in place, is illustrated in Figure 3d. The placement of these branches can be adjusted along the primary mast of the base structure according to specific requirements.

The upper section of these branch mounts employs the same clamping bracket design; however, instead of a hinge, it utilizes a weather-resistant, high-strength multi-strand cable, facilitating the rapid attachment of drone capsules. The branches were designed to accommodate various capsule iterations and can withstand a static force of up to 680 N (150 lb) before any plastic deformation occurs. Figure 3c depicts the branches mounted on the purchased hub, with two pitcher plant capsules attached.

A critical component of this design is the solar panels installed at the top of the structure, which serves as the primary power source for the sustainable vertiport, supplying sufficient energy to support up to eight drones. Due to their extensive surface area, these solar panels are subject to significant wind loads. The four solar panels, as illustrated in Figure 3b, are mounted on a rigid body structure engineered to withstand wind speeds exceeding 112 km per hour (70 mph). Linear actuators are mounted on the back of each solar panel and connected to the rigid support structure. These actuators, with a stroke length of 30 cm (1 ft) and a dynamic load capacity of 1468 N (330 lb), enable the panels to track the sun's position throughout the day. They also reposition the panels to a

neutral stance in high wind conditions and adjust their orientation to accommodate incoming drones. Figure 3a shows the solar panels mounted atop the vertiport structure.

4. Structural Analysis of Drone Vertiport

The height of the vertiport structure introduced several challenges, particularly due to the central pole extending over 6 m (20 ft), creating a substantial tilting force. Ensuring the structure's stability and preventing it from reaching a critical load under high wind conditions is essential. To evaluate the wind-induced loads on the structure, simulations were performed using COMSOL. Figure 4a presents the von Mises stress analysis results with a deformation scale of one, based on a wind load of 30 m/s (67 mph) applied to the model. Although the solar panels are not depicted in the figure, their effects were calculated beforehand to determine the resulting load at the top of the structure.

The simulation results indicate that the structure begins to tip at this wind speed (30 m/s), and the original design with aluminum legs starts to yield. The stress and displacement values at specific points on the structure are detailed in Table 1, corresponding to the locations marked in Figure 4b. Points 6 and 7, located near the base of the legs, exhibited the highest stress levels, as anticipated. As the structure experienced concentrated loading on a single leg, the material reached its yield strength, leading to failure. To address this issue, the legs were redesigned using AISI 1018 steel, a material known for its enhanced yield strength, durability, and robustness. An analysis was conducted to evaluate the performance of the redesigned structure under both static and dynamic

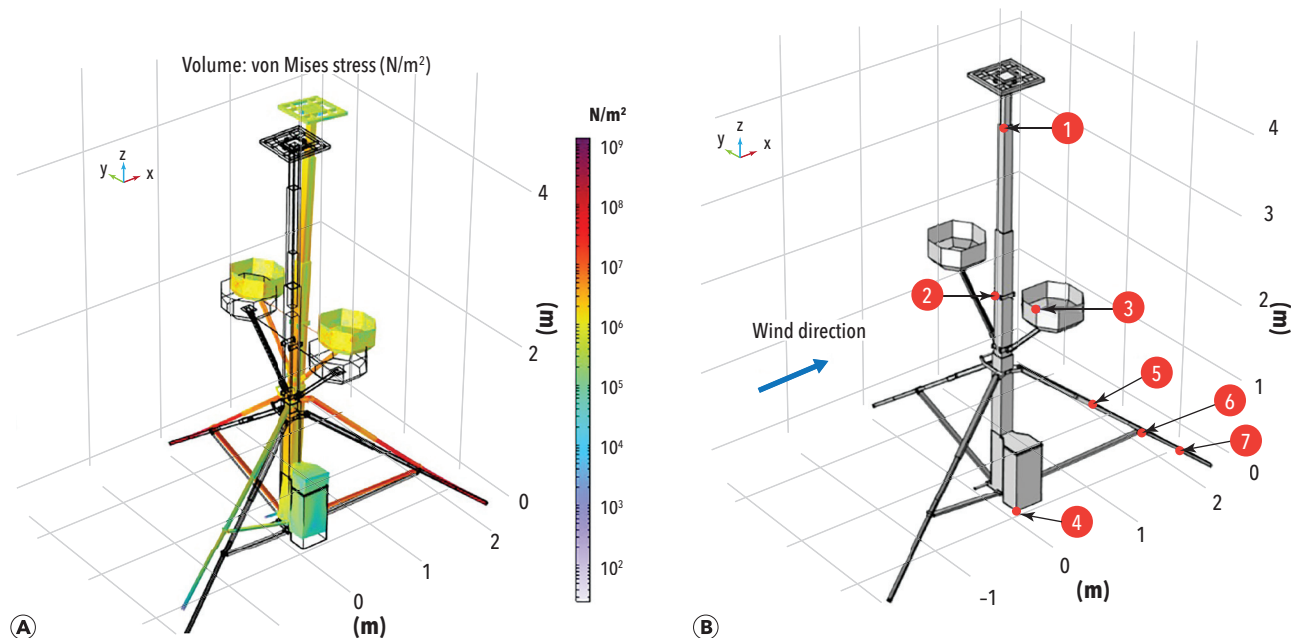


Figure 4. Views of (a) von Mises stress for gravity applied and 30 m/s wind loading, and (b) stress and displacement points.

TABLE 1

COMSOL results; tabulated displacement and stress, gravity applied, and 30 m/s wind loading

Point	Displacement in x (m)	Displacement in y (m)	Displacement in z (m)	von Mises stress (N/m ²)
1	4.16E-01	2.70E-01	0.12864	7.36E+05
2	2.12E-01	1.40E-01	0.1255	1.77E+06
3	2.54E-01	1.69E-01	0.2150	3.12E+06
4	-2.96E-02	-1.46E-02	0.16679	1.29E+07
5	5.81E-02	4.13E-02	0.057984	1.01E+07
6	1.99E-02	1.53E-02	0.020503	3.86E+07
7	4.61E-03	3.78E-03	0.0046386	1.46E+08

conditions, including wind loads of up to 30 m/s (~67 mph). The new design demonstrated the ability to withstand anticipated environmental stresses with minimal deflection, and the stress levels remained well below the yield strength of the steel, ensuring overall stability and reliability.

5. Power Supply of the Drone Vertiport

The system is designed with an isolated grid, necessitating a renewable energy source to minimize maintenance and ensure continuous operation (see Figure 5). Drawing inspiration from nature, particularly how trees harness solar energy, solar panels were chosen as the primary energy source, allowing the vertiport to function in various environments. During daylight hours, the solar panels will power the system, while a power

bank stores excess energy to maintain operations overnight, ensuring the system runs continuously. Any surplus energy generated by the panels is stored in the power bank located at the base of the vertiport.

The energy flow within the system starts with electricity generated by the solar panels, which then passes through a controller. This controller regulates the voltage and current from the solar panels, protecting the power bank from any erratic behavior or excessive current that could cause damage. An inverter, connected in parallel with the power bank, is used

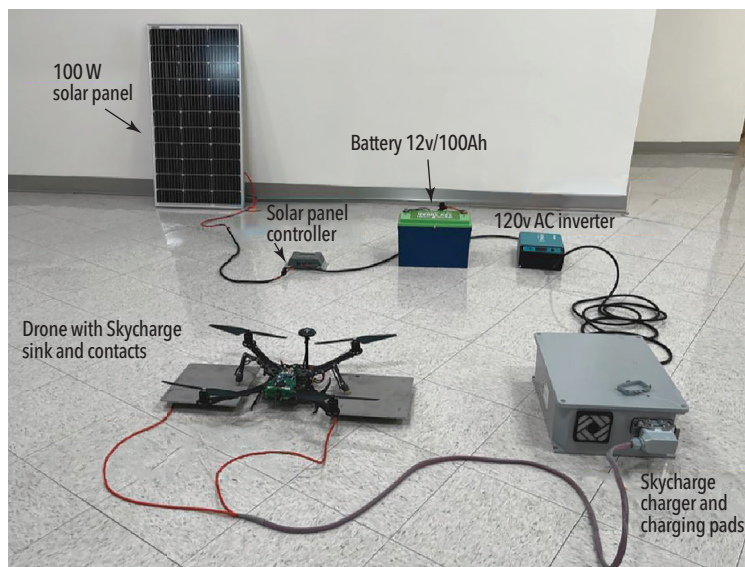


Figure 5. View of the system's main isolated grid.

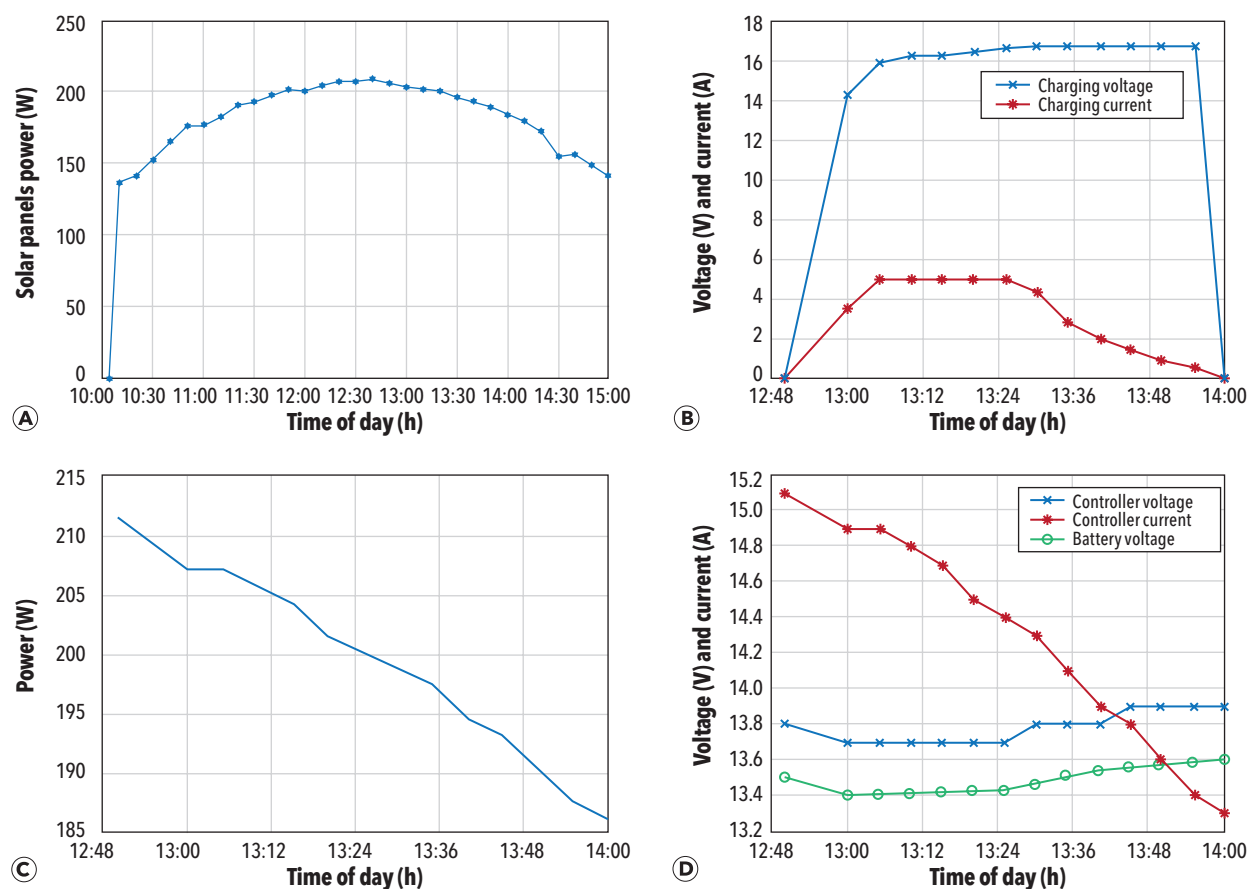


Figure 6. (a) Power from solar panels throughout the day; (b) charging system data for drone battery; (c) power; and (d) voltage and current from solar panels with active charging system.

TABLE 2
Collected data on the power bank and solar panels

Time (p.m.)	Solar panel voltage (V)	Solar panel current (A)	Voltage from controller (V)	Battery voltage (V) (actual)	Battery current (A)	Battery level (%)
12:50	14	15.1	13.8	13.5	15.1	97
1:00	13.9	14.9	13.7	13.4	14.9	97
1:05	13.9	14.9	13.7	13.4	14.9	97
1:10	13.9	14.8	13.7	13.42	14.8	97
1:15	13.9	14.7	13.7	13.42	14.7	97
1:20	13.9	14.5	13.7	13.43	14.5	97
1:25	13.9	14.4	13.7	13.43	14.4	97
1:30	14	14.3	13.8	13.8	14.3	97
1:35	14	14.1	13.8	13.54	14.1	97
1:40	13.9	13.9	13.8	13.54	13.9	97
1:45	14	13.8	13.9	13.56	13.8	97
1:50	14	13.6	13.9	13.57	13.6	97
1:55	14	13.4	13.9	13.58	13.4	98
2:00	14	13.3	13.9	13.6	13.3	98

TABLE 3
Collected data on the Skycharge device

Time (p.m.)	Energy (Wh)	Provided voltage (V) by Skycharge	Provided current (A) by Skycharge	Drone battery charge (Ah)	Drone battery level (%)
12:50	0	0	0	0	0
1:00	0.39	14.25	3.6	0.034	1
1:05	5.8	15.933	5.009	0.376	11.4
1:10	14.7	16.27	5.009	0.918	27.82
1:15	18.542	16.322	5.009	1.154	34.97
1:20	25.996	16.345	5.009	1.62	49.09
1:25	31.609	16.634	5.009	1.971	59.73
1:30	40.056	16.79	4.374	2.501	75.79
1:35	45.899	16.79	2.864	2.835	85.91
1:40	48.86	16.764	1.997	2.999	90.88
1:45	50.776	16.764	1.466	3.122	94.61
1:50	52.286	16.764	0.952	3.206	97.15
1:55	53.537	16.764	0.582	3.285	99.55
2:00	53.985	16.764	0	3.312	100

to power any AC devices. A notable challenge in this design is the conversion from DC to AC and then back to DC, which can lead to power losses through heat. However, this issue is mitigated by the fact that the equipment is primarily used to test the feasibility of supporting multiple drones with off-the-shelf components.

The first experiment aimed to evaluate the power output of the solar panels over the course of a day. A single solar panel was positioned flat at approximately 10:00 a.m., and the power output was recorded every 15 min until 3:00 p.m., resulting in a total of 30 data points. Plotting these data points against time produced the results shown in Figure 6a. This data provides a baseline for the amount of power generated around midday. The next step involved assessing the power consumption of the contact-based charging system while charging a single drone battery. The device measured both the power output and consumption during this process, and the resulting data are plotted to illustrate the power usage of the system (see Figure 6b).

The Skycharge charging system for drone batteries is an intelligent charging system that adjusts the charging voltage and current according to the drone battery’s charge level. From Figure 6b, we can see that as the drone battery’s charge level increases, the charging current gradually decreases. The capacity of the drone battery is 3300 mAh. Once the drone battery was fully charged, the system immediately stopped providing voltage. For better understanding, see the collected data in Table 3.

Before analyzing the data to estimate the number of drones that can be supported throughout the day, a final experiment was conducted to evaluate the system’s overall performance.

This experiment tested whether the controller could effectively regulate an additional load connected in parallel to the battery. For the setup and datasets collected during this experiment, the solar panels were laid flat on the ground surface, providing key insights into the system’s ability to handle varying power demands while maintaining stable operation. Tables 2 and 3 show the collected data on the battery and solar panels, as well as on the Skycharge device. The power, voltage, and current data are shown in Figures 6c and 6d, respectively.

The results from the final experiment demonstrated that the grid system is capable of supporting an additional load while simultaneously charging a battery, provided the load does not consume a substantial portion of the energy generated by the solar panels. Using the collected data, an estimation was made to determine the number of drones the system could support throughout the day. These calculations were performed manually using a calculator. It was observed that the battery could power the inverter until its charge dropped to 15%, but it could only be recharged up to 96%. During all trials, the battery started with a 20% charge, and within one hour, its charge increased at a rate of 50% per hour. Based on this data, the graph shown in Figure 7 was generated. Given the conclusion that the vertiport’s electrical grid can support up to eight drones during daylight hours, it is recommended to limit the number of drones to seven or fewer. This reduction ensures sufficient power allocation for the main computing system, maintaining optimal operational efficiency and stability.

For this part of the study, the objective was to determine the optimized number of drones the vertiport’s power bank can support. The power bank has a capacity of 1280 Wh, while each drone battery has a capacity of 48.84 Wh. Using

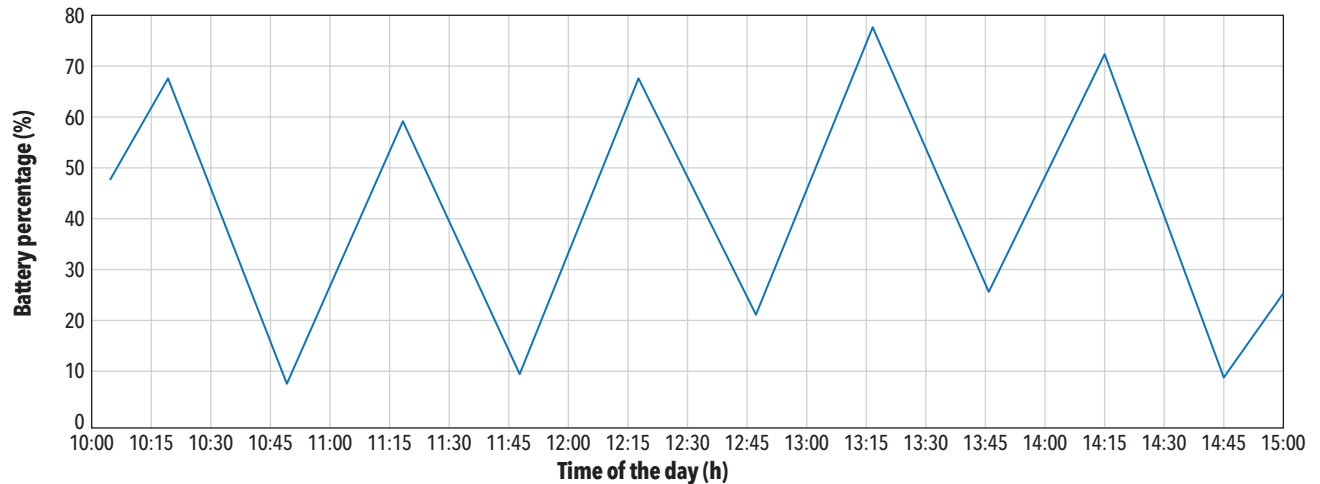


Figure 7. Estimated charging pattern for eight drones.

experimentally collected charging and discharging data for both the power bank and drone batteries, it was estimated that the vertiport's power bank could support up to eight drones continuously, along with other vertiport components.

The estimation assumes that a swarm of eight drones actively conducted surveillance tasks over a 5 h period. At the start of the estimation at 10:00, the power bank level was assumed to be ~50%. During this time, the solar panels were actively generating power to charge the power bank. After 15 min of charging (from 10:00 to 10:15) without drones connected, the power bank level increased to 69%. At 10:15, all eight drones returned to the vertiport with battery levels between 10% and 15%, initiating simultaneous charging.

From 10:15 to 10:45 (30 min), the drones charged sufficiently to conduct another 30-min surveillance task, reducing the power bank level to ~9%. After the drones departed for their next mission, the power bank recharged, reaching ~60% by 11:15 through the solar charging system. At this time, the drones returned, and the process repeated. During this cycle, the power bank level dropped from 60% to 10%.

The power drop of the power bank was not consistent throughout the process due to the solar panels providing power to both the drone batteries and the power bank. At 1:45 p.m, the power drop of the power bank was at its lowest (~26%), coinciding with the highest power generation rate of the solar panels due to the optimal orientation of the sun. The solar panels operate at maximum capacity when the sun's orientation is perpendicular to them. As the sun's position changed, the power generation rate decreased, causing the power bank's energy depletion rate to increase gradually. Throughout the process, the solar panels remained horizontally aligned with the ground surface, with no adjustments made to their orientation.

6. Drone Integration to Vertiport and Precision Landing

The drone used for this project is equipped with a flight system that combines a flight controller and an onboard computing unit. The onboard processor handles all data collected

from the drone's sensors and cameras and runs the necessary software to manage communication and configuration for flight operations. The flight controller operates with open-source firmware, which can only be accessed via the terminal on the onboard processor unless a direct-wired connection is established with the flight controller's port, typically required only for firmware updates via image flashing.

The primary reason for selecting this drone was its high functionality and the robust usability of its autopilot features. These capabilities are enabled by a modular software architecture running on the onboard computing unit. This architecture consists of services, pipelines, and tools. The services include software that handles the processing, calculation, configuration, and maintenance of the drone's individual components. For example, the camera server manages optical input, processes the data based on the task, and configures the cameras for identification and filtering. Tools are used to manipulate or inspect services, such as examining the drone's IMU (inertia measurement unit) servers or battery status through the PX4 software. The pipelines, a critical component of this architecture, function as data carriers between different services that request specific information. This architecture is particularly valuable to the project as it allows for the integration of data from these pipelines into custom software applications. An example of this architecture in action is a visual-inertial odometry (VIO) system, which requires camera data from the camera processing module and IMU data from the inertial measurement unit module to calculate VIO, demonstrating the interconnected functionality of the system.

6.1. AprilTag Relocation

For landing precisely in any specific location, we use AprilTags detected by the drones utilizing an in-built deep learning algorithm. Building on the understanding of the drone's software and hardware capabilities, the focus shifts to deep neural networks and AprilTag detection. The drone is already equipped with software to detect and localize AprilTags using

VIO data from the camera. The detection process is facilitated by TensorFlow Lite, a pre-trained deep learning neural network, specifically a convolutional neural network (CNN). This type of deep learning AI is designed to recognize patterns across various media, including video, audio, and text [55, 56]. Upon detecting an AprilTag, the camera places five reference points: four at the corners and one in the center. These points are then used to calculate the position of the tag relative to the drone using trigonometric functions, enabling precise localization and navigation.

Utilizing this data for relocalizing the drone involves more complexity than simply inputting Cartesian coordinates (XYZ). In autopilot mode, the drone does not navigate using XYZ coordinates; instead, it relies on a different orientation convention known as Euler angles or RPY (roll, pitch, yaw). The conversion between these two systems is feasible through the application of Euler angles of angular velocity. However, a challenge arises because there are 12 possible Euler angle sequences, and it is not immediately clear which sequence is being used for the coordinate system conversion. Further research indicates that the ZYX sequence is commonly employed for most drones, leading to the following rotation matrix:

$$\begin{aligned}
 (1) \quad Z_r &= [\cos(r) \ -\sin(r) \ 0, \ \sin(r) \ \cos(r) \ 0, \ 0 \ 0 \ 1] \\
 (2) \quad Y_p &= [\cos(p) \ 0 \ \sin(p), \ 0 \ 1 \ 0, \ -\sin(p) \ 0 \ \cos(p)] \\
 (3) \quad X_y &= [1 \ 0 \ 0, \ 0 \ \cos(y) \ -\sin(y), \ 0 \ \sin(y) \ \cos(y)] \\
 (4) \quad Z_r \ Y_p \ X_y &= M = \begin{bmatrix} C_p C_r & C_r S_p S_y - C_y S_r & S_r S_y + C_r C_y S_p \\ C_p S_r & C_r C_y + S_r S_p S_y & C_y S_r S_p - C_r S_y \\ -S_p & C_p S_y & C_p C_y \end{bmatrix} \\
 (5) \quad \tan^{-1} \left(\frac{M_{21}}{M_{11}} \right) &= roll^*; \quad \tan^{-1} \left(\frac{M_{31}}{\sqrt{1 + M_{31}^2}} \right) = pitch^*; \\
 \tan^{-1} \left(\frac{M_{33}}{M_{32}} \right) &= yaw^*
 \end{aligned}$$

Understanding these conventions is crucial for comprehending how the drone calculates its path to relocalize above the AprilTag. The drone achieves this by rotating its axis and determining its position over time based on angular velocity. This underscores the importance of specifying the correct commands and orientations when working with robot operating system (ROS) and configuring parameters that enable the drone to hover above the AprilTag before landing. Additionally, it is essential for developing algorithms that manage scouting and landing operations. By leveraging the AprilTag detector service through the Modal Pipe Architecture, the RPY values can be extracted and utilized within ROS.

6.2. AprilTag Detection

Data was collected using the drone to assess its AprilTag detection capabilities in an indoor environment (see Figure 8). The drone utilized a tag-detection system, which continuously ran to capture AprilTag location data. Upon detecting the AprilTag's size and position, the drone processed its own RPY data to navigate toward the tag. For this experiment, an AprilTag

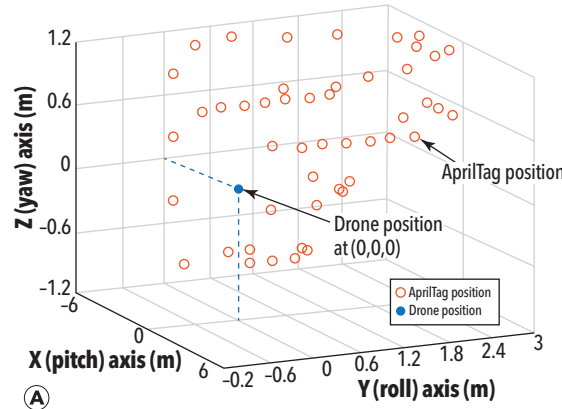
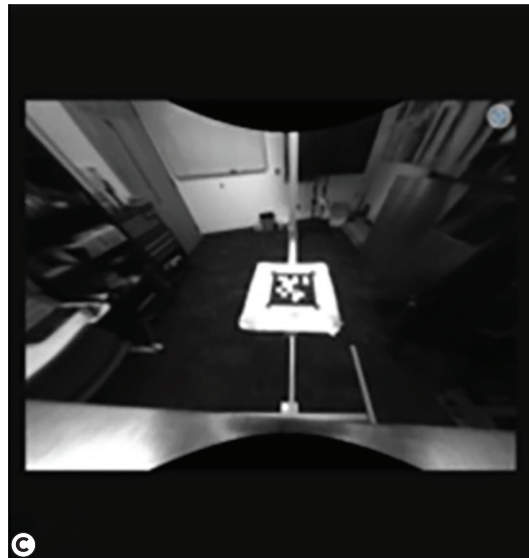
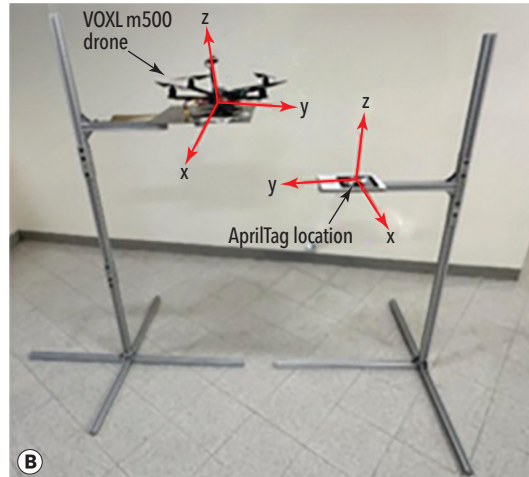


Figure 8. Visual points from drone to AprilTag: (a) graphical representation of AprilTag detection range; (b) experimental setup; and (c) drone camera view.



measuring 6 in. $\times$ 6 in. was used. The minimum and maximum distances at which the drone could successfully detect the AprilTag were recorded.

The coordinate system was established relative to the drone's position, and the location of the AprilTag was measured accordingly. The drone's ability to detect the AprilTag was evaluated across various positions, encompassing nearly all possible placements of the tag. This testing consisted of 32 trials focusing on AprilTag detection accuracy and the drone's RPY adjustments relative to the tag. Detection was successful in 21 of the 32 tests, highlighting the system's ability to detect and navigate to the AprilTag based on coordinate system alignment. Additionally, 34 tests were conducted to identify the minimum and maximum detectable distances of the AprilTag. Detection was successful in 26 of these tests, providing a quantified range of the drone's AprilTag detection capability. It was observed that the drone has a specific detection range within which it can reliably identify the AprilTag. Figure 8 provides a graphical representation of this detection boundary, illustrating the area within which the drone successfully detected the AprilTag at any given point. The figure shows the AprilTag detection range of the drone, with the unchanged position of the drone considered as the origin (0,0,0) of the 3D coordinate system. The distance is measured in meters.

6.3. MAVLink and ROS Implementation

A notable challenge encountered during the integration process was the limitation of the drone's onboard computer, which restricts the direct installation of packages or applications without utilizing Docker. In a typical ARM Linux environment, the 'sudo apt install' command would suffice to install necessary packages. However, for this specific drone, the procedure requires creating a designated directory and downloading a compatible Docker image, such as "voxl-cross." After configuring the image, it must be built into a tar.gz file. This file is then transferred to the onboard computing unit using a wired connection and a debugging tool to push the file into the root shell directory. It is crucial to ensure that the Docker daemon is running as a background service before proceeding with building and deploying the image.

MAVROS, unlike MAVLink and ROS, operates as an active command-line interface, functioning akin to a frontline application that communicates directly with the flight controller through pipelines connected to the vision processing hub. The integration of MAVROS is particularly important because it enables direct communication with the flight controller, allowing for arming and disarming of the drone without relying on external signals from a transmitter or QGroundControl.

In previous testing phases, the drone's autopilot and AprilTag detection capabilities were evaluated using MAVLink and vision-processing-hub demonstration packages [57]. With the implementation of MAVROS, the process begins by initiating ROScore and the necessary nodes for flight, followed by executing the required packages to facilitate communication with the PX4 software on the flight controller. Once the

connection between PX4 and MAVROS is established, the ROS script is initiated to arm and control the drone, all of which is executed with a single command from the terminal. Despite the generally smooth operation, sporadic communication errors between MAVROS and PX4 were encountered, indicating unexpected command inputs. However, these errors did not significantly impact the overall flight performance.

6.4. Drone Relocation Results

The coordinate system was established relative to the drone's position, and the location of the AprilTag was measured accordingly. The drone's ability to detect the AprilTag was evaluated across various positions, encompassing nearly all possible placements of the tag. This testing consisted of 32 trials focusing on AprilTag detection accuracy and the drone's RPY adjustments relative to the tag. Detection was successful in 21 of the 32 tests, highlighting the system's ability to detect and navigate to the AprilTag based on coordinate system alignment. Additionally, 34 tests were conducted to identify the minimum and maximum detectable distances of the AprilTag. Detection was successful in 26 of these tests, providing a quantified range of the drone's AprilTag detection capability.

To test the drone's ability to relocate using AprilTag detection, the drone was taken to an open field, and a QR code was placed on a flat surface. The objective was for the drone to detect the QR code mid-flight and autonomously land on it. Initially, the drone was set to position flight mode and manually controlled using a transmitter to fly closer to the QR code. Upon detecting the QR code, the drone was switched to off-board flight mode (see Figures 9a and 9b). In this mode, the drone accurately determined the position of the QR code and hovered steadily at a height of 1.5 m (5 ft) above it. After maintaining a stable hover, the drone was switched back to position flight mode and landed on the QR code.

To rigorously evaluate the system's AprilTag detection and precision landing capabilities, extensive testing was conducted in both indoor and outdoor environments. Nine outdoor flight tests were performed to assess the impact of environmental factors, including wind, shadow, and varying detection distances. During some trials, vibrations were intentionally introduced on the branch structure to simulate wind effects. Despite these disturbances, the drone reliably detected the AprilTag and executed precise landings, demonstrating the system's robustness under dynamic conditions (see Figure 9c).

7. Future Work

The next steps in this project focus on enhancing the autonomous capabilities of the drone system. A key area for development is refining the use of MAVROS to create software that can autonomously plan flight paths and incorporate algorithms to assist the drone in locating its designated landing site. Once the drone can reliably navigate its flight path independently, the integration of a second drone into the system will be pursued to explore coordinated swarm operations. Additionally, there will be a focus on integrating an automatic

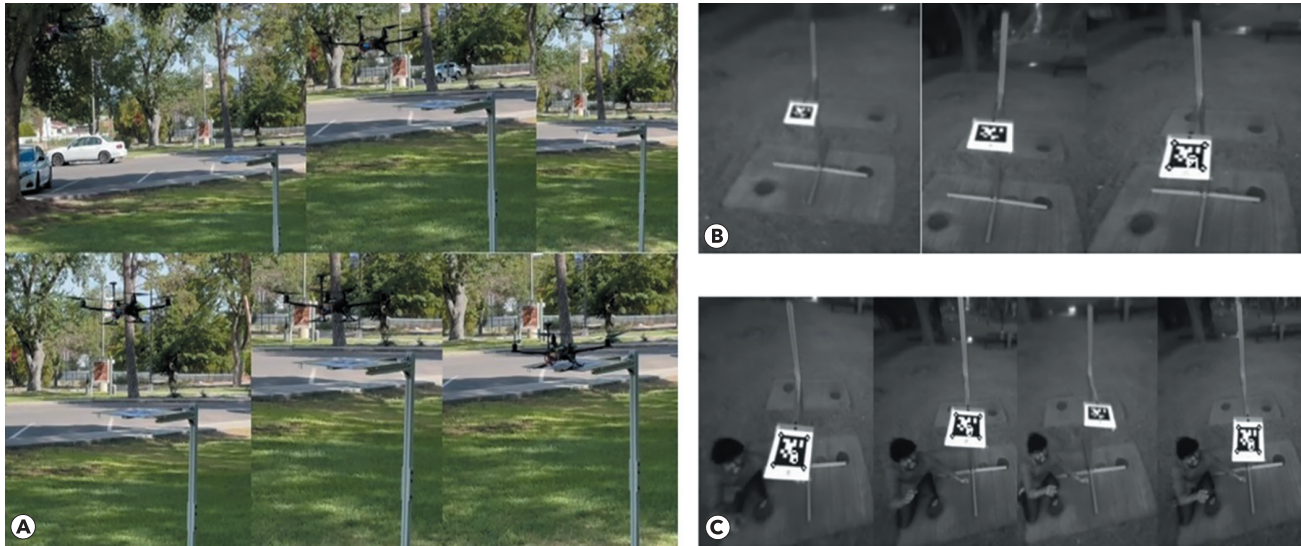


Figure 9. Photographs of AprilTag detection by the drone during (a, b) precision landing and (c) under dynamic conditions.



Figure 10. Proposed concept and current prototype of the vertiport.

charging system. This will involve configuring the drones to establish a closed circuit with the charging pads upon landing, allowing for seamless recharging without manual intervention. These advancements will further the system's ability to operate autonomously in inaccessible environments, enhancing its versatility for various applications beyond the original scope of detecting abandoned oil wells emitting greenhouse gases. Views of the proposed concept and the current prototype are shown in Figure 10.

8. Conclusions

Drones have a wide range of applications across various sectors, including smart cities, towns, villages, and industrial and mining areas. This work focused on the development of a bioinspired vertiport system to support drone-based methane detection missions. The vertiport provides a robust and efficient infrastructure for drone storage, charging, and landing, enabling autonomous operations in remote areas where methane-emitting orphaned wells are located. These wells are often located in remote areas that are challenging for technicians to access. Additionally, methane inhalation poses significant health risks. Identifying orphaned wells emitting methane gas across the US is a costly process due to their increasing numbers and hard-to-reach geographical locations. The task requires expensive equipment, which is also difficult to move from place to place, operated by experienced and expert human technicians. As orphaned wells are often scattered randomly across a particular site, this makes them difficult to reach, making the task even more arduous and time-consuming. In this context, the drone vertiport system presents an effective solution to this problem. It requires only two human technicians to place and activate the vertiport system at any site, and the autonomous system will do the rest. The drones will continuously scan the site to detect methane emissions from orphaned wells in a proper surveillance manner and send data to a remote data analysis and control center. This approach will reduce the overall operational cost as well as the human effort involved. It also saves time and lowers the risk to human safety.

Given the high costs associated with plugging orphaned wells, this autonomous system provides a cost-effective approach by prioritizing wells with the highest emissions for remediation. The strategy aims to minimize overall methane emissions by addressing the most critical sources first, thereby reducing the maximum emissions with the minimum number of wells plugged. The drone vertiport system is designed to be sustainable, portable, and fully autonomous, powered by solar energy, and capable of continuously supporting up to six drones simultaneously. These drones are equipped with advanced autonomous features, including precision landing using QR codes (AprilTags). The vertiport capsules are automated and feature a contact-based charging system, ensuring seamless and continuous drone operations. Future work will focus on enhancing drone communication and path planning algorithms, as well as optimizing the drone battery

management system, to further improve the efficiency and effectiveness of the system in various environments.

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REFERENCES

- Kang, M., C. M. Kanno, M. C. Reid, X. Zhang, D. L. Mauzerall, M. A. Celia, Y. Chen, and T. C. Onstott. 2014. "Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania." *Proceedings of the National Academy of Sciences of the United States of America* 111 (51): 18173–77. <https://doi.org/10.1073/pnas.1408315111>.
- Romanzo, N. N. 2020. "Locating Undocumented Abandoned Oil and Gas Wells." Master's thesis. State University of New York at Binghamton. Binghamton, NY.
- US Department of the Interior. 31 January 2022. "Biden administration announces \$1.15 billion for states to create jobs cleaning up orphaned oil and gas wells." <https://www.doi.gov/pressreleases/biden-administration-announces-115-billion-states-create-jobs-cleaning-orphaned-oil>.
- Carbon Tracker. 1 October 2020. "Taxpayers may have to pay \$280 billion in onshore plugging costs for oil and gas wells." <https://carbontracker.org/taxpayers-may-have-to-pay-280-billion-in-onshore-plugging-costs-for-oil-and-gas-wells/>.
- Mannan, F., L. Moore, S. Shao, X. Sun, and M. Hassanalian. 2024. "Sustainable and Portable Vertiports Enabling Autonomous Drone Swarm Inspection in the Oil and Gas Industry." *AIAA Aviation Forum and ASCEND 2024*, 29 July–2 August 2024, Las Vegas, NV. <https://doi.org/10.2514/6.2024-3888>.
- Zagrai, A., and M. Hassanalian. 2020. "Drones as a Driving Force for Smart Towns: Technology and Accessibility." *AIAA Propulsion and Energy 2020 Forum (Virtual)*, 24–26 August 2020. <https://doi.org/10.2514/6.2020-3967>.
- Hassanalian, M., A. Mirzaeinia, and K. Lee. 2020. "Smart Cities and Organizing the Drones' Applications in Urban Areas: N.E.ST (Networking, Efficient, Strategies)." *AIAA SciTech 2020 Forum*, 6–10 January 2020, Orlando, FL. <https://doi.org/10.2514/6.2020-1944>.
- Mirzaeinia, A., S. Bradley, and M. Hassanalian. "Drone-Station Matching in Smart Cities through Hungarian Algorithm: Power Minimization and Management." *2019 AIAA Propulsion and Energy 2019 Forum*, 19–22 August 2019, Indianapolis, IN. <https://doi.org/10.2514/6.2019-4151>.
- Mirzaeinia, A., and M. Hassanalian. 2019. "Minimum-Cost Drone – Nest Matching through the Kuhn-Munkres Algorithm in Smart Cities: Energy Management and Efficiency Enhancement." *Aerospace (Basel, Switzerland)* 6 (11): 125. <https://doi.org/10.3390/aerospace6110125>.
- Mirzaeinia, A., M. Hassanalian, and K. Lee. 2020. "Drones for Borders Surveillance: Autonomous Battery Maintenance Station and Replacement for Multirotor Drones." *AIAA SciTech 2020 Forum*, 6–10 January 2020, Orlando, FL. <https://doi.org/10.2514/6.2020-0062>.
- Lukow, S., M. Sherman, M. Gammill, and M. Hassanalian. 2021. "Design and Fabrication of Electromagnetic Attachment Mechanism for a Hybrid Drone for Mars Exploration." *AIAA SciTech 2021 Forum (Virtual)*, 11–15 and 19–21 January 2021. <https://doi.org/10.2514/6.2021-1296>.
- Dunaway, C., J. Montoya, S. Lukow, and M. Hassanalian. 2023. "Bioinspired Unmanned Aircraft System Nest Concepts for Urban Cities." *AIAA SciTech 2023 Forum*, 23–27 January 2023, National Harbor, MD (and online). <https://doi.org/10.2514/6.2023-1330>.
- Dinelli, C., J. Racette, M. Escarcega, S. Lotero, J. Gordon, J. Montoya, C. Dunaway, et al. 2023. "Configurations and Applications of Multi-Agent Hybrid Drone/Unmanned Ground Vehicle for Underground Environments: A Review." *Drones (Basel)* 7 (2): 136. <https://doi.org/10.3390/drones7020136>.

14. Aboelegg, A., D. Wetz, J. Lehr, P. Roghanchi, and M. Hassanalian. 2023. "Intrinsically Safe Drone Propulsion System for Underground Coal Mining Applications: Computational and Experimental Studies." *Drones (Basel)* 7 (1): 44. <https://doi.org/10.3390/drones7010044>.
15. Tullu, A., M. Hassanalian, and H. Y. Hwang. 2022. "Design and Implementation of Sensor Platform for UAV-Based Target Tracking and Obstacle Avoidance." *Drones (Basel)* 6 (4): 89. <https://doi.org/10.3390/drones6040089>.
16. Sun, H., H. Yan, M. Hassanalian, J. Zhang, and A. Abdelkefi. 2023. "UAV Platforms for Data Acquisition and Intervention Practices in Forestry: Towards More Intelligent Applications." *Aerospace (Basel, Switzerland)* 10 (3): 317. <https://doi.org/10.3390/aerospace10030317>.
17. Shahmoradi, J., P. Roghanchi, and M. Hassanalian. 2022. "Design, Analysis, and Prototyping of a Spherical Drone for Underground Mines." *International Journal of Theoretical and Applied Multiscale Mechanics* 4 (1): 58–82. <https://doi.org/10.1504/IJTAMM.2022.122895>.
18. Darvishpoor, S., J. Roshanian, A. Raissi, and M. Hassanalian. 2021. "Configurations, Flight Mechanisms, and Applications of Unmanned Aerial Systems: A Review." *Progress in Aerospace Sciences* 121:100694. <https://doi.org/10.1016/j.paerosci.2020.100694>.
19. Shahmoradi, J., E. Talebi, P. Roghanchi, and M. Hassanalian. 2020. "A Comprehensive Review of Applications of Drone Technology in the Mining Industry." *Drones (Basel)* 4 (3): 34. <https://doi.org/10.3390/drones4030034>.
20. Mirzaeinia, A., M. Hassanalian, M. Shekaramiz, and M. Mirzaeinia. 2019. "Loader and Tester Swarming Drones for Cellular Phone Network Loading and Field Test: Non-stochastic Particle Swarm Optimization." *Journal of Autonomous Intelligence* 2 (2): 14–24. <https://doi.org/10.32629/jai.v2i2.46>.
21. Hassanalian, M., and A. Abdelkefi. 2017. "Classifications, Applications, and Design Challenges of Drones: A Review." *Progress in Aerospace Sciences* 91:99–131. <https://doi.org/10.1016/j.paerosci.2017.04.003>.
22. Racette, J., C. Dunaway, M. Escarcega, J. Montoya, C. Dinelli, V. Androulakis, H. Khaniani, S. Shao, P. Roghanchi, and M. Hassanalian. 2023. "Research and Design of Precision-Landing Drone in an Underground GPS-Denied Environment." AIAA Aviation 2023 Forum, 12–16 June 2023, San Diego, CA (and online). <https://doi.org/10.2514/6.2023-3625>.
23. Irizarry, J., M. Gheisari, and B. N. Walker. "Usability Assessment of Drone Technology as Safety Inspection Tools." *ITcon* 17 (2012): 194–212. <https://www.itcon.org/2012/12>.
24. Seiber, C., D. Nowlin, B. Landowski, and M. E. Tolentino. 2018. "Tracking Hazardous Aerial Plumes Using IoT-Enabled Drone Swarms." 2018 IEEE 4th World Forum on Internet of Things (WF-IoT): 377–382. 2018. <https://doi.org/10.1109/WF-IoT.2018.8355118>.
25. Aliyari, M., B. Ashrafi, and Y. Z. Ayele. 2022. "Hazards Identification and Risk Assessment for UAV-Assisted Bridge Inspections." *Structure and Infrastructure Engineering* 18 (3): 412–28. <https://doi.org/10.1080/15732479.2020.1858878>.
26. Burgués, J., and S. Marco. 2020. "Environmental Chemical Sensing Using Small Drones: A Review." *Science of the Total Environment* 748:141172. <https://doi.org/10.1016/j.scitotenv.2020.141172>.
27. Cruzan, M. B., B. G. Weinstein, M. R. Grasty, B. F. Kohn, E. C. Hendrickson, T. M. Arredondo, and P. G. Thompson. 2016. "Small Unmanned Aerial Vehicles (Micro-UAVs, Drones) in Plant Ecology." *Applications in Plant Sciences* 4 (9): 1–11. <https://doi.org/10.3732/apps.1600041>.
28. Steffen, L. "Defibrillator-Equipped Drones Are Already Saving Lives!" 6 February 2022. Intelligent Living. <https://www.intelligentliving.co/defibrillator-equipped-drones-are-already-saving-lives/>.
29. Ausonio, E., P. Bagnerini, and M. Ghio. 2021. "Drone Swarms in Fire Suppression Activities: A Conceptual Framework." *Drones (Basel)* 5 (1): 17–19. <https://doi.org/10.3390/drones5010017>.
30. Wing Aviation LLC. Accessed 25 February 2025. <https://wing.com/>.
31. Amazon. "Amazon Prime Air Prepares for Drone Deliveries." 13 June 2022. <https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries>.
32. United Parcel Service of America Inc. April 2020. "UPS Flight Forward, CVS to Launch Residential Drone Delivery Service in Florida Retirement Community to Assist in Coronavirus Response." <https://www.globenews.wire.com/news-release/2020/04/27/2022615/0/en/UPS-Flight-Forward-CVS-To-Launch-Residential-Drone-Delivery-Service-In-Florida-Retirement-Community-To-Assist-In-Coronavirus-Response.html>.
33. Amazon. "Amazon Reveals the New Design for Prime Air's Delivery Drone—Here's Your First Look." 10 November 2022. <https://www.aboutamazon.com/news/transportation/amazon-prime-air-delivery-drone-reveal-photos>.
34. US Federal Aviation Administration. Accessed 25 February 2025. "Package Delivery by Drone (Part 135)." https://www.faa.gov/uas/advanced_operations/package_delivery_drone.
35. US Federal Aviation Administration. Accessed 25 February 2025. "Unmanned Aircraft System Traffic Management (UTM)." https://www.faa.gov/uas/research_development/traffic_management.
36. US Department of Transportation. 2022. *UTM Concept of Operations Version 2.0 (UTM ConOps v2.0)*, 10–53. US Federal Aviation Administration. <https://www.faa.gov/researchdevelopment/trafficmanagement/utm-concept-operations-version-20-utm-conops-v20>.
37. Dominique, D., and F. Dominique. 2017. "A Position and Orientation Independent Drone Charging System." *Journal of Engineering (Stevenage, England)* 2017 (9): 536–38. <https://doi.org/10.1049/joe.2017.0325>.
38. Chittoor, P. K., B. Chokkalingam, and L. Mihet-Popa. 2021. "A Review on UAV Wireless Charging: Fundamentals, Applications, Charging Techniques and Standards." *IEEE Access: Practical Innovations, Open Solutions* 9:69235–66. <https://doi.org/10.1109/ACCESS.2021.3077041>.
39. Mourgelas, C., S. Kokkinos, A. Milidonis, and I. Voyiatzis. 2020. "Autonomous Drone Charging Stations: A Survey." Proceedings of the 24th Pan-Hellenic Conference on Informatics (PCI 2020): 233–236. New York, NY: Association for Computing Machinery. <https://doi.org/10.1145/3437120.3437314>.
40. SkyX. "The First SkyX 'xStation' Gets Deployed." 8 June 2017. <https://skyx.com/news/the-first-skyx-xstation-gets-deployed/>.
41. Volatus Aerospace Corp. "Aerieport Drone Nesting Station." Accessed 25 February 2025. <https://volatusaerospace.com/aerieport-drone-nesting-station/>.
42. Raciti, A., S. A. Rizzo, and G. Susinni. 2018. "Drone Charging Stations Over the Buildings Based on a Wireless Power Transfer System." 2018 IEEE/IAS 54th Industrial and Commercial Power Systems Technical Conference (I&CPS), 7–10 May 2018, Niagara Falls, Ontario, Canada: 1–6. <https://doi.org/10.1109/ICPS.2018.8369967>.
43. Achtelik, M. C., J. Stumpf, D. Gurdan, and K.-M. Doth. 2011. "Design of a Flexible High-Performance Quadcopter Platform Breaking the MAV Endurance Record with Laser Power Beaming." 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, 25–30 September 2011, San Francisco, CA: 5166–5172. <https://doi.org/10.1109/IROS.2011.6094731>.
44. Gentry, N. K., R. Hsieh, and L.K. Nguyen. 2016. Multi-Use UAV Docking Station Systems and Methods. US Patent 9,387,928 B1, filed 18 December 2014, and issued 12 July 2016.
45. Wang, M. 2016. Systems and Methods for UAV Docking. US Patent 9,457,915 B2, filed 17 August 2015, and issued 4 October 2016.
46. Coldewey, D. 30 September 2021. "Matternet's Automated Drone-Docking Station Makes Its Real-Life Debut in Switzerland." TechCrunch. <https://techcrunch.com/2021/09/30/matternets-automated-drone-docking-station-makes-its-real-life-debut-in-switzerland/>.
47. HEISHA. 15 August 2022. "D50 Drone Dock." HEISHA Robot Charging Station. <https://www.heishatech.com/autonomous-drone/d50-autonomous-drone-in-a-box/>.
48. FlytBase Inc. 2022. "Hextronics Drone Docks Powered by FlytBase." Complete Drone in a Box Automation Software. <https://www.flytnow.com/drone-docks/hextronics>.
49. Skycharge. Accessed 25 February 2025. "Drone Box Hangar - Skyport DP5." <https://www.skycharge.de/drone-box-hangar>.

50. Deloitte Consulting, L. L. P. 2020. *UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4 Version 1.0*, 7–58. New York, NY: National Aeronautics and Space Administration.
51. FlyOnE. Accessed 25 February 2025. “Lilypad Elevate.” <https://flyone.com.au/lilypad-elevate/>.
52. Herkenhoff, B., I. Morris, A. Ebrahimkhanlou, and M. Hassanalian. 2021. “Application and Potential Design of an Amphibious Drone Hub: Water Lily and Bioinspiration Concepts.” AIAA Aviation 2021 Forum (Virtual), 2–6 August 2021. <https://doi.org/10.2514/6.2021-2783>.
53. Gibbs, J. P., and E. J. Stanton. 2001. “Habitat Fragmentation and Arthropod Community Change: Carrion Beetles, Phoretic Mites, and Flies.” *Ecological Applications* 11 (1): 79–85. [https://doi.org/10.1890/1051-0761\(2001\)011\[0079:HFAACC\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011[0079:HFAACC]2.0.CO;2).
54. Alves De Oliveira, S., M. Monteiro De Castro, and F. Prezoto. 2010. “Foundation Pattern, Productivity, and Colony Success of the Paper Wasp, *Polistes versicolor*.” *Journal of Insect Science* 10 (1): 125. <https://doi.org/10.1673/031.010.12501>.
55. Krogus, M., A. Haggemiller, and E. Olson. 2019. “Flexible layouts for fiducial tags.” 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 4–8 November 2019, Macau, China: 1898–1903. <https://doi.org/10.1109/IROS40897.2019.8967787>.
56. Wang, J., and E. Olson. 2016. “AprilTag 2: Efficient and robust fiducial detection.” 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 9–14 October 2016, Daejeon, South Korea: 4193–4198. <https://doi.org/10.1109/IROS.2016.7759617>.
57. Tadesse, K., G. M. Fricke, J. P. Hecker, and M. E. Moses. “April Tag Detection: Calculating Distance Using ROS Transform Package.” https://kirubeltadesse.github.io/assets/iros-extended-abstract_2.pdf.

GUIDED BY HEARING: ROBOTIC MOTION PLANNING FOR PRECISION IN GAS LEAKAGE LOCALIZATION

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ABSTRACT

This research proposes a motion planning framework for a robot equipped with a bioinspired hearing system to enhance its sound source localization, specifically for gas leak detection. Similar to how animals use movements, such as changing positions or rotating their ears, to precisely localize a sound source, this framework enables the robot to improve its estimation of both direction and distance through strategic motion. The proposed method uses the time difference of arrival (TDOA) between two wideband optical microphones, obtained through this motion, to accurately estimate the direction and distance of a sound source. We first introduce the underlying concepts and validate the approach using experimental data collected with a collaborative robotic arm. We then demonstrate the implementation of the method on a quadruped robot. The results show that the method can be effectively deployed on mobile robots, achieving directional and distance accuracy for gas leak localization.

KEYWORDS: gas leakage, source localization, quadruped robot, robotic dog, robotic inspection

Introduction

Gas leakage is a significant source of failure in various industries, including oil and gas, clean energy systems such as hydrogen-based fuel cells, and the automotive sector. Early detection of gas leaks is crucial to prevent catastrophic failures, ensure safety, and reduce environmental impact. Gas leakage detection and localization involve using a wide range of gas sensing hardware, including metal oxide (MOX) gas sensors, e-noses, and photoionization detectors (Francis et al. 2022). Relying on human labor is demanding, while installing sensor equipment can be expensive and often financially unfeasible. As a result, there is growing interest in using mobile robots for inspection, such as Boston Dynamics' Spot (Guizzo 2019).

While the use of robots for industrial inspection is not new, the application of mobile robots for inspection remains an active research area. A review of various pipeline robots, considering factors such as inspection accuracy, adaptability, cost, and efficiency (Ambati et al. 2020), as well as the development of inspection robots for nuclear power plants (Yamamoto 1992; Fu et al. 2006), demonstrates a long-standing interest in this field. Furthermore, the use of robots has expanded into other industrial applications, including waste deposits and electric power cables (Jiang et al. 2005); civil engineering tasks like inspecting building facades and concrete structures (Ilyas et al. 2021); examining structures such as ships, wind turbines, and aircraft (Almadhoun et al. 2016); and underwater facility inspections (X. Wang et al. 2022). More recently, several systems have been proposed for surveying nuclear power plants to assess radiation levels (Abadi et al. 2023; Mitchell et al. 2023). In the context of gas source localization, Francis et al. (2022) provide an overview of gas detection principles and review existing works that propose the use of mobile inspection vehicles.

Since vertebrates became terrestrial 370 million years ago, reliable information has been essential for making survival decisions (Munoz and Blumstein 2020; Thewissen and Nummela 2008). In our paper, we draw inspiration from the remarkable evolutionary strategies employed by vertebrates in their survival and adaptation within the animal kingdom. The fundamental principle of aeroacoustics leak detection revolves around the generation and propagation of sound waves when gas escapes from a pipeline (S. Wang and Yao 2020). These acoustic signals carry crucial information about the leak, such

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