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A Mid-Air Charging Mechanism for Extended Flight Duration

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This paper introduces a practical approach to sustaining uninterrupted drone operations during extended flight missions by developing and integrating specialized aerial recharging mechanisms. The proposed solution establishes robust connections between drones and designated aerial charging stations providing timely charging services during flight. This approach leads to an in-air charging solution that addresses the critical challenge of limited flight time due to battery capacity constraints. The integrated charging system comprises three essential components: a charging platform, a magnetic connector, and a landing gear. To ensure a stable and efficient recharging process during flight, each component is designed to cooperate with each other. The charging platform provides a secure docking station, the magnetic connector ensures a reliable connection, and the landing gear aids in precise alignment during the recharging process. Real-flight tests were conducted to demonstrate the effectiveness of the developed mechanisms, showing their practical applicability in the real environment. Based on the flight test results, it is shown that the proposed charging mechanism can enable mid-flight charging for battery-powered drones, reducing the need for frequent ground-based charging.

I. Introduction

The rapid growth of drone technology in modern society has opened up new opportunities across various industries, including surveillance, monitoring, and delivery services [1]. As drones continue to develop and enhance their capabilities, the need for extended flight missions has become increasingly important to meet the diverse demands of these applications. However, traditional battery-powered drones face significant challenges due to their limited battery capacity and thus the need for frequent recharging, making it difficult to maintain continuous operations during extended missions [2, 3].

To address this challenge, researchers and engineers have been exploring innovative solutions to enhance the operational capabilities of drones. One of the focused directions in recent research is the development of effective charging/recharging methods [4, 5]. One promising solution is the development of drone charging stations, which extend the operational range and duration of drones. These stations support continuous drone operations by reducing the need for frequent battery replacements, thereby minimizing manual intervention and ensuring smoother, more efficient operations [6–10]. Different designs for landing platforms have been developed to enhance the effectiveness of drone operations [11]. Usually, these charging stations features landing pads which is capable of automatic recharging.

Another promising solution is wireless charging, which uses a technique called Wireless Power Transfer (WPT) which is the transmission of electrical energy without physical connectors, using electromagnetic fields to transfer power from a transmitter to a receiver [12–14]. This technique shows significant potential for extending the operational time of drones by enabling them to recharge while in flight [15]. However, the technology still faces unique challenges such as lower energy efficiency over distances and alignment issues, lower power transfer rates, heat generation, interference, weight considerations, and the cost [12].

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Considering the advantages and limitations of existing charging mechanisms, this paper presents a practical approach to tackle the aforementioned challenge by proposing an integrated charging system designed to sustain uninterrupted drone operations during extended flight missions. The proposed solution establishes robust connections between drones and designated charging stations installed on larger drone platforms, thereby facilitating efficient mid-air recharging. This innovative system addresses the limitations of traditional battery-powered drones and enhances operational efficiency by enabling continuous flight without the need for frequent landings or returning to a ground charging station. Instead of using a wireless method, our approach involves charging by docking, which will be discussed in more detail later.

The integrated charging system comprises three main components: a charger, a landing platform, and landing gear, all engineered to closely cooperate with each other. The charging platform is mounted on a large drone, while the landing gear is attached to a smaller drone. In this setup, both the large and small drones are quadcopters. Through a series of flight tests, the effectiveness of the developed charging system has been empirically validated, demonstrating its practical applicability in real-world scenarios.

This paper is structured as follows: Section II describes the mid-air charging process, Section III details the charging system, Section IV describes the guidance, navigation, and control (GNC) system, Section V discusses the flight and charging tests, and Section VI presents the conclusion.

II. Mid-Air Charging

Mid-air charging is a process that allows drones to recharge their batteries while still in flight, without the need to land on the ground. This approach significantly extends the operational range and duration of drone missions by enabling continuous operation without frequent interruptions for ground-based recharging.

In mid-air charging, drones connect to designated charging stations that are typically installed on larger, airborne platforms, working as temporary mobile landing platforms. Figure 1 illustrates a schematic of a mid-air charging. We name the drone requiring charging service “receiver" and the drone providing charging service “supplier".

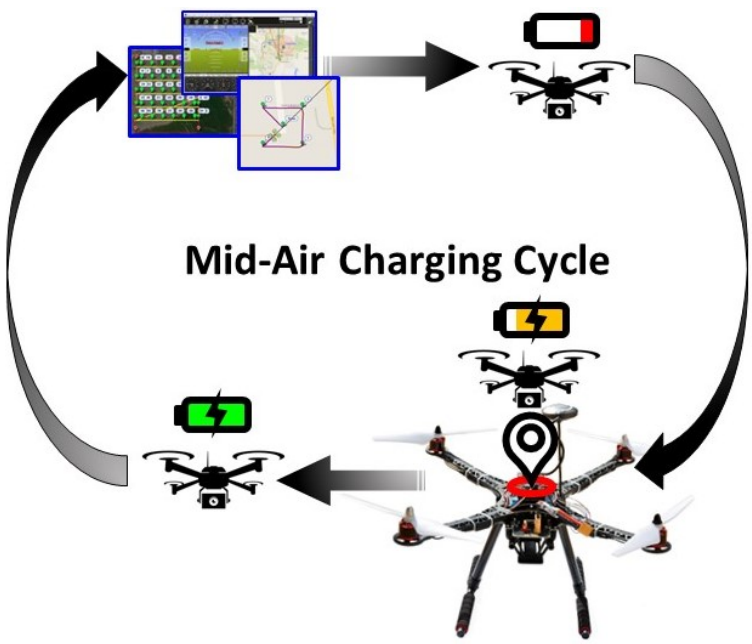

Fig. 1 Schematic of the mid-air charging

When the receiver drone’s battery is low, it connects to the supplier drone’s mounted charging station. This connection is facilitated by the integrated charging system, which ensures a secure and efficient transfer of power. After several minutes, once the battery is sufficiently charged, the small drone takes off again and resumes its mission. One key advantage of this approach is that, during the charging process, the supplier drone can transport the receiver drone closer to its target mission area, thereby reducing the receiver drone’s travel time and conserving its battery for the primary mission tasks. Additionally, the robust connection enabled by the magnetic connector ensures stable and consistent charging, which leads to uniform performance and reliability of the charging mechanism. This method not only extends the operational range and duration of the small drone but also enhances the overall efficiency and effectiveness of the mission. By integrating these advanced charging capabilities, the system demonstrates significant potential for practical application in various real-world scenarios.

III. Charging Platform

The charging platform developed for in-air recharging of drones comprises three essential components: the charger, landing platform, and landing gear combined with prop guards, as shown in Fig. 2. Next, we will explain the functionality of each component.

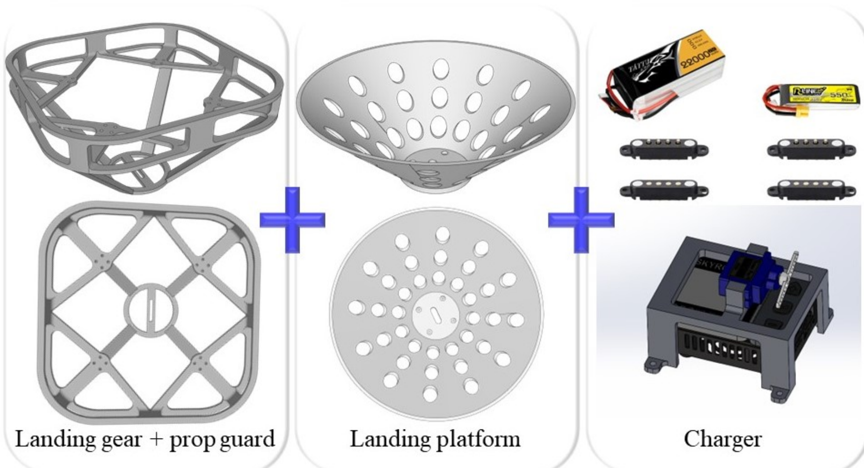

Fig. 2 Charging Components

A. Autonomous Charger

The charger mechanism employed in this system utilizes a straightforward setup. At its core, the process involves transferring power from the battery of a supplier drone to that of a receiver while both are airborne. This is achieved through a series of components working closely to facilitate smooth charging during the flight. The core of this mechanism is the SkyRC B6 Neo Charger, a device for charging drone batteries. The charger enables automatic activation and deactivation of the charging process by being coupled with a servo motor, which controls the switch between activation and deactivation. Using a Raspberry Pi, the servo motor initiates the charging operation when the voltage of the receiver drone falls below a predefined threshold. This ensures that the charging process is precisely timed and executed before the receiver drone's battery depletes. The whole charger is represented in Fig. 3.

Figure 4 illustrates the schematic of the electrical connection for the charger. Magnetic connectors are integrated into the output port of the charger, facilitating the transfer of power between the drones. These connectors serve as the interface through which electrical energy flows from the supplier drone's battery to the receiver drone's battery. Their magnetic properties ensure a secure connection between the two drones, even during aggressive flight maneuvers. The connectors for the application have been selected as 2.54 mm, 4-pin Pogopin magnetic connectors.

B. Landing Platform

To ensure precise docking of the small drone onto the charging platform, a landing funnel shown in Fig. 5 has been developed. Shaped like a funnel, this system helps the receiver drone align correctly with the charging mechanism. The design went through several adjustments to optimize its performance. The funnel's dimensions were carefully measured and calibrated to fully enclose the receiver drone on the landing platform. This precise sizing ensures a secure fit and reliable connection with the charger. By guiding the receiver drone into the correct position, the landing funnel plays a crucial role in the efficiency and effectiveness of the charging process, ensuring a secure connection with the charger.

Utilizing magnetic connectors capable of self-alignment, the funnel provides sufficient space for rotational movement while maintaining stable positioning during charging. The clearance at the base of the funnel permitted smooth pivoting

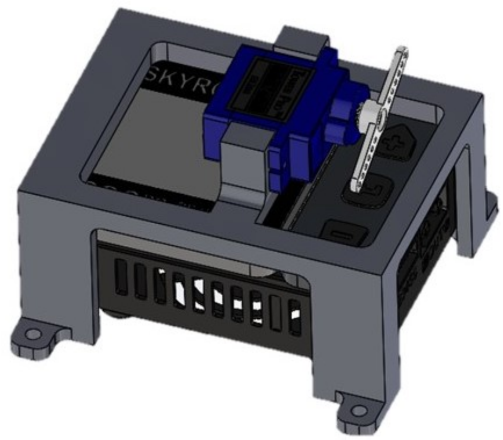

Fig. 3 Charger combined with the servo motor

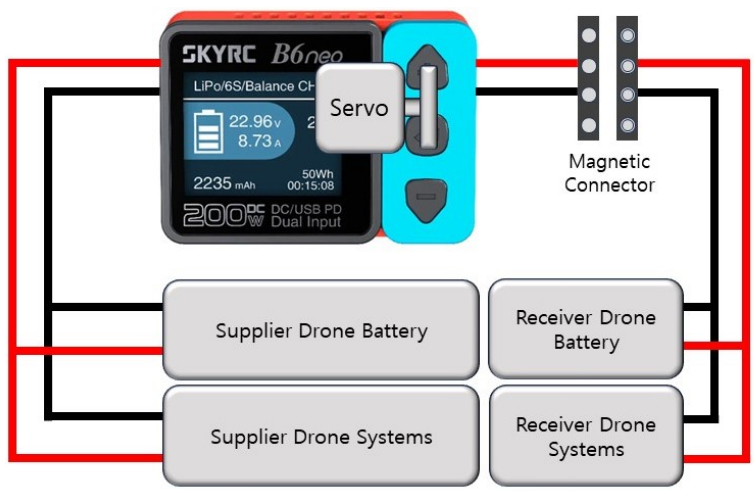

Fig. 4 Schematic of the electrical connection for the charging system

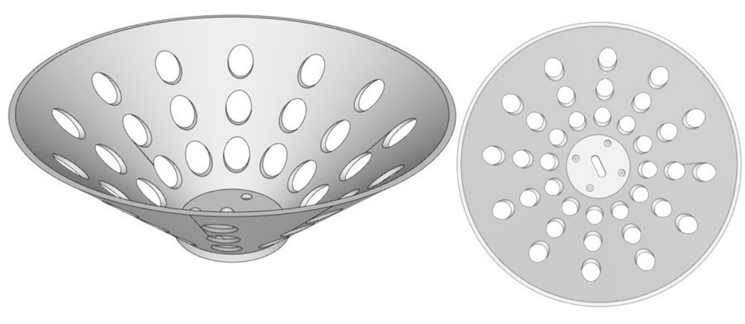

Fig. 5 Landing platform: side view (left), and upside-down view (right)

of the small drone's landing platform, while a servomotor supplied the necessary force for detachment during takeoff. To mitigate additional weight and aerodynamic drag induced by the funnel's geometry during the large drone's flight, holes were strategically placed. These features not only reduce weight but also minimize the wash effects generated by the receiver drone's propellers during landing and takeoff, thereby enhancing operational efficiency. Furthermore, to facilitate the integration of the landing platform, charging platform, and microcontroller (Raspberry Pi), the base of the funnel was subtly elevated off the center of the supplier drone. This design modification ensures precise alignment and effective operation of all components.

C. Landing Gear

A specialized landing gear design has been developed, as shown in Fig. 6, to ensure safe and secure docking of the receiver drone. This design notably includes integrated prop guards, which serve to protect the drone's propellers during rendezvous and docking, preventing potential damage. The incorporation of these prop guards is crucial for maintaining the integrity of the propellers during repeated docking maneuvers. Additionally, this landing gear design works in conjunction with a landing funnel, which further aids in the docking process. The combination of the landing funnel and the robust landing gear design significantly reduces the need for precise alignment during docking. By providing a larger target area during the mid-air landing process, this setup ensures a more reliable docking procedure, enhancing the overall efficiency and safety of the recharging operation.

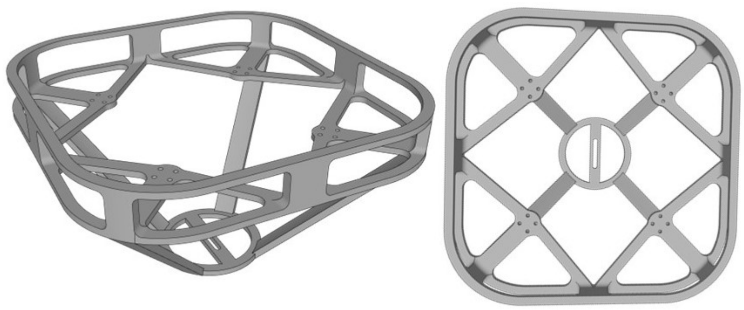

Fig. 6 Landing Gear: side view(left), and upside-down view(right)

IV. Guidance, Navigation, and Control

The GNC systems are essential for the effective operation of the integrated drone charging platform. These systems enable autonomous rendezvous, docking, and re-take-off during mid-air operations. In this work, the GNC has been specifically designed for the supplier drone and its primary mission, which is in-air charging. Since rendezvous, re-take-off, and carrying out various missions depend on the GNC for the receiver drone, the docking maneuver should be precisely managed by the supplier drone. This section details the design and implementation of the GNC systems utilized in the integrated charging platform. An overview of the GNC's design and structure is provided in Fig. 7, which illustrates the integration of its guidance, navigation, and control subsystems.

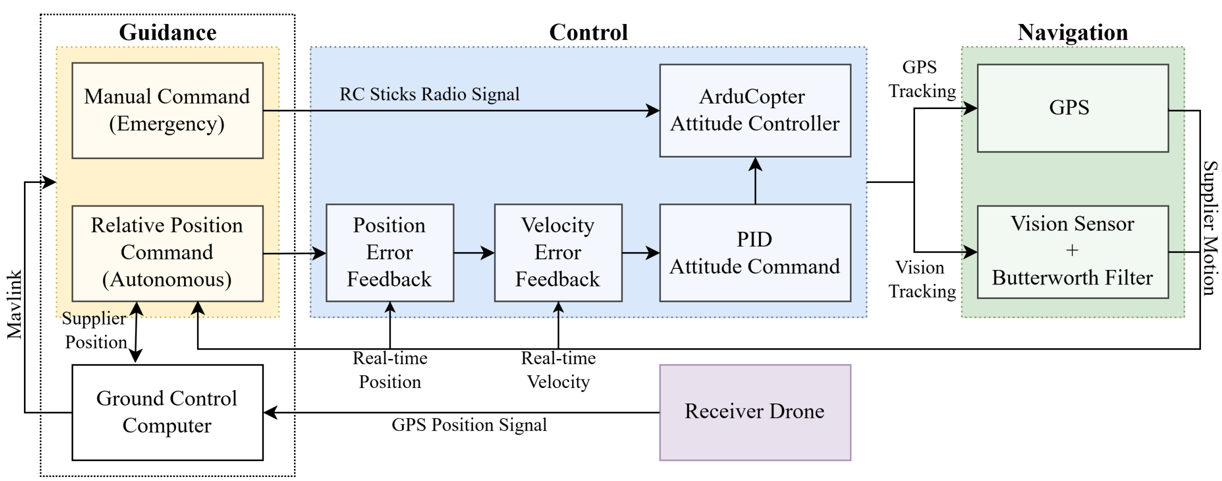

Fig. 7 GNC block diagram

A. Guidance

For the guidance system, the approach involves the supplier drone tracking the receiver drone rather than the receiver drone generating its own path for docking. This method is chosen because the receiver drone has a lower payload capacity compared to the supplier drone. Adding extra hardware, such as the Raspberry Pi and vision sensor, would significantly increase the payload of the receiver drone, potentially compromising its performance and flight time. Therefore, to maintain the lightweight nature of the receiver drone, all essential hardware components, including the Raspberry Pi and vision sensor, are installed on the supplier drone. This setup ensures that the receiver drone remains agile and efficient, while the supplier drone, carries the necessary equipment for precise tracking and docking maneuvers. As shown in Fig. 7, the guidance system is governed by the ground control computer via Mavlink, which facilitates seamless between the drones. Additionally, a manual command can override the autonomous in-air charging maneuver by operators at any time during the mission to mitigate potential risks or respond to unexpected events.

The reference signal for the supplier drone's tracking has two stages:

1) GPS-Based Tracking
   Initially, based on the GPS data from both drones, the reference signal commands the supplier drone to fly closer to the receiver drone, maintaining a vertical distance within 5 meters. During this phase, the GPS data ensures that the supplier drone approaches the receiver drone. When the accuracy for the GPS signal tracking meets certain accuracy, the guidance system commands the supplier drone to perform a stabilized hover.
2) Vision-Based Tracking
   Once the supplier drone is within 5 meters of the receiver drone, it transitions to a stabilized hover. At this point, the primary sensor switches from GPS to the vision-based sensor. The vision sensor provides more precise data for generating the reference signal, guiding the supplier drone to the exact position needed for docking.

The guidance sequence for the mid-air docking is illustrated in Fig. 8.

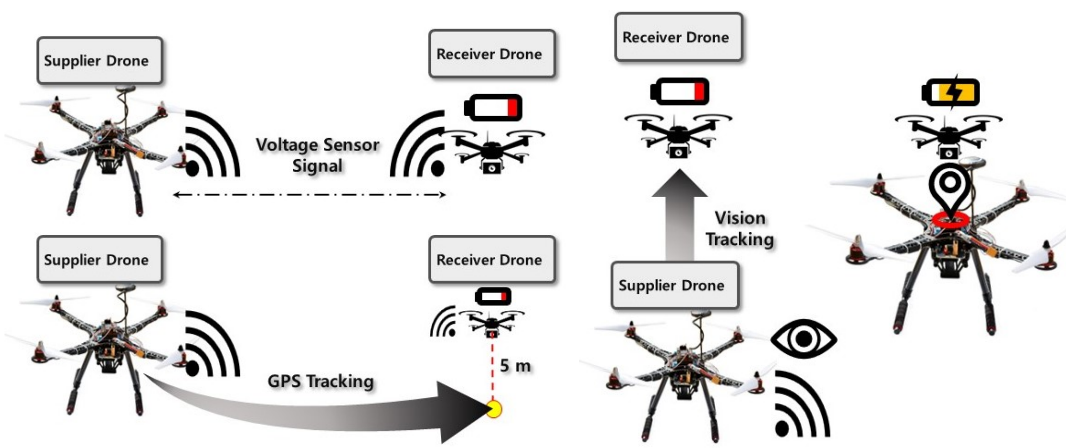

Fig. 8 Guidance sequence: GPS-based tracking (left), and vision-based tracking (right)

B. Control

The control system employs embedded proportional-integral-derivative (PID) controllers provided by the Ardupilot firmware [16]. Before conducting the target flight, the drones were auto-tuned using Ardupilot's auto-tune feature. This process involved flying the drones in specific patterns, allowing the firmware to automatically optimize the PID parameters for enhanced performance.

The Ardupilot controller adopts a traditional inner/outer loop control structure, as depicted in Fig. 7. The guidance block first sends the relative position command to the supplier drone. Using real-time sensor data from the supplier drone, the system calculates both position and velocity errors. These errors are then processed to generate the final attitude command through the inner loop PID controller, which sends the command to the ArduCopter attitude controller for execution.

C. Navigation - Vision-Based Sensor

Along with GPS navigation, the supplier drone employs a Raspberry Pi camera for enhanced tracking precision. GPS enables reliable positioning during the initial long-range approach, while the vision-based sensor ensures precise alignment and control during the critical short-range navigation and docking phase

The supplier drone is equipped with an upward-facing camera to aid in docking. Once the receiver drone is within the camera's field of view (within 5 meters vertically), a vision-based algorithm takes over to control the supplier drone's motion. This algorithm employs a combination of color-based and contour-based vision techniques to ensure precise detection of the target.

The receiver drone's landing gear is painted red to make it stand out from the environment. The color-based vision algorithm identifies the highest concentration of red pixels by creating a binary mask that isolates red regions in the image. This method serves as a redundancy baseline, being straightforward and computationally efficient, although it can be affected by changes in lighting conditions.

To complement this, the primary method for locating the receiver drone is the contour-based vision algorithm, which uses edge detection and contour detection techniques. First, the image undergoes preprocessing, including conversion to hue, saturation, and value (HSV) color space and Gaussian blurring, to reduce noise. The algorithm then applies edge detection (using the Canny edge detector [17]) to highlight the edges within the image. Once contours are identified, a Gaussian blur is applied to reduce the number of detected contours [18]. The relevant contour is then selected by comparing it with the results from the color-based method, ensuring accurate identification of the receiver drone.

To eliminate external noise from the vision-based algorithm, a Butterworth low-pass filter is implemented. The filter reduces the effects of noise from real-time positioning calculations of the receiver drone relative to the supplier drone. Distances in the x-direction, y-direction, and total magnitude are calculated and filtered in sets of 10 data points. The optimal cutoff frequency for each distance was determined systematically by calculating the mean squared error (MSE) before and after filtering. The frequency that maximized noise reduction was selected, providing the least disturbed live data for the main vision tracking algorithm.

V. Experimental Tests

All designs mentioned in Section III have been manufactured using 3D printing and integrated as shown in Fig. 9. The supplier drone used in the setup is an S500 quadcopter frame equipped with 2212-920 KV brushless motors and 10X4.7 multi-rotor propellers. These motors are optimized for two 4S Lithium Polymer (LiPo) cells. The frame and landing gear are made of high-quality carbon fiber, and the frame size is 500 mm. The empty weight of the drone, including the motors and blades, is 1.074 kg, while the maximum payload capacity is 1.5 kg at 85% throttle.

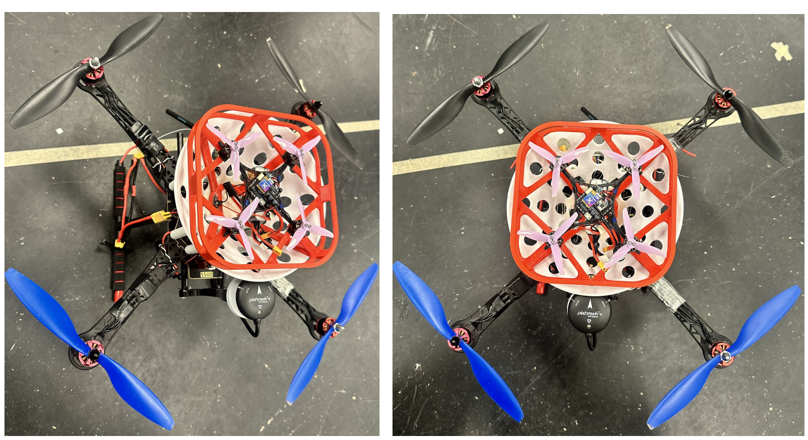

Fig. 9 Integrated mid-air charging platform mounted on the supplier drone

The receiver drone's frame is also carbon fiber with a frame size of 76.2 mm, and the receiver drone's battery is 3S LiPo cells with a capacity of 550 mAh. The total weight of the small drone with the landing gear attached is 0.18 kg.

Finally, the landing funnel mounted on top of the large drone weighs 0.03 kg. When combined, the total weight of the hardware shown in Fig. 9 is 1.257 kg, which is well within the maximum payload capacity of the supplier drone.

Although the weight and materials have been specifically tailored for this application, it is worth noting that the size of the platform, landing gear, and batteries can be adjusted for different applications and other types of drones.

Two types of experimental tests, the charging system test and the flight test, have been conducted to validate the practical applicability of the developed charging system.

A. Charging Test

The first experiment aims to validate the safety and reliability of the charging system depicted in Section III. This validation is critical to ensure that the charging process is both efficient and does not pose any risks to the drone or its components. The test setup is arranged indoors to control environmental variables and ensure accurate results. Both receiver and supplier drones are equipped with their respective batteries for the duration of the experiment.

The receiver drone in this experiment uses a 3S LiPo battery, which has a nominal voltage of 11.1 V and a fully charged voltage of 12.6 V. For consistency, each iteration of the experiment begins with the battery at an initial voltage of 11.6 V. This starting point ensures that the battery is partially discharged, providing a realistic scenario for the charging process.

The primary objective of this test is to monitor two critical parameters: the temperature of the battery and the time it takes to reach full charge. Monitoring the temperature is essential because excessive heat can indicate problems with the charging process and potentially lead to safety issues, such as battery swelling or fire. The time taken to reach a full charge is equally important as it reflects the efficiency of the charging system.

To comprehensively evaluate the charging system, the experiment involves varying the charging current. This means adjusting the capacity of the charger to see how different rates affect the charging process. For instance, the charger might be set to charge at 1C, 2C, or higher, depending on the battery's specifications and safety limits. By changing the charging current, the experiment can determine the ideal rate that balances between charging speed and safety.

During each iteration, data on the battery's temperature and voltage is collected continuously until the battery reaches the final voltage of 12.6 V. This data helps to identify any abnormal temperature rises and ensure that the battery charges within a reasonable time limit. The results imply whether the charging system can safely and effectively charge the drone's battery without causing overheating or other issues.

Table 1 shows the results of the charging experiment. Despite the higher charging rate, the mean and maximum temperatures observed at 5C were lower than those at 3C. This indicates that the charging system effectively manages heat even at higher currents, which is crucial for maintaining battery safety and longevity. The charging time is significantly reduced at the 5C rate compared to that charged at the 3C rate, with the battery reaching full charge in less than half the time. This increased efficiency is beneficial for applications requiring rapid charging times for drone operations. At last, in both scenarios, the batteries reached the target final voltage of 12.6 V demonstrating the charging system's ability to consistently achieve a full charge regardless of the charging rate. Based on these results, the lower temperatures and reduced charging times at higher capacities highlight the system's robustness and potential for practical applications where quick and safe battery recharging is essential.

Table 1 Charging experiment results

Charging Rate	Initial Vol (V)	Mean Temp ($^{\circ}C$)	Max Temp ($^{\circ}C$)	Final Vol (V)	Time (s)
3c	11.41	26.65	28.00	12.6	700
5c	11.40	25.30	25.55	12.6	300

B. Flight Test

The primary objective of the flight test was to evaluate the functionality of the developed mid-air charging system, focusing on smooth docking, secure charging, and efficient re-take-off. The test was conducted outdoors in an open field, involving two pilots: one operating the ground control computer and the other handling a transmitter to manage the supplier drone in case of an emergency.

The receiver drone followed a predefined flight path that included take-off, hovering, and landing maneuvers. At a designated point in time during its mission, the receiver paused and started hovering mid-air and sent a charging request signal to the ground control computer, indicating the need for a recharge.

The supplier drone initially performed way-point tracking, awaiting a charging signal from the receiver drone. Upon receiving the signal, the supplier drone tracked the x-y position of the receiver drone and maintained an approximate altitude of 5 meters below from the receiver drone. Once visual contact was established, the supplier switched to vision-based tracking for precise alignment, initiating a docking maneuver.

The supplier drone gradually approached the receiver drone using vision-based tracking for precise alignment. Upon achieving successful docking, the supplier drone initiated the battery charging process while maintaining stable mid-air positioning with the receiver drone securely attached. After completing the charging operation, the receiver drone can either resume its predefined mission by taking off from the supplier's landing platform or remain on the platform, allowing the supplier drone to either land or continue flying to another location while carrying the receiver drone.

Figure 10 presents a recorded time-lapse of the supplier's tracking and docking process during the flight test including the re-take-off of the receiver drone after getting docked. The test demonstrated the system's capability to perform all phases of the in-air charging mission reliably and efficiently in a realistic outdoor environment, including the precise mid-air docking and charging.

To see the whole flight test footage, visit `https://www.youtube.com/watch?v=-_ggvUPjFC8`.

Fig. 10 Autonomous fight test sequence - filmed during the real test

One significant challenge observed was the effect of downwash from the receiver drone on the supplier drone. As the receiver drone approached and flew over one of the supplier drone's motors, the downwash created an additional downward force, destabilizing the supplier drone's hovering state. This issue highlighted the need for further refinement in managing aerodynamic interactions between the two drones during the docking process. One simple solution can be decreasing the receiver drone's weight which will result in decreased thrust and downwash accordingly.

VI. Conclusion

This paper presents a practical approach to addressing the challenge of maintaining continuous drone operations during extended flight missions by proposing an integrated mid-air charging system. The system is designed to facilitate mid-air recharging, thereby eliminating the need for drones to frequently land and connect to ground-based charging stations. The integrated charging system, comprising a charger, a landing platform, and landing gear, has been designed and implemented. The supplier drone, equipped with the charging platform, and the receiver drone, equipped with the landing gear, demonstrated successful mid-air docking and re-take-off through the flight tests. These tests validated the system's practical applicability and its ability to enhance operational efficiency by enabling continuous flight without frequent landings.

Experimental tests, including charging and flight tests, were conducted to validate the safety, reliability, and efficiency of the charging system. The charging test results showed that the system effectively manages heat even at higher charging rates, achieving a full charge in less time while maintaining safe temperature levels. The flight test demonstrated smooth docking and re-take-off mid-flight, further confirming the system's effectiveness.

However, the tests also revealed challenges, such as the impact of downwash from the small drone on the large drone's stability. Addressing these aerodynamic interactions is crucial for future implementations.

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