Robotic Ground System for Autonomous Battery Replacement

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Introduction

Each day, new technologies emerge as innovators strive to enhance human life, exemplified by the rise of small-scale aircraft, or drones, revolutionizing tasks like remote monitoring, supply delivery, and aerial videography. However, challenges arise regarding drone flight duration and mission length due to limitations of lithium polymer (LiPo) batteries commonly used to power these aircraft weighing under 50 pounds. While LiPo batteries excel in energy density and discharge rates, they struggle with lifespan and require lengthy recharging periods, hindering extended flight missions. An approach to solve this issue is by creating a replicable ground system, the Robotic Ground System (RGS) which operates autonomously to replace depleted drone batteries with fully charged ones, ensuring continuous power for onboard hardware and preserving critical mission data. This system aims to extend drone flight endurance by implementing hot-swappable battery stations strategically placed on the ground.

Autonomous Swapping Methodology

Battery swapping on the Robotics Ground Station occurs in 5 distinct stages that operate autonomously from the controller boards:

- **Stage 1 - Autonomous Landing:** A standardized UAV lands on the Ground Control Station using the AR marker to increase precision.
- **Stage 2 - Battery Transfer:** A robotic arm extracts the battery from the drone and transfers the battery from the GCS to the BVM
- **Stage 3 - Battery Swap:** The Battery Vending Machine accepts a depleted battery and dispenses a full battery back to the robotic arm
- **Stage 4 - Battery Transfer:** A robotic arm transfers the full battery from the BVM to the GCS
- **Stage 5 - Takeoff:** The full battery is inserted back into the drone and a takeoff procedure initiates, resuming the mission.

Individual Sub-systems

The Robotics Ground System is made up of three sub-systems: the Ground Control Station, the Battery Vending Machine, and the Battery Transfer Pod. Altogether, they are able to switch a drone's battery anonymously to provide a seamless and efficient battery swapping process. Each sub-system in the RGS is able to integrate and communicate with each other, ensuring drones are able to operate continuously with minimal downtime for battery swapping.

1. **Ground Control Station (GCS):** Provides a safe and secure pit stop location for drone to land and begin the process of battery swapping. Handles all the data from the RGS to be sent to the VPS and User Interface Webapp Dashboard
2. **Battery Vending Machine (BVM):** Circular rotating subsystem that charges, manages and stores 8 LiPo batteries on standby for the process of battery replacement.
3. **Battery Transfer Pod (BTP):** Main subsystem that integrates the GCS and BVM together. Bi-directional Pod equipped with a robotic arm that swaps and transports the battery back and forth.

Figure 1a: *Standard Quadcopters*

Figure 1b: *Quadcopter on Ground Control Station*

Figure 1c: *Battery Vending Machine Prototype*

Figure 1d: *Battery Transfer Pod Prototype*

System Intergration

The multiple components of the RGS simply does not enhancing the endurance of UAV's but helps supports the battery swapping method. When integrated, these components enable a seamless battery replacement process, ensuring that the drone is ready to take off within 5 minutes of landing.The CAD model of the RGS was designed using Fusion 360 and subsequently constructed using PLA material to produce the 5ft x 7ft Robotic Ground System. This approach combines advanced design techniques with practical manufacturing methods to achieve a functional and scalable system for UAV battery management and swift operational turnaround.

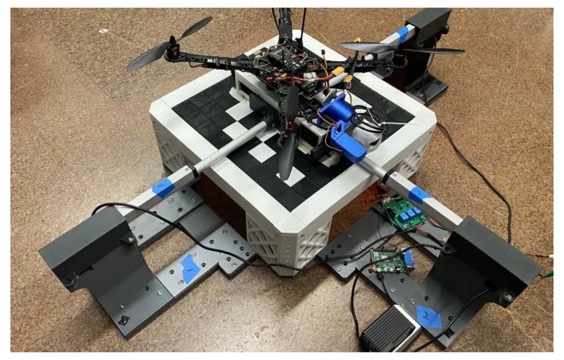


Figure 2a: *GCS Secures Drone into Place*

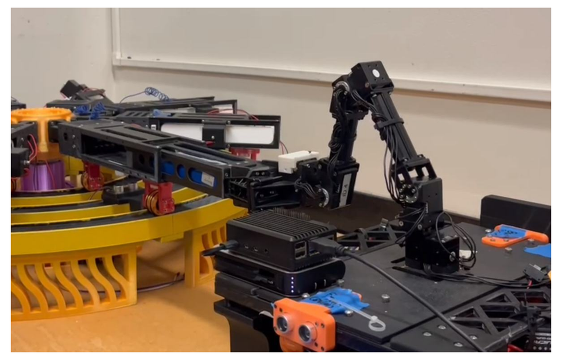


Figure 2b: *BTP Grabbing Battery from BVM*

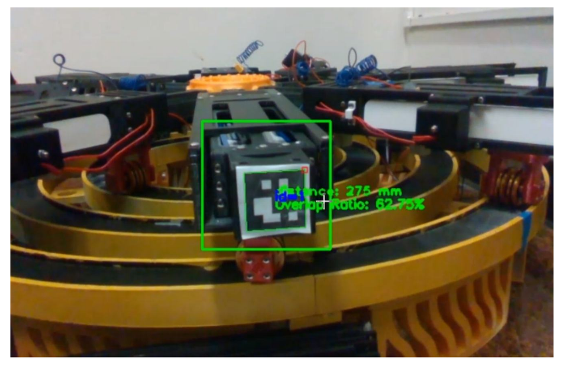


Figure 2c: *Camera Scanning ArUco Marker on BVM*

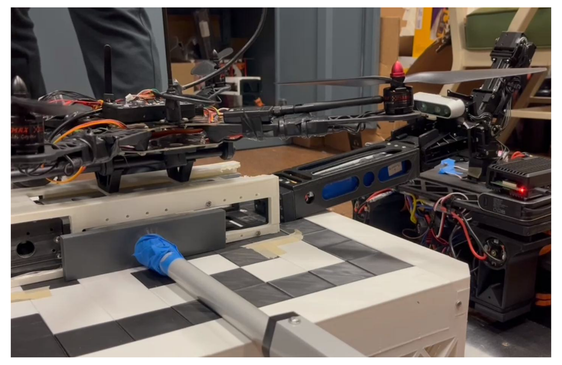


Figure 2d: *BTP Grabbing Battery Out of Drone on GCS*

The main integration in the Robotic Ground System:

- **Drone Connection with GCS:** Drone scans the GCS's 7x7 AR marker to land autonomously onto. Induction coils on both sides, connects wirelessly to signal the GCS being occupied by the drone which gets adjusted and secured into place by locking mechanism.
- **BTP at GCS:** The GCS will signal the BTP to begin the process of battery swapping, initializing the camera on the Robotic Arm to start scanning for the battery on the drone. The arm grabs the battery from the drone seamlessly. Additionally, the BTP will need to put a new battery back into the drone stationed on the GCS.
- **BTP at BVM:** The integration between the BTP and BVM facilitates the seamless insertion and retrieval of fully charged batteries, ensuring smooth progression to subsequent operational phases. This coordinated movement streamlines the battery swapping process, optimizing efficiency and reliability within the system.

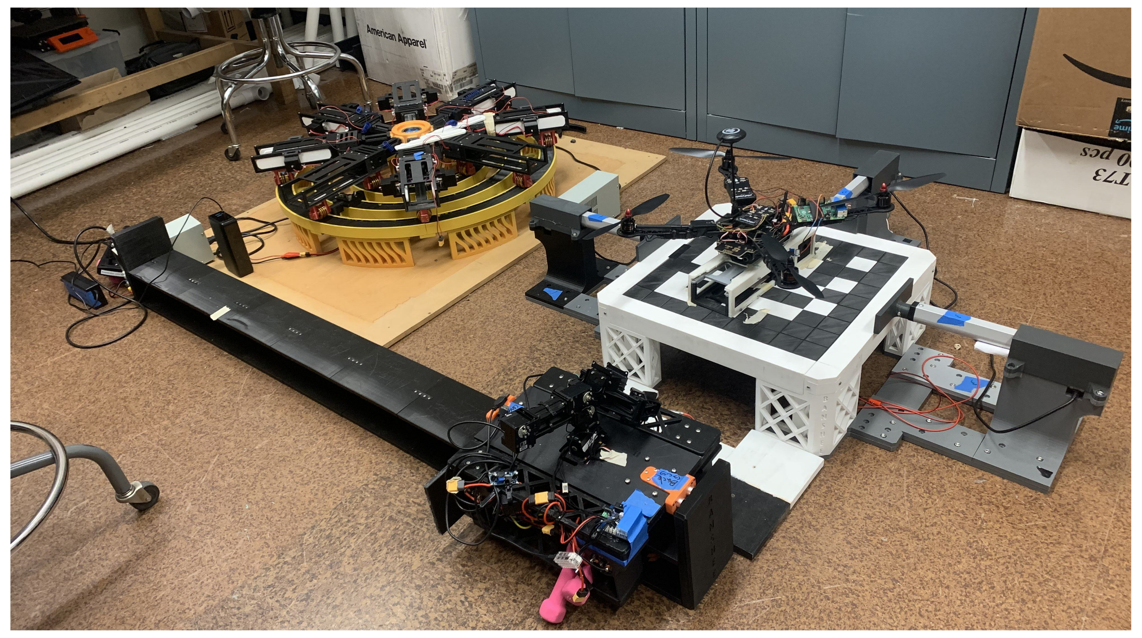


Figure 2e: *Rendered CAD model of Robotics Ground System*

Communication of System Intergration

With multiple individual systems, the Robotic Ground System's integration process requires different communication protocols to reliability accept and send signals within each other to autonomously operate in a sequential pattern. The RGS uses both wireless and serial communication between the system to ensure a seamless and rapid connection between each stage.

- **TCP IP Socket:** Transmission Control Protocol (TCP) facilitates connection-oriented communication, ensuring reliable bidirectional communication between server and clients over a network. The GCS hosts a TCP socket server and passively listens for incoming connection requests. In the RGS system, the BTP establishes an initial connection and maintains it, while drones connect upon landing and disconnects after takeoff. The GCS utilizes multi-threading for client connections, effectively managing timing and sequencing for both systems synchronously, such as drone locking, RGB leds, telemetry data upload, battery hot-swapping.
- **Wireless RF Modules:** To minimize wiring complexity within the Battery Voltage Monitoring (BVM) system, RF modules (nRF24L01) are employ to transmit data wirelessly from the battery chambers to the central hub controller of the BVM. This data comprises the individual cell voltages of each LiPo battery housed within the chambers. Furthermore, the central hub controller is responsible for relaying all gathered data to the Ground Control Station (GCS) for further processing and monitoring via nRF24L01 modules as well.
- **I2C Communication:** I2C is a fast and efficient serial communication protocol that facilitates data transfer using only three wires between connected hardware devices. The GCS Raspberry Pi encounters challenges when directly interfacing with the nRF24L01 module for data collection. Given its critical role in gathering and transmitting data from the RGS to the VPS, the RPi relies on I2C communication with an Arduino board. This method ensures reliable transmission of voltage data from the BVM system to the GCS, enhancing the overall operational efficiency and data integrity of the system.

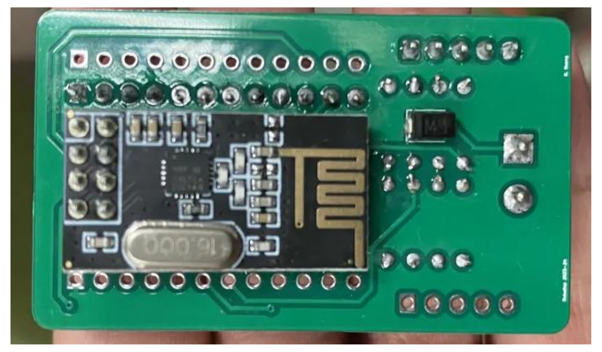


Figure 3a: *nRF24L01 PCB in Battery Chamber*

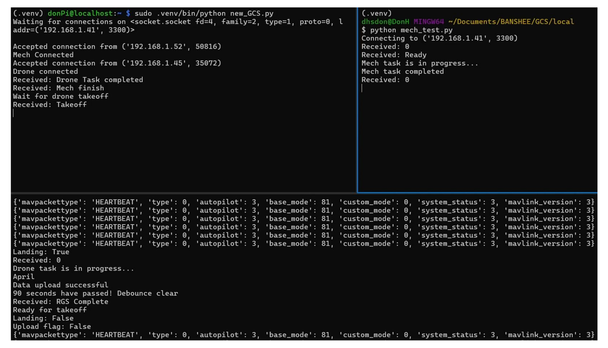
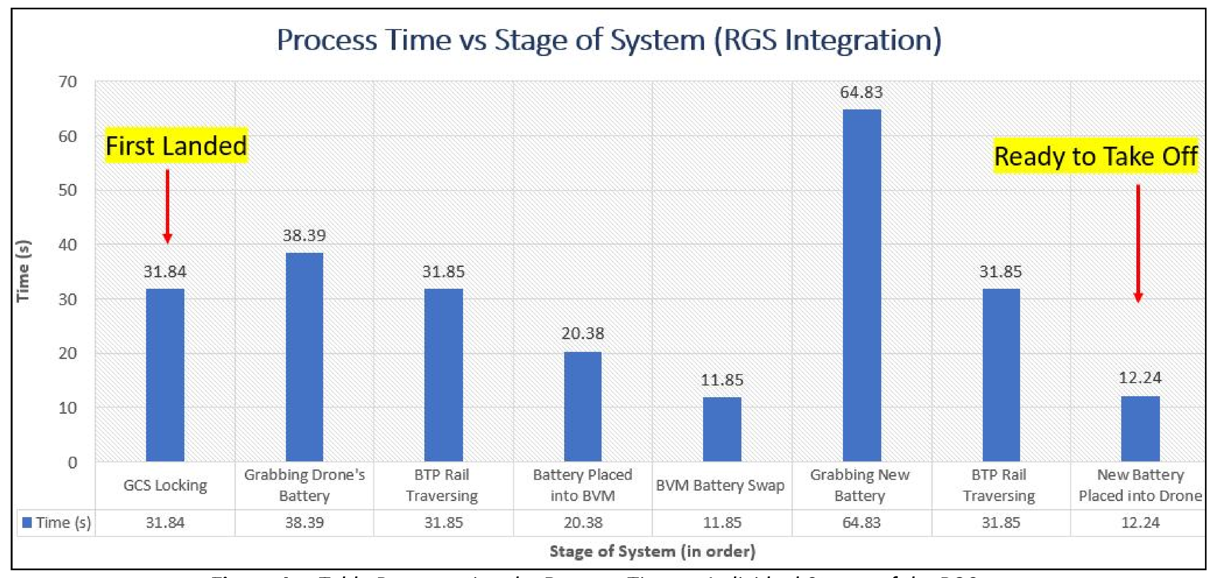


Figure 3b: *Controlling the BTP using a Transmitter*

Completion Timing

With the Robotic Ground System featuring the three distinct systems, facilitating the battery swapping process with the quickest timing matters. The timely replacement of batteries directly impacts the overall objective of prolonging UAV flight duration.

By timing each movement of the RGS integrated system, it demonstrates a overall turnover time of **243.23 seconds or 4.05 minutes**. This time only includes the process of battery swapping from the start of the initial induction coil connection to the complete placement of the new battery into the drone.



	GCS Locking	Grabbing Drone's Battery	BTP Rail Traversing	Battery Placed into BVM	BVM Battery Swap	Grabbing New Battery	BTP Rail Traversing	New Battery Placed into Drone
Time (s)	31.84	38.39	31.85	20.38	11.85	64.83	31.85	12.24

Figure 4a: *Table Representing the Process Time vs Individual Stages of the RGS*

Intergration Flowchart

A physical prototype of the RGS serves as a preliminary model for testing the battery swapping process. Designed to be cost-efficient, the RGS was developed at a total production cost of $2900, encompassing hardware electronics and materials. This investment covers the essential components necessary for efficient battery management and operational functionality within the system.

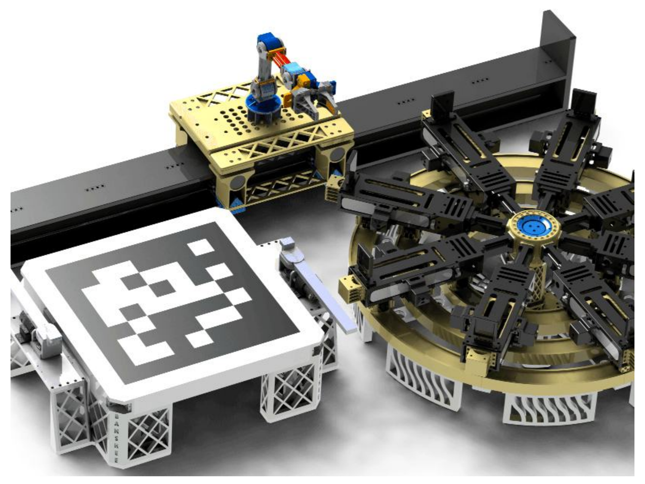


Figure 5a: *Physical Prototype of the RGS*

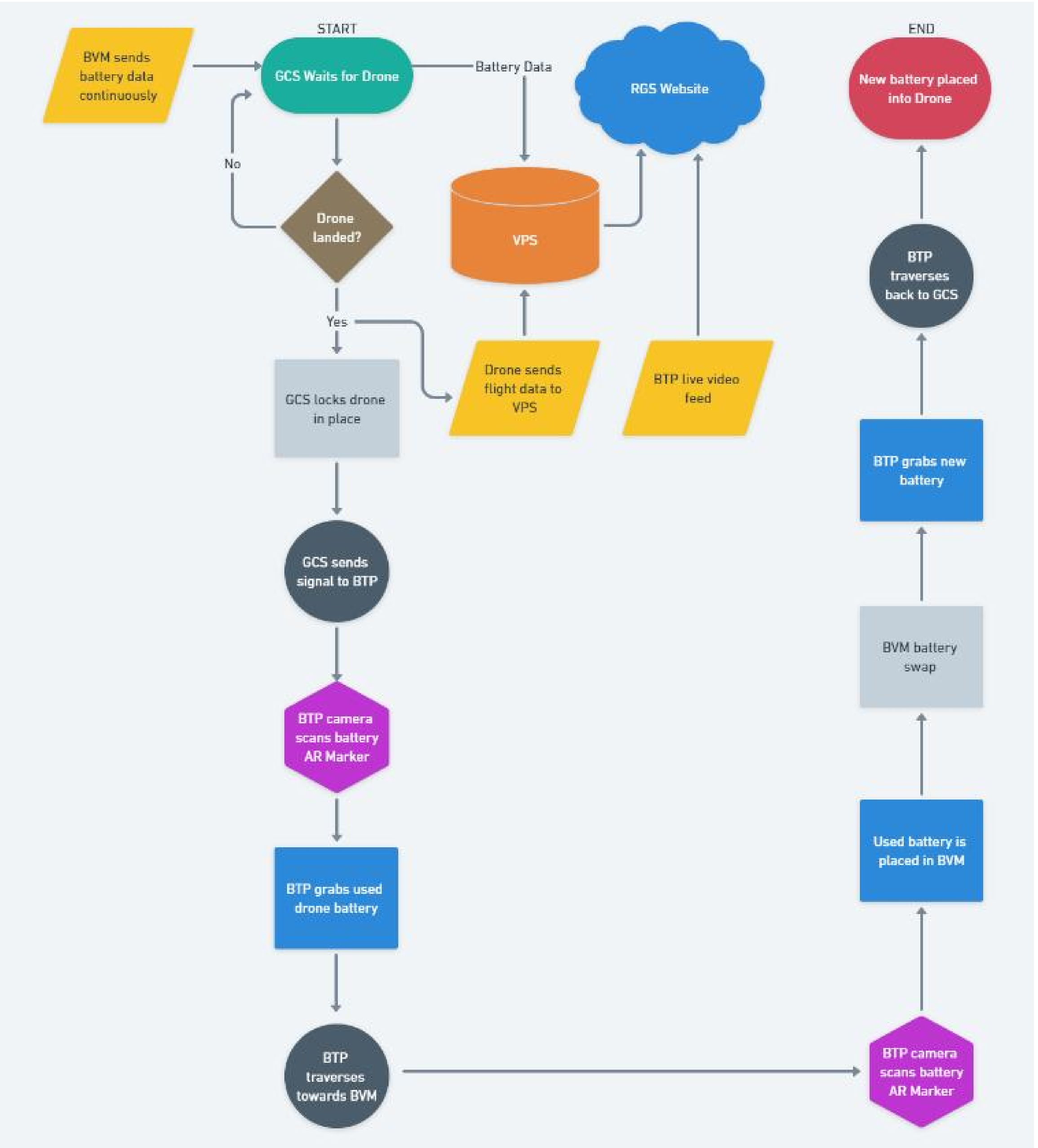


Figure 5b: *Process of Robotic Ground System Flowchart*

Conclusion

The Robotic Ground System utilizes its four stations and five stages of operation to perform autonomous battery swapping for UAVs. UAVs that utilize the RGS have a theoretical infinite flight time based on the power replenishing mechanism and the number of deployed stations. When a UAV utilizes the Robotic Ground System to swap its depleted battery for a new one, it undergoes a turnaround time of two minutes. After the swap has completed, the UAV is capable of resuming its flight mission without the need for human interference.

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