AN AUTONOMOUS SYSTEM FOR DOCKING AND BATTERY SWAPPING IN UAVS

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Abstract

This study presents an autonomous robotic docking and battery swapping system for UAVs (Unmanned Aerial Vehicles) designed to operate at altitudes of 500 feet or higher using a custom aerostat for elevation. The system aims to address the critical issue of limited battery life in UAVs by providing a cost-effective and efficient solution that reduces downtime associated with manual battery replacement. Our approach includes a pulley-belt-based parallel docking mechanism made of carbon fiber rods, aluminum extrusions, and a vertical linear actuator for battery swapping. The docking system ensures the UAV is securely held during the battery exchange, which is facilitated by a custom 3D-printed battery casing and a linear conveyor belt system with conductive copper plates for charging. Additionally, the docking system utilizes load cells to confirm the UAV's landing, ensuring accurate and reliable battery swaps. We have chosen an air-based battery swapping system on an aerostat so that the UAV can avoid using extra control to lower its altitude to land on the ground, as taking off and landing are the most power-intensive phases of flight. This integrated system, constructed from lightweight materials, not only enhances the autonomy of UAV operations but also envisions a future hub where multiple UAVs can dock, swap batteries, and resume their missions while their batteries recharge, significantly extending their operational capabilities and efficiency. .

Keywords: Autonomous Systems; Aerospace; Aerostat; Robotics; Unmanned Aerial Vehicles (UAV); Mechanical

1. Introduction

As Unmanned Aerial Vehicles (UAVs) become increasingly integrated into a diverse array of applications, ranging from military surveillance to commercial package delivery, the demand for these vehicles to possess enhanced functionality and greater autonomy continues to rise. This shift towards more autonomous operations is driven by the need for UAVs to perform complex tasks over extended periods without human intervention. However, one of the primary challenges impeding this progress is the limited battery life of UAVs. The short operational duration of batteries necessitates frequent returns to base for recharging or battery swapping, which not only interrupts missions but also requires human involvement, thus reducing the overall efficiency and autonomy of UAV operations.

The typical UAV flight duration is significantly curtailed by the energy expended during take-off and landing phases, often leading to considerable downtime when battery replacement is performed manually. Standard charging times for UAV batteries can range from 60 to 90 minutes depending on environmental conditions and the specific power requirements, while the average flight time might only be around 34 minutes, varying with the configuration and make of the UAV. Although there are batteries available that offer faster charging capabilities, they are often not commercially viable due to their high cost or limited availability. Consequently, the UAV industry faces a critical need for innovative solutions that can extend flight times without necessitating prohibitively expensive technology upgrades.

To address this issue, autonomous battery swapping systems have been proposed and, in some cases, implemented. However, many existing systems are complex and costly to manufacture, making them less accessible for widespread use. These systems typically involve intricate robotic manipulators or sophisticated mechanical designs, which can be cumbersome and challenging to deploy, especially in mobile or varied operational environments. Moreover, the integration of these systems often requires significant modifications to the UAVs and their support infrastructure, further increasing the cost and complexity.

Recognizing these challenges, our research aims to develop a more efficient, cost-effective solution for extending UAV operational time through an autonomous docking and battery swapping system. This system is designed to be integrated into an aerostat platform, which can be deployed at altitudes of up to 500 feet, thus allowing UAVs to perform battery swaps mid-mission without returning to a ground-based station. The aerostat serves as a stable, elevated docking platform, reducing the energy expenditure associated with repeated take-offs and landings.

Our proposed system utilizes a pulley-belt-based parallel docking mechanism constructed from lightweight materials such as carbon fiber rods and aluminum extrusions. The docking mechanism securely holds the UAV during the battery exchange process, which is facilitated by a custom 3D-printed battery casing and a linear conveyor belt system with conductive copper plates for charging. Load cells are employed to confirm the UAV's precise landing, ensuring accurate and reliable battery swaps. This integrated system not only enhances the autonomy of UAV operations by minimizing human intervention but also envisions a future where multiple UAVs can dock, swap batteries, and resume their missions while their batteries recharge, significantly extending their operational capabilities and efficiency.

By focusing on lightweight construction, our approach addresses the key limitations of existing battery-swapping solutions, offering a scalable, versatile system that can be adapted for various UAV applications. This research contributes to the advancement of UAV technology, paving the way for more autonomous, efficient, and cost-effective UAV operations that can meet the growing demands of modern aerial tasks.

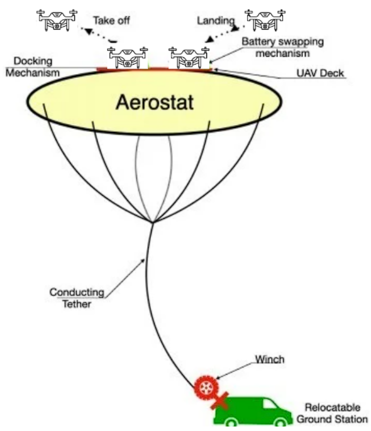

Figure 1 – Proposed docking and battery swapping hub

2. Literature Review

Based on our survey of current battery-swapping systems in [1], they can be generally classified into two categories:

2.1 Robotic Manipulators

Robotic manipulators generally involve a linear manipulator or robotic arm-type device that is directly used for the battery swapping process as shown in Fig. 2.

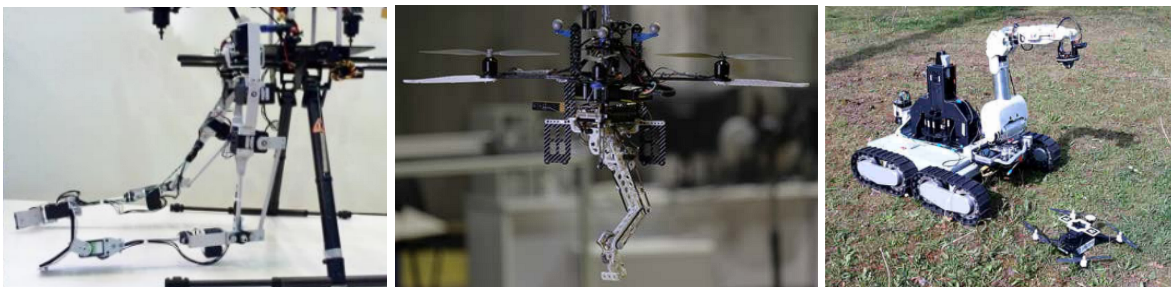

Figure 2 – Robotic Manipulators [7] [8]

2.2 Linear and rotary systems

In these types of systems, the UAV is usually docked onto a movement-based system, this movement can be linear or rotary as shown in in Fig 3.

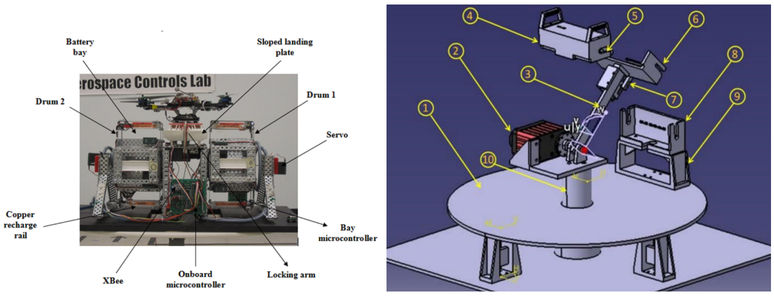

Figure 3 – Linear and rotary based systems [7] [8]

Type	Weight	Margin for errors	Cost	Speed of Operation	Complexity	Application on mobile platforms
Robotic Manipulator (DOF > 3)	High	High	High	Low	High	Directly applicable
Scissor Mechanism	Average	Average	Average	High	Average	Possible with modifications
Linear Robots	Low	Average	Low	High	Low	Possible with modifications
Rotary	Low	Low	Low	Average	Average	Possible with modifications

Table 1 – Comparison Table giving an overall picture [1]

After a detailed literature review, the various battery swapping systems classifications, various parameters, and applications are summarised in Table 1.

2.3 Design challenges

In the context of battery swapping, we have dynamic systems that are expected to have rapid adaptability to the UAV that lands for battery swapping. Having a system with more degrees of freedom gives us better flexibility as well as variance. With more degree of freedom, the variables to control the system increase and the controller needs to be designed in such a way to ensure that it identifies the variables and hindrances and adapts accordingly. After evaluation of various control system architectures, we propose the use of partially adaptive controllers because using their combination with present reference values, one could take advantage of the model-based design, with its stability guaranteed while simultaneously allowing for fast data-driven convergence and robustness to uncertainties. The same has been demonstrated in [9] and is called modular control.

The structure of the battery-swapping system mounted on the aerostat can affect the weight balance the vibrations and the moments caused during the landing and take-off UAV. Considering both linear and circular systems, in either case, there will be an unbalanced moment about an axis that needs to be balanced creating more problems with the aerostat as shown in Fig. 4 and 5.

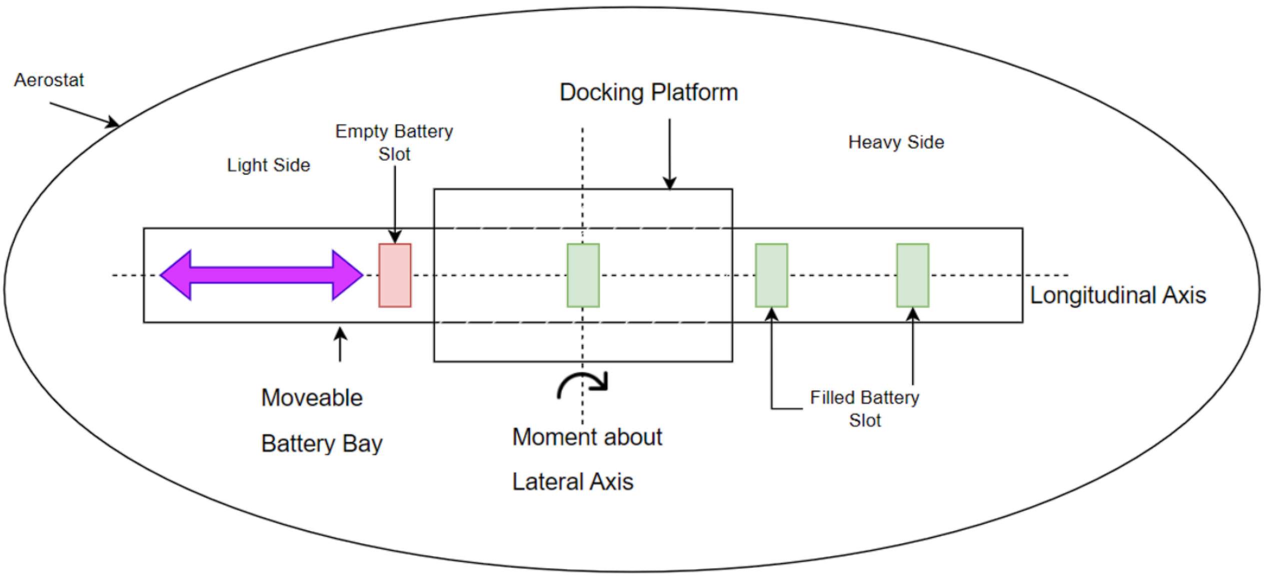

Figure 4 – Top view of linear system on aerostat [1]

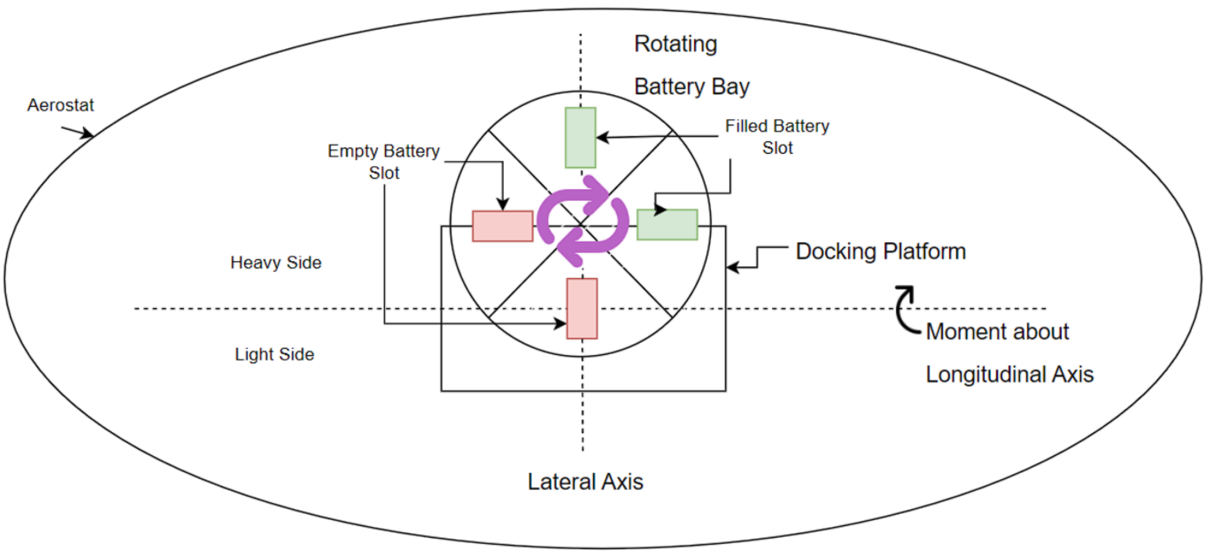

Figure 5 – Top view of circular system on aerostat [1]

3. Methodology

3.1 Proposed System

We propose a linear mechanism where the battery will be placed onto a linear sliding belt by another linear actuator. This system will be integrated on top of an aerostat which will allow the system to reach an altitude of 500 feet. The linear system proposes better control and stability compared to the circular system. Since an aerostat is involved the system has to be as light as possible our aerostat system has a volume of 70 m^3 it is oblate spheroid in shape and all the given system is mounted on top of the aerostat which helps to ease in the detection of landing zone for the UAV. We have to make sure that the UAV does not topple on top of the system. During the battery swapping process, the UAV should not move so it should be arrested properly to restrict motion on the landing board it should also stabilize the UAV in such a way as to prevent the blades of the UAV from coming in contact with the aerostat. For this, we have divided the system into two - battery swapping and docking. The aerostat is connected via a ground-conducting tether this tether provides electricity to the system

3.1.1 Battery swapping

The design of the proposed battery swapping system prioritizes a cuboidal frame configuration made of 2020 aluminum extrusions. This selection is motivated by several factors contributing to its effectiveness. Firstly, the cuboidal frame's geometry simplifies the manufacturing process, making it a cost-effective and efficient choice. Secondly, the cuboid's shape proves advantageous in serving as a base mount for the battery docking system. Its inherent stability and well-defined edges provide a secure foundation for this critical component.
The dimensions of the battery swapping system are specifically chosen to be 1000 mm x 300 mm x 320 mm. The Linear actuator is only restricted to vertical motion. The cuboidal frame allows for the modular integration of various subsystems necessary for the battery-swapping operation. These subsystems will be explored in greater detail in subsequent sections of this paper.

Battery casing For battery swapping a custom battery casing was created which would easily allow attaching/detaching the battery from the UAV, pushing/retrieving the battery from the docked UAV, attachment of the battery in the swapping belt, and charging of the battery.

The top portion of the battery box has two latches (MC - 37F) which can attach to the non-magnetic push latches on the UAV as shown in Fig. 5. At the side of the battery box, some ribs allow the battery box to stay in the belt and also house pogo pins for connection discussed in the next section. The casing is manufactured by 3d printing as shown in Fig. 6.

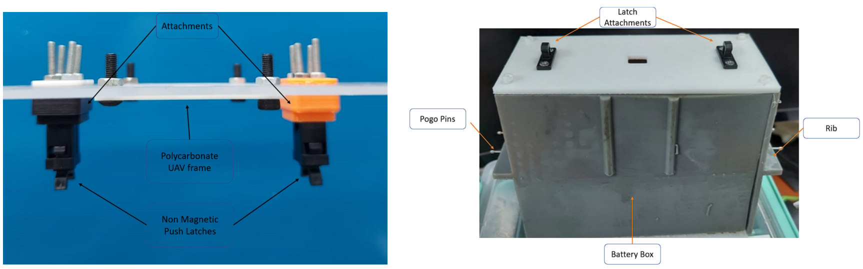

Figure 6 – Prototype of UAV frame with latches and manufactured battery box

Conveyer belt A linear conveyor belt system was designed and manufactured to house, swap, and charge the batteries as shown in Fig. 7. The rib in the battery box prevented it from dropping and made it fit into the conveyor belt. The pogo pins come in contact with the conducting copper plate in the belt that allows for the charging of the batteries as shown in Fig. 7 and 8.

Linear actuator for battery swapping this system is placed vertically and it helps to move the battery from the UAV to the battery swapping belt and vice versa. This will be placed under the battery swapping belt so that it can push the appropriate battery upwards or bring the appropriate battery downwards. The system is based on a lead screw mechanism which is guided by two carbon fiber rods as shown in Fig. 9. The top part of this plunger is designed so that it fits the underside of the battery enabling its transport as shown in Fig. 10. The proposed battery-swapping algorithm is shown in Fig. 11.

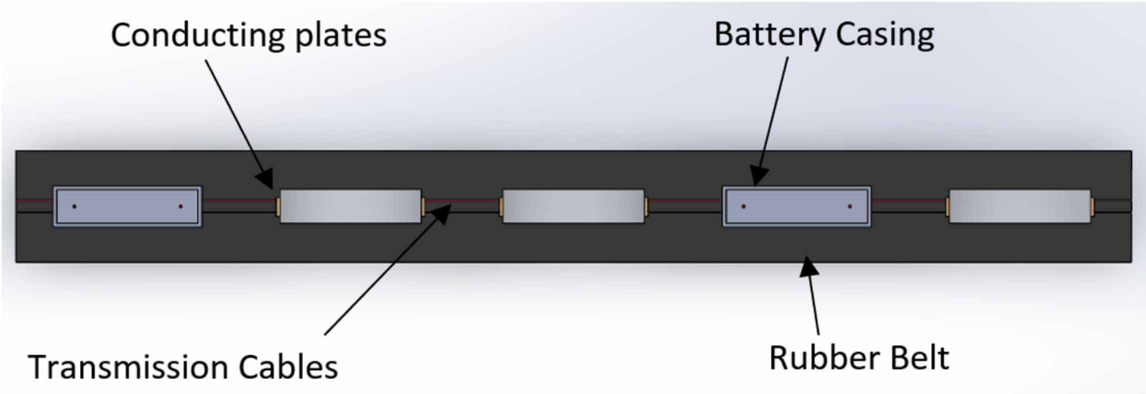

Figure 7 – Linear belt concept

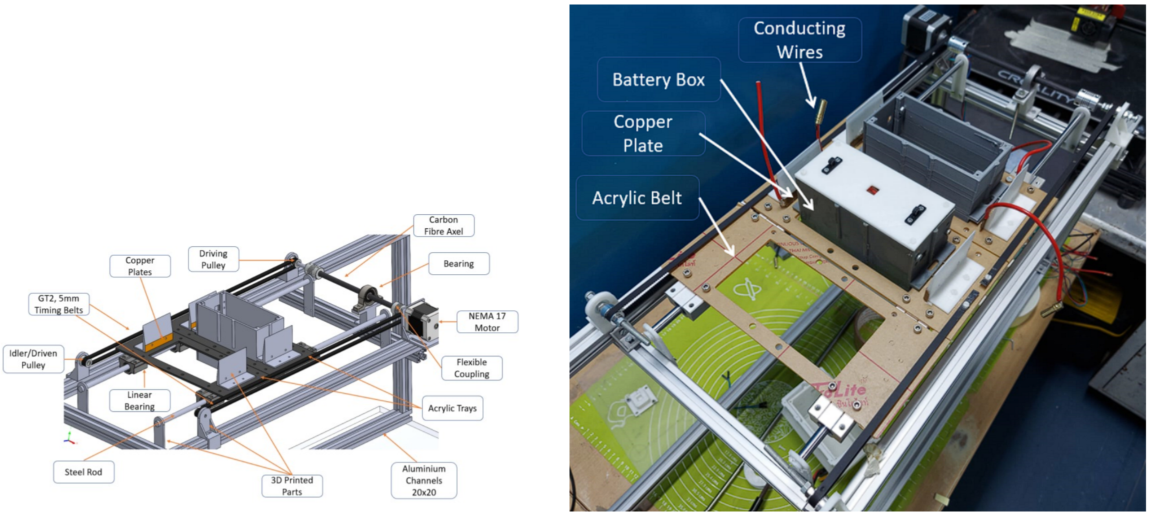

Figure 8 – Designed and manufactured belt system

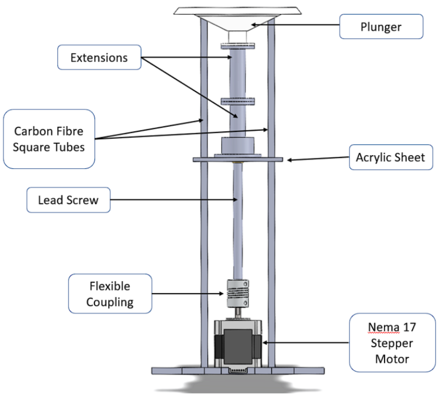

Figure 9 – Design of plunger

3.1.2 Docking

For this study, the UAV that is used is based on the S500 carbon fiber frame. To ensure battery swapping the UAV must be in a stable enough position. This can be achieved by docking the UAV. The docking system was created using plywood for weight efficiency and had a dimension of 600×600 mm this was considered using an iterative method based on the aerostat dimension with a volume of 70-meter cube and configuration we also had to consider the dimensions of the quadcopter. The system contains two stepper motors the sliding rods were moved using NEMA-17 stepper motors and Gt2 belts the sliding rods were made using plywood. To avoid the toppling of the drone during arresting mode the drone legs were modified and also attached with plywood to avoid toppling. The

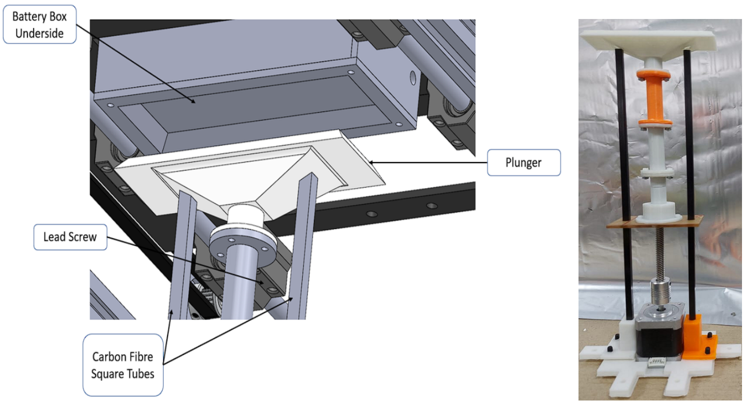

Figure 10 – Plunger slotting underside of the box and manufactured lead screw mechanism

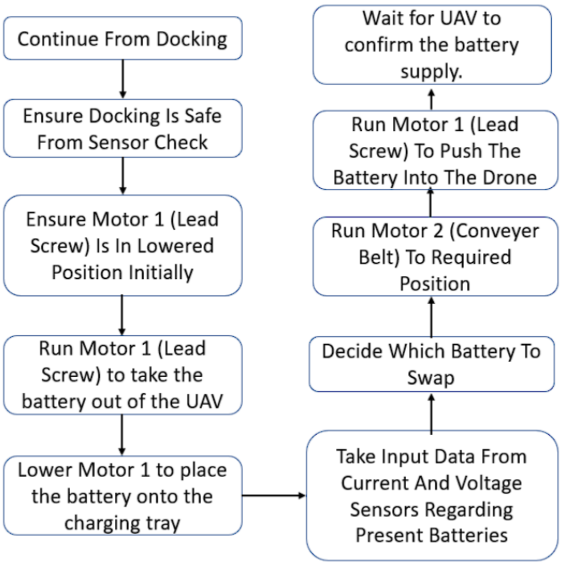

Figure 11 – Algorithm for battery swapping

system aims to capture and hold the UAV using four sliding plates that will slide and fit into its modified legs ensuring the UAV is in its correct position for battery swapping as shown in Fig. 12 and 13. The docking system is to be placed on top of the battery swapping system with the hole aligned with the plunger.

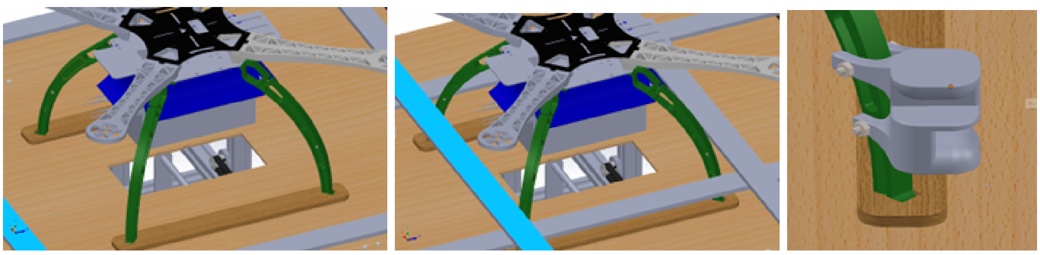

Figure 12 – Initial idea for docking with modified UAV legs

Once the UAV sends the signal to the docking station that it has landed, load cells in the docking system would confirm the landing and only then would battery swapping start. This provides additional robustness to the system and avoids unnecessary execution of battery swapping when the UAV has landed elsewhere. The load cell is placed in such a way that the docking board will be above it and battery swapping will be below it as shown in Fig. 14 and 15.

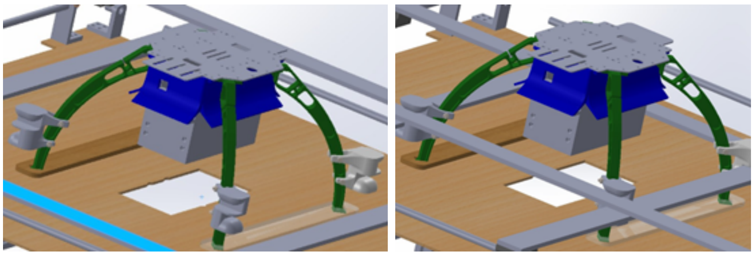

Figure 13 – Undocked and docked UAV

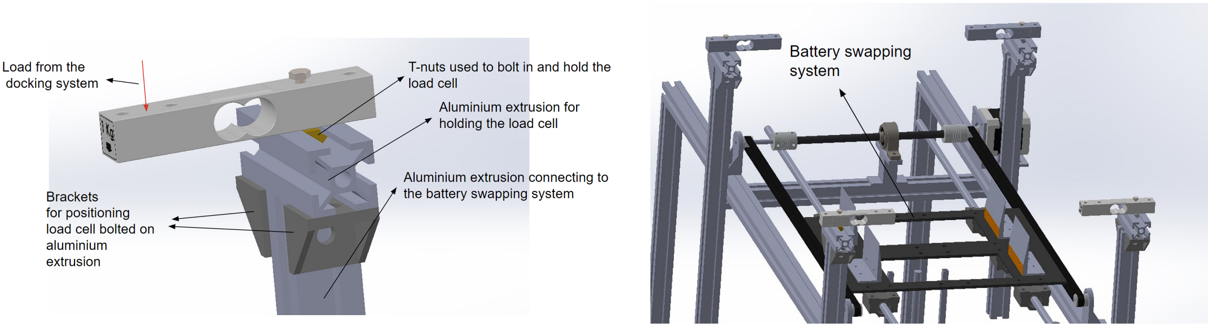

Figure 14 – Load cell integration with battery swapping

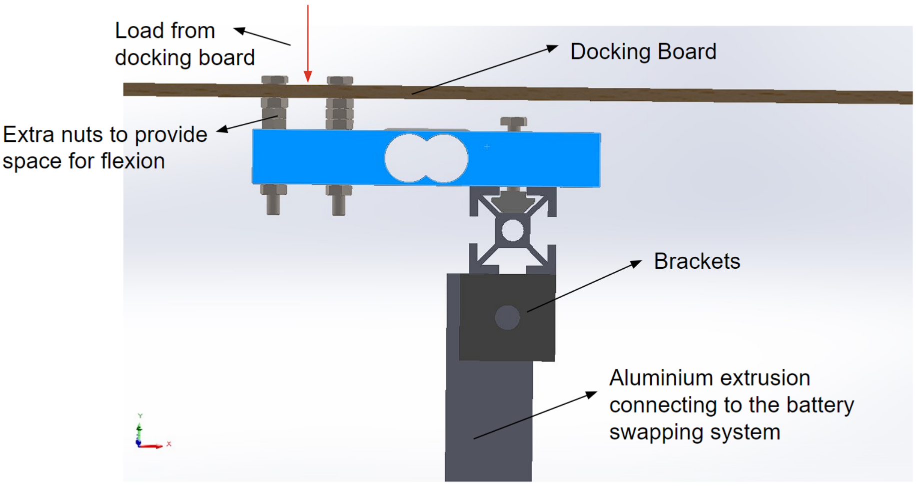

Figure 15 – Load cell integration with docking board

An algorithm has been developed for the load cells as shown in Fig. 16. In case all load cells are not ready, the algorithm will point out which load cell is not working. The calculation of the calibration factor of the load cell is to be done beforehand at that particular height. Once the drone lands, the load cell can confirm whether the drone has landed in the desired landing platform or not.

The same process can also be achieved using lasers or modified conductive drone legs, which are currently being discussed in our study. Ideally, all three systems should be implemented for an efficient and accurate system. However, we have implemented only the load cell system for our current study. For future studies, we may consider the other two systems.

All the above components were integrated into the docking board that will be placed above the battery-swapping system. This docking board with its integrated parts will be the final docking system

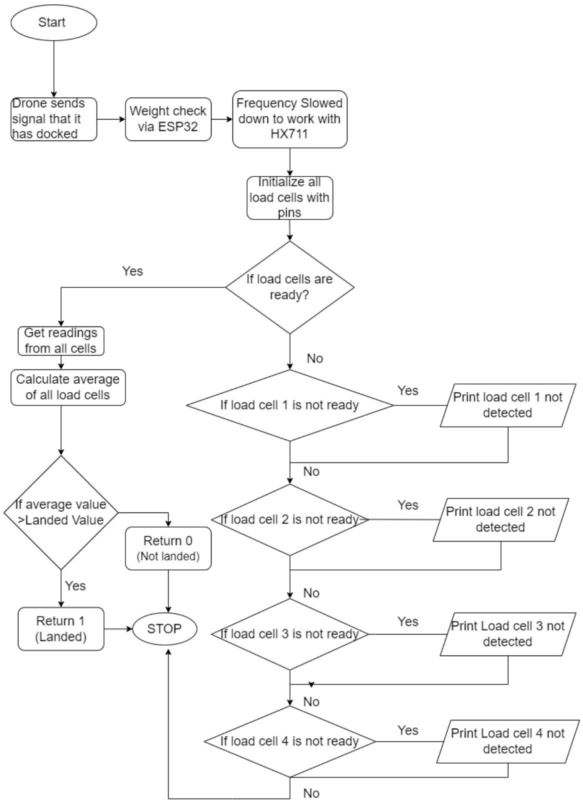

Figure 16 – Algorithm for load cells

Figure 17 – Manufactured S-500 drone

that will be used for UAV landing and holding it in position while the battery swaps as shown in Fig. 18. The sliding rods in the docking system that slide into the modified UAV legs ensure that the UAV is positioned correctly for battery swapping.

4. Conclusions and Future Work

This study demonstrates a full concept of docking and battery swapping for UAVs at the proposed altitude. The battery-swapping system has been executed successfully. The current docking board fabricated is based on acrylic material, and aluminum extrusions and has an outer size of 800 x 800 mm which flexes and is ideal for the mount on top of an oblate spheroid aerostat with 120-meter cube volume. The docking system although functional at the ground, hinders functionality at altitude for the current Aerostat dimension. For future works, we will focus on fabricating a docking system

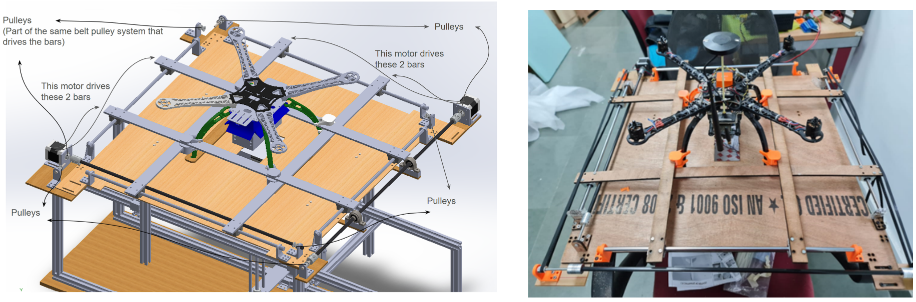

Figure 18 – Final CAD design for the docking system

similar to the old one, but this time with metal (aluminum) to prevent flexion. The second iteration CAD model is shown in Fig. 19. We will be trading off the weight gained due to the use of metal in the aerostat design. After the docking board is ready it will be integrated with the battery swapping system. An appropriate aerostat for the final system will be fabricated that can support the system at the proposed altitudes.

Figure 19 – Manufactured docking board

It employs components constructed from aluminum extrusions, 3D-printed parts, and acrylic sheets. facilitates a linear travel range of 800 mm, enabling efficient battery exchange within the drone's operational area. Additionally, it incorporates a dedicated vertical actuation using Nema-17 stepper motors capable of lifting and descending to a maximum of 300 mm as shown in Fig. 20.

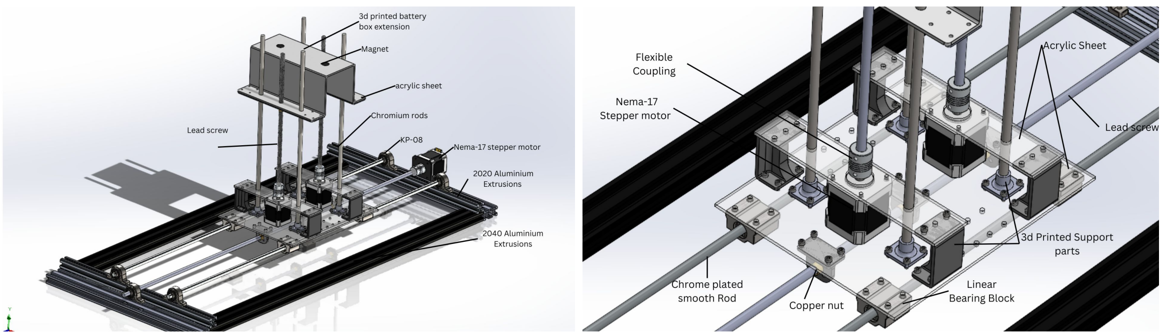

Figure 20 – Design of battery swapping system

The swapping operation commences with the drone landing on a designated platform equipped with linear actuators integrated within the landing board. This actuator actuates the discharged battery upwards along the vertical axis of the stepper motor, the battery stays in a fixed position on top of the battery box extension with the help of a magnet attached to the battery box presenting it for detachment. Concurrently, a fresh battery stored within the system undergoes a similar vertical movement using a separate Actuonix PQ-12 linear actuator located within the swapping mechanism and drone itself. Once both batteries are positioned appropriately, a secure detachment and re-attachment process is facilitated. There are linear actuators present on the drone that are used to keep the drone battery in a fixed position during flight and also free the battery during the swap the linear actuators present on the drone are powered using a secondary battery. This system can be innovated further to be mounted on an aerostat. This system is presented in Fig. 21,22.

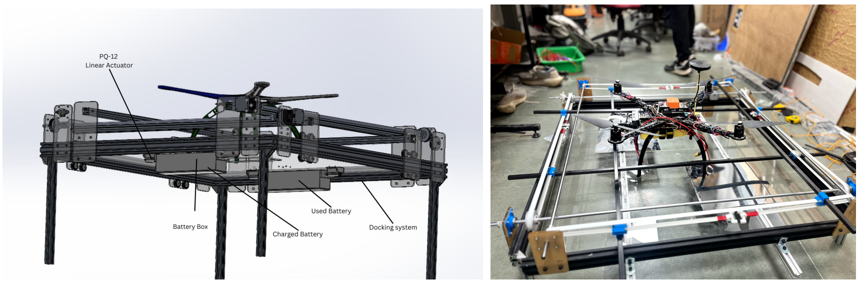

Figure 21 – Docking CAD and fabrication

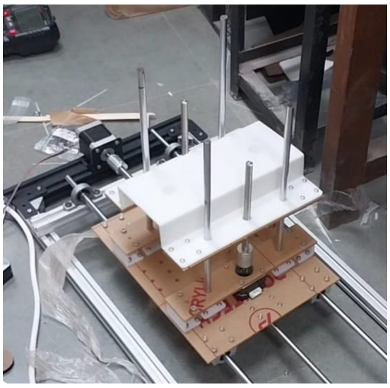

Figure 22 – Manufactured battery swapping system

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6. Copyright Statement

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