# Combined Docking–and–Recharging for a Flexible Aerial / Legged Marsupial Autonomous System

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*Abstract*—**In this work we address the flexible physical docking-and-release as well as recharging needs for a marsupial system comprising an autonomous tiltrotor hybrid Micro Aerial Vehicle and a high-end legged locomotion robot. Within persistent monitoring and emergency response situations, such aerial / ground robot teams can offer rapid situational awareness by taking off from the mobile ground robot and scouting a wide area from the sky. For this type of operational profile to retain its long-term effectiveness, regrouping via landing and docking of the aerial robot onboard the ground one is a key requirement. Moreover, onboard recharging is a necessity in order to perform systematic missions. We present a framework comprising: a novel landing mechanism with recharging capabilities embedded into its design, an external battery-based recharging extension for our previously developed power-harvesting Micro Aerial Vehicle module, as well as a strategy for the reliable landing and the docking-and-release between the two robots. We specifically address the need for this system to be ferried by a quadruped ground system while remaining reliable during aggressive legged locomotion when traversing harsh terrain. We present conclusive experimental validation studies by deploying our solution on a marsupial system comprising the MiniHawk micro tiltrotor and the Boston Dynamics Spot legged robot.**


**Figure 1**: The Flexible Aerial / Legged Marsupial Autonomous (FALMA) system. *Detail:* The Docking & Recharging Backpack (DRB) design facilitating repeated deployment cycles, in situ fast-recharging on the go, and stable marsupial docking during aggressive legged locomotion.

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## 1. Introduction

Mobile robots have been consistently performing breakthroughs in a wide range of challenging application domains over the course of the last decade, including the persistent ground-based monitoring of urban constrained areas of interest ([1], [2]), as well as airborne surveillance over wide-field countryside locations ([3], [4], [5], [6]), the exploration of unknown GPS-denied settings ([7], [8], [9], [10], [11], [12], [13], [14]), the 3D mapping and inspection of civilian infrastructure ([15], [16], [17], [18]), the rapid deployment in support of emergency response situations ([19], [20], [21], [22]), and finally even the remote planetary exploration of extraterrestrial environments [23]. Across these examples, emphasis is placed on advancing the mobility, perception, and planning intelligence capabilities of distinct aerial or ground-based robotic systems, in an effort to address specialized mission requirements. A more recent field deployment paradigm for autonomous robotics has successfully demonstrated the potential of heterogeneous aerial / ground robot teaming, especially in narrow and unstructured extreme settings [24]. Therein, legged locomotion systems proved their dominance in tackling harsh real-world terrain, and with the complement of multirotor Micro Aerial Vehicle (MAV) agents that can be one-shot launched to provide high vantage point views, have enabled the emergence of a *marsupial* autonomous system-of-systems.

Attempting to extend these experiences in wide-area open-field missions taking place in the wild, the operational advantages contributed by *legged locomotion* are evident – e.g., offering the ability to navigate over variously structured ground, comprising of uneven terrain with rubble, but also staircases and other human-made structures–. On the other hand, it is the class of *hybrid aerial* Vertical Take-Off and Landing (VTOL) / Fixed-Wing (FW) micro robots that offer the combined versatility of both precision-flight launching from and landing onto the back of a mobile ground system, while also performing forward-flight-based surveillance over larger fields.

Moreover however, to make such a Flexible Aerial / Legged Marsupial Autonomous (FALMA) system –as illustrated in Figure 1– viable, it is imperative to extend its capabilities to offer *long-term autonomous* operation, by facilitating a) repeated aerial system deployments without requiring human operator intervention, while b) ensuring the operational robustness of the overall marsupial robot. This work contributes the required system-of-systems architecture and emphasizes on the subsystems design that grants these capabilities. We propose a combination of a (commercially available) legged ground robot and a custom (but open-design) hybrid VTOL/FW micro aerial robot that supports in-situ battery recharging based on an external power source. We detail the development of a specialized Docking & Recharging Backpack (DRB) for the legged robot, which allows the hybrid MAV to safely dock onto it, and be recharged by a separately carried battery module in order to facilitate back-to-back aerial system deployments. We emphasize the design considerations that ensure stable docking and holding in-place of the aerial robot even while the legged system performs dynamic locomotion and full-range body pose orientation. We demonstrate the obtained capacity of the overall marsupial system to safely retain the aerial agent in its place during such aggressive locomotion, while at the same time ensuring uninterrupted compliant electrical contact for consistent recharging. We finally separately validate these design contributions with specialized experimental validation studies.

The remainder of this paper is structured as follows: Section 2 discusses relevant prior work in the field. Section 3 overviews our proposed approach for a FALMA system and its intended operational profiles. Actual implementation specifics are elaborated in Section 4. Experimental results covering the system's main operational capabilities are shown in Section 5, and our conclusions are drawn in Section 6.

## 2. Related Work

Several docking and recharging designs have been developed to allow charging or battery replacement as solutions to extend the limited operational capacity of various robotic systems, especially aerial robots ([25], [26], [27], [28], [29], [30], [31]). Authors of [32] propose the use of a 3D printable multi-link arm capable of latching on to an aerial vehicle serving as a docking tool as well as a way to provide localization in GPS-denied environments. Other works in this domain ([25], [26], [27], [28]) aim to achieve docking of aerial vehicles onto stationary landing stations for the purpose of charging either by establishing an electrical contact between the vehicle and the station or by wireless power transmission [30], [31]. ICAROS Aerial Intelligence [29] provides an autonomous solution for docking inside a Pelican case while having wireless charging capability as well as an option for tethered operation. Most of these systems lack mechanisms to hold the MAV in place after docking and thus cannot guarantee a secure electrical connection while undergoing dynamic motion of a mobile agent that ferries the charging station, while others use wireless charging with which to overcome this issue at the expense of being inefficient and slow as compared to contact-based fast charging approaches.

The work in [33] presents a heterogeneous system of robots in the context of swarm exploration following a hierarchical approach in which multiple exploring wheeled robotic agents, termed scouts, are carried on a conveyor belt supported plank-like structure mounted on a larger wheeled robot. Authors of the work [34] demonstrate a nested marsupial system consisting of a bi-manual mobile manipulator carrying a MAV that further carries a miniature ground wheeled vehicle taking advantage of the complementary capabilities of the three systems in the event of disaster. Both of these approaches use a similar flat-top carrier that nests the smaller agent while lacking a mechanism that would hold it in place, essentially viable for deployment in an environment with mostly even terrain. More recent works [24] deploy robotic system-of-systems comprising a legged robot carrying an MAV robot on its back aimed towards exploiting their complementary capabilities for collaborative mapping and exploration of unknown environments. To securely hold the MAV in place while the legged robot is in motion, a custom designed mechanism employing an electropermanent magnet along with flexible elastic straps is utilized. Despite following the paradigm of a marsupial system, neither of them take advantage of a fundamental capability that can be offered by the parent system, i.e. replenishing the energy reserves of the child system.

In this work, we propose the design of a novel docking and recharging backpack system that mounts rigidly to the back of a legged robot, designed specifically for our hybrid VTOL fixed-wing MAV, to facilitate long-term autonomy. The angled geometric structure of the design allows the aerial vehicle to passively align itself by sliding back and nestling towards the edge of the platform once it has landed upon it. Furthermore, the actuated claws engage to latch onto the skids of the MAV to provide a three-fold benefit, a) securely hold the MAV during any dynamic motion of legged robot over uneven terrain, b) establish and maintain electrical contact between conductive wire residing on the inner surface of the two middle claws and the skids ensuring uninterrupted charging of the MAV, and finally c) facilitate multiple docking and takeoff cycles without human intervention.

The overall marsupial system facilitates a wide-field deployment over extended terrain by combining the advanced terrain mobility over uneven terrain offered by the legged robot and the versatility of the hybrid VTOL capable of taking off and landing onto the docking station along with forward-flight operation over extended ranges.

## 3. Proposed Approach

This section details the primary components of the Flexible Aerial / Legged Marsupial Autonomous system and outlines its envisioned combined operation.

### *Tiltrotor Hybrid Micro Aerial System*

The flying platform used is the MiniHawk VTOL [35], [36], a rapidly-prototyped and open-design (https://github.com/StephenCarlson/MiniHawk-VTOL) fixed-wing / VTOL micro-tiltrotor class [37], [38], [39], [40] aircraft, designed with the focus on adaptability for research and ease of manufacture. The aircraft has an 800 mm wingspan, a wing area of 17 $dm^2$, an all-up-weight of 1.1 kg to 1.4 kg, and can sponsor a variety of sensory devices and computing subsystems. A "belly-pod" contains an Intel T265 Visual Inertial Odometry module and a bottom-mounted RGB camera. These are combined with a Benewake TFMini Plus micro 1D LiDAR sensor and the mRo PixRacer Pro flightstack with its accompanying magnetometer and IMU suite. A Khadas VIM3 single-board computer manages the high-level autonomy tasks for the aerial system, and offers GPS-denied navigation in unstructured outdoor environments. The "belly-pod" skids are amended with recharging contact wires, such that the proposed Docking & Recharging Backpack mechanism can service an electrical connection simultaneously to grasping and securing the vehicle, as will be followingly detailed.

*Legged Locomotion System*

The FALMA system additionally comprises the Boston Dynamics Spot, a $12-$ DoF quadrupedal legged robot with a 14kg payload capacity that offers a runtime of 90 minutes. Rails on the back of the Spot allow for mounting of our Docking & Recharging Backpack and additional sensing payloads if required. The body of the Spot has 5 pairs of stereo camera capturing monochromatic images which provide a $360^o$ vision and an operating visual range of up to 4 m. The legged robot is armed with locomotion pipelines that tackle both obstacle avoidance as well as navigation over various terrains that include structured environments like stairs and slightly elevated platforms, as well as uneven grounds with rubble. In the context of our vision for marsupial long-term autonomous missions, Spot and the MiniHawk VTOL can rendezvous to provide docking and fast recharging in-the-field, effectively facilitating repeated deployments and enabling a wider operational window.

*Multi-Modal Recharging System*

The MiniHawk was designed to accommodate a set of flexible solar cells in the upper wing surface for multi-day recurrent migratory missions using a land-to-recharge mission cycle, as previously described in [36], [5]. The enabling device for these activities is the Power Management Stack (PMS) [3], which handles power collection and switching of the entire aircraft power bus for deep-sleep hibernation. This device is easily adapted to accept power from either the wing-mounted solar array or from a secondary external source, in this case being the recharging contacts affixed to the skids. Both sources may be present simultaneously, with the Power Management Stack selecting from the input with the highest input voltage via a pair of low-loss power diodes. Thus, the vehicle can be recharged drawing either from the onboard solar array, or from an externally connected battery present on the Docking & Recharging Backpack.

*Marsupial Docking & Recharging*

The FALMA system allows for the significant extension of the MiniHawk's feasible operating window, by offering the potential for ground ferrying and repeated deployments through back-to-back launching and docked-recharging cycles. While the MiniHawk on its own can also sustain itself via solar power harvesting for extended periods of time, solar is not always a viable option, nor does it lend itself for fast-recharging. Also, there are scenarios where the MiniHawk may not find suitable landing zones, e.g., around brush or rocky terrain. The agile legged system equipped with the DRB can provide a suitable landing site, as well as offer fast-recharging. Moreover, the combined marsupial system can continue to operate as a single unit; Spot being a legged ground system is characterized by increased endurance, and can therefore keep executing mission objectives while the MiniHawk remains docked. It is highlighted however, that this assumes that the mechanical docking and electrical recharging operations should –by-design– remain uninterrupted, even during aggressive legged locomotion.

In our vision, when Spot encounters an obstacle such as a shear cliff, canyon, body of water, etc. the MiniHawk can then be released and otherwise facilitate the mission objectives. This tandem system can be leveraged for long-term combined ground-and-aerial reconnaissance, surveillance, exploration, mapping, security, search and rescue, forest fire tracking, and others. Additionally however, we also envision that this system architecture may allow for wide-area deployments with multiple FALMA systems working interchangeably. The legged ground robots can actively address mission objectives while the MiniHawks transfer between the multiple docking stations. Mobile resource allocation optimization is a requirement to achieve this level of capacity, and lies within the scope of future work possibilities opened by our proposed architecture.

## 4. System Design

Central to the FALMA system's operation is the Docking & Recharging Backpack, which is presently detailed with respect to its core design aspects.

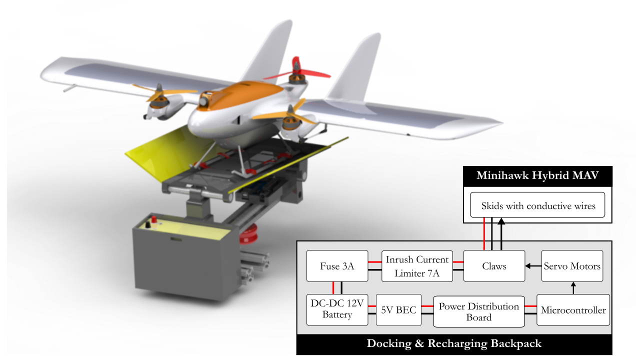


**Figure 2**: Docking & Recharging Backpack design overview. *Detail:* Subsystems Block Diagram.

*Docking & Recharging Backpack Design*

The design of the Docking & Recharging Backpack aims for durability and reliability. The frame of the DRB is made from 6063-T6 aluminum alloy. The use of aluminum minimizes the propagation of vibrations while maximizing the strength-to-weight advantage that aluminum provides when compared to steel. To further reduce vibrations, thereby extending the operational life of the system, a damper is positioned aft of the mounting screws. With the damper in place, this reduces the strain on the legged ground robot's accessory rail by reducing the moment induced by the DRB. The landing area is designed to gently center the skids of the vehicle so that, even if an approach is not optimal, it will still trigger the docking and charging sequence. This is accomplished by the overall "W" shape of the docking pad. The landing area on the system is made of Acrylic Styrene Acrylonitrile thermoplastic treated with an automotive-grade ceramic wax to reduce friction and allow the MiniHawk to simply slide into position. Acrylic Styrene Acrylonitrile is both lightweight and resistant to Ultra-Violet (UV) radiation. Minimizing the overall mass of the DRB then maximizes the operational time of the FALMA system and resistance to UV radiation increases the time between required service intervals.

The heaviest component of the system is the $12$ V closed-cell, deep-cycle, lead-acid battery. This battery type was selected since it has lower memory than its lithium counterparts and can be nearly completely discharged without damaging the cells. This battery type provides acceptable performance throughout a wide range of temperatures and reduces the potential of combustion or catastrophic failure if punctured or damaged when compared to its lithium counterparts. It can easily be replaced and the area can be reconfigured to accommodate different types and sizes.

The docking pad passively "slides" the MiniHawk backward into position since it is angled upward by $10^o$. The MiniHawk naturally hovers at a $9^o$ "nose up" pitch angle, so when it lands it does not put additional stress on the rear of the skids. The claw latching system is activated using a rear contact switch, which drives a microcontroller to activate a set of powerful $5$ kg·cm rated servos. These are responsible to revolve two aluminum shafts, which are attached to the claws; it is highlighted that the claws are constructed out of compliant Thermoplastic Polyurethane, and that the middle claw of each shaft is lined with conductive $14$ gauge wire. The summary of this system is presented in Figure 2.

There are three sets of claws. By-design, they constantly remain in contact with the skids of the MiniHawk to ensure it is firmly held in place. The forward and aft claws, or "docking" claws, are $5$ mm longer and thicker than the middle "charging" ones. The thicker section of the docking claws is designed to resist flexing under load, allowing for better retention of the skid, while the section closer to the shaft is designed to flex more so that the skids remain under tension. The docking claws are much thicker to limit the amount of compliance, and provide the majority of force applied to the skids to prevent unwanted movement when the MiniHawk is docked, as shown in Figure 3. In the same figure the middle charging claws can be seen that contain the conductive wire, which is responsible for transferring electrical power to charge the MiniHawk. The middle charging claws are much thinner to provide maximum compliance, and ensures that the conductive wire does not break contact with the conductive material on the MiniHawk's skids. Even if the skids lift slightly due to the legged robot traversing difficult terrain, the compliant claws remain under tension and in contact, thus reliably and consistently charging the MiniHawk.

*Docking & Recharging Backpack Operation*

The system works by –using gravity alone– allowing the MiniHawk to naturally slide to the rear of the docking pad where the portside skid contacts the switch at the rear of the docking area. If the MiniHawk approaches from a less-than-desirable yaw angle, the overall "W" shape of the landing area gently guides the skids into the desired position as the MiniHawk continues to descend. Once the aerial robot has finished its descent, the impact force of the MiniHawk sliding rearward easily overcomes the $65$ grams of force required to activate the switch. Once the switch is depressed, the microcontroller activates the $5$ kg·cm servos that drive the claws. The claws then apply $1.43$ kg of force to each skid to

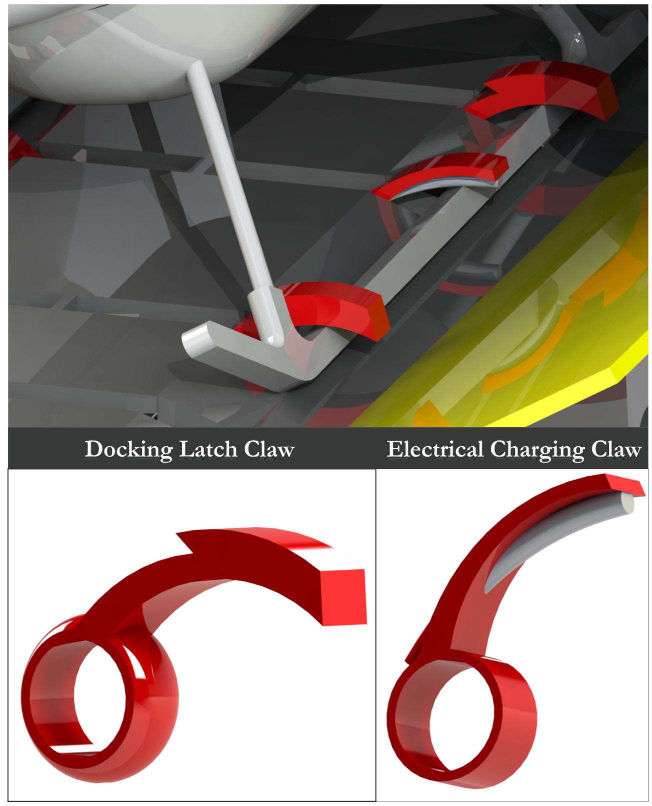


**Figure 3**: *Top Row:* MiniHawk VTOL secured to Docking & Recharging Backpack. *Bottom Row:* i) Docking Claw with increased material at the area that contacts the skids. Increased material reduces the amount of flex in that particular region of the part. ii) Electrical Charging Claw with conductive wire.

prevent unwanted movement as shown in Figure 3. Once the charging claws contact the conductive material on the skids, the circuit is closed, and the MiniHawk PMS can initiate recharging. Electrical protective measures consist of a $3$ A fuse and an inrush current limiter on the DRB.

Since the claws provide nearly twice the force required to hold the MiniHawk upside down, there is very limited movement during legged locomotion. The entire system can be moved and aggressively shaken, yet the connection remains consistent and strong. This is achieved by the use of compliant Thermoplastic Polyurethane. Compliance reduces the strain on the servos, while still maintaining compression on the skids due to the underside of the docking claws being held in tension.

## 5. Experimental Study

We experimentally validated the FALMA system across its three main operational capabilities, and present here the corresponding results.

*VTOL Landing & Passive Docking*

The first set of experimental validation studies correspond to the landing operation of the MiniHawk onto the DRB during the phase that the FALMA system is regrouping after a deployment cycle. More specifically, we investigate the reliability and repeatability of the landing process by having the legged robot hold its pose, and manually piloting the aerial robot in VTOL mode to approach the landing pad from various different initial poses.

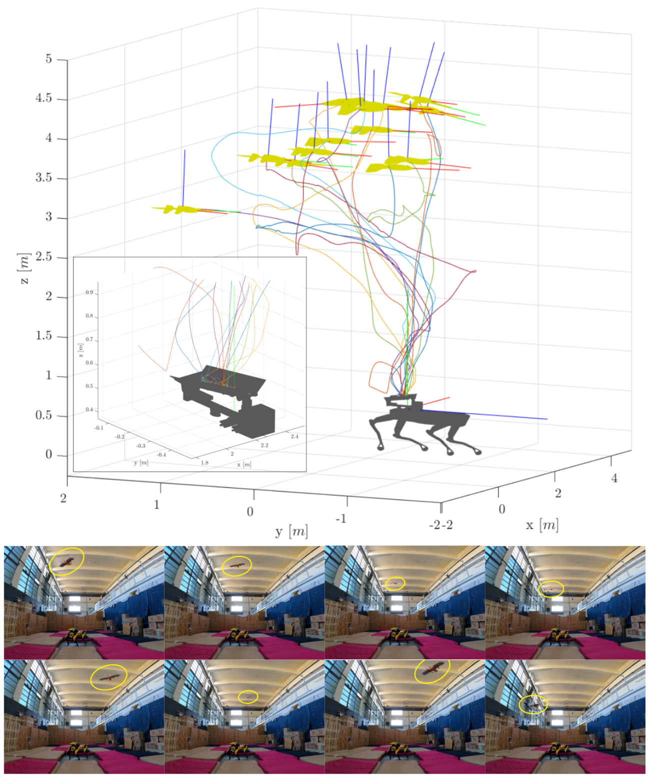


**Figure 4**: *Top row:* Reliability validation of the passive docking process during aggressive landing approaches, through a motion-captured experimental study. *Bottom row:* Indicative instances of the landing repeatability experiments inside the motion capture space.

It is highlighted that despite the aggressive piloting which follows non-prescribed trajectories until the eventual approach onto the DRB, the passive docking provisions of this design ensure that the aerial robot, once it has adequately approached the landing pad, can just drop-and-slide-back into place, where it is subsequently latched by the active claw mechanism. This can be observed in Figure 4, where we demonstrate an indicative set of fifteen varying back-to-back landing sequences. These were conducted within a 15x7x5 m motion capture volume –shown in the bottom– covered by an array of 10 VICON Vantage V8 cameras, offering sub-mm motion resolution. This allows us to accurately capture the evolution of the final docking motion, illustrated in the subfigure plot that is zoomed-into the DRB. As seen, the resulting motions have minimal rebound and all naturally "fall into" position, owing to our contributed design. The corresponding video sequences will be presented during the live conference presentation.

*Aerial System Recharging*

The second experimental demonstration aims to illustrate the obtained capacity for mobile recharging facilitated by the combined DRB –and– MiniHawk Power Management Stack design. As mentioned in the previous Section, the aerial robot's PMS is capable of selecting between ambient (solar) harvesting and externally powered recharging by probing the skids input voltage line. After docking and once the DRB recharging claws are latched into place as illustrated in Figures 1 and 3, the external battery voltage of $\simeq$ 12 V is applied, allowing to initiate a fast-recharging cycle as illustrated in Figure 5.

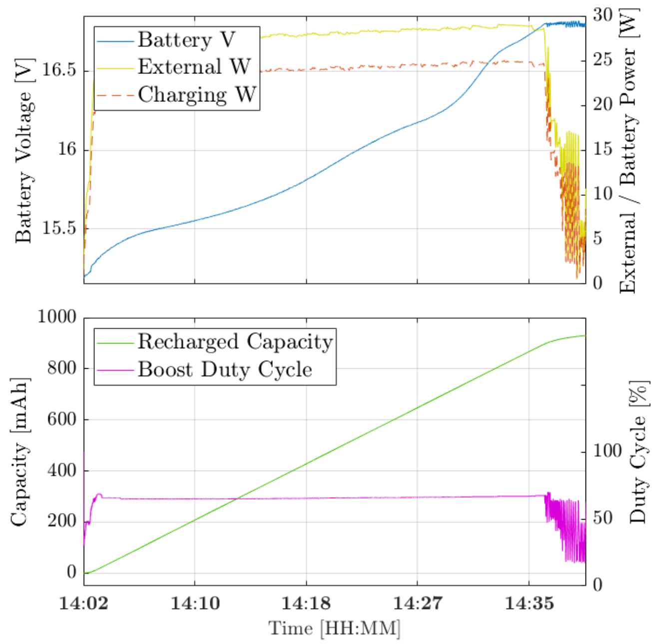


**Figure 5**: Externally-powered recharging of the MiniHawk VTOL by the DRB. *Top row:* MiniHawk battery voltage and input & battery recharging power. *Bottom row:* Minihawk battery recharged capacity and Power Management Stack boost conversion duty cycle.

The top row presents the evolution of recharged voltage of the MiniHawk's onboard battery once the operation is initiated. We also illustrate the input power drawn by the PMS from the external source as well as the output power flowing into the battery during the cycle. The bottom row presents the recharged capacity and the duty cycle setpoint used by the PMS when performing the required boost voltage conversion.

It is highlighted that the proposed FALMA system architecture incorporates the aerial system Power Management Stack specifications in order to facilitate high-power recharging –alongside the already established low-power solar-based operation–. This makes fast-recharging possible; indicatively in the presented example, a $\simeq$ 30 min window is enough to recharge approximately 1000 mAh of battery capacity. This is a critical enabling feature to make systematic use of the aerial robot scout-launching possible during long-term deployments of the FALMA system. The final required feature refers to the ability to keep this operation consistent at all times, a feature which is addressed in the following Subsection.

*Resilient Docking & Recharging during Dynamic Legged Locomotion*

The last experimental validation sequence focuses on the FALMA system's capacity to reliably operate as a marsupial unit during aggressive locomotion sequences. More specifically towards this evaluation, we focused on a combined qualitative / quantitative study, by replicating certain challenging traversability conditions in a lab mockup environment that the Spot legged robot has to overcome, while at the same time recording inertial and electrical connection data onboard the MiniHawk robot. The results are illustrated in Figure 6.

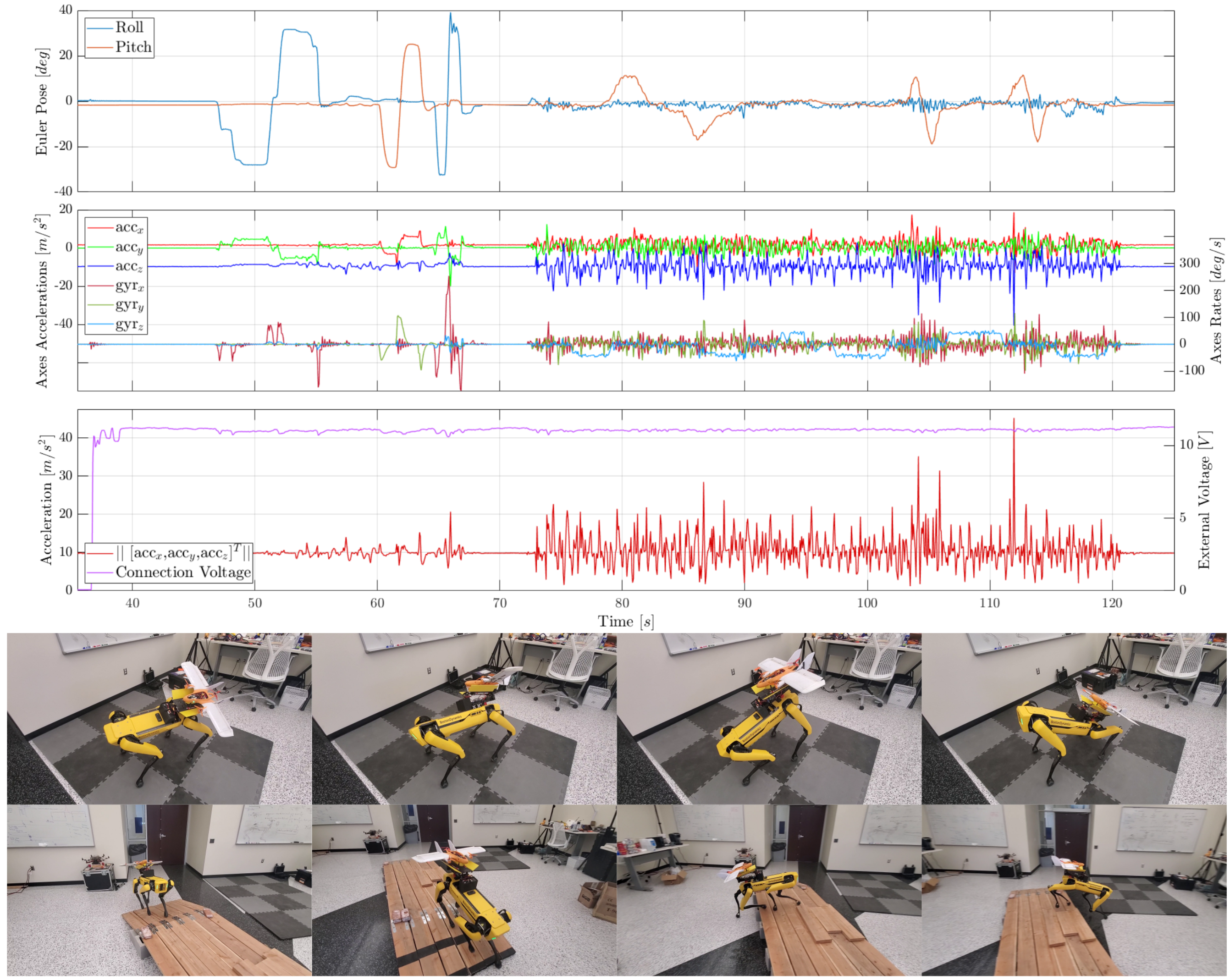


**Figure 6**: FALMA system mechanical and electrical reliability testing during active locomotion. *Top rows:* Body inertial values recorded onboard the MiniHawk robot, and electrical connection voltage across external power line. *Bottom row:* Corresponding indicative instances of aggressive pose orientation and legged locomotion on incline surfaces and above obstacles in a mockup environment.

The top-row subplot showcases the MiniHawk body angles during the sequence. Between 40 s and 70 s we command the legged robot to extreme body poses, both in roll and pitch, leading aerial robot to acquire equivalent orientations. Throughout this, the DRB manages to safely retain the skids in place. More interestingly, around the 65 s mark we command the legged system to similar extremes but much more violently, however the system still remains intact. This faster-rate orientation change which reaches a peak of $>$ 300 deg/s is also visible in the mid-row subplot, which illustrates the per-axis body accelerations and rotational rates as recorded by the MiniHawk Inertial Measurement Unit. For the following section of the sequence after the 70 s mark, we focus on performing legged locomotion within the mockup lab testing space, walking on level terrain as well as on incline slopes and over elevated obstacles, while the FALMA remains assembled. As can be seen by the acceleration values, whose estimated magnitude is shown in the bottom-row subplot with a red-colored line, the aerial robot body undergoes accelerations up to $\simeq$ 45 m/s$^2$. This peak specifically corresponds to phases where the legged robot has to traverse over elevated sections, such as when commanded to step over a bridge to traverse it. All the aforementioned maneuvers, namely a) extreme body-pose orientations, b) locomotion over flat and incline sections, and c) traversing over elevated obstacles, are summarized in the set of indicative video instances presented in the bottom row of the figure; the corresponding footage will be presented during the live conference presentation.

What should be finally highlighted, is the fact that during this entire sequence, additionally to not risking disassembly despite the aggressive legged locomotion maneuvering, the FALMA system also does not compromise its consistent recharging operation. The electrical contact that ensures power flow from the DRB into the MiniHawk PMS and battery remains uninterrupted, which is observed through the consistency of the input voltage measured by the PMS across the skids power input line; this corresponds to the magenta line in the bottom-row subplot. This feature is obtained due to the compliant design of the electrical charging claws, and is crucial to ensuring the long-term consistent operation of the FALMA system according to the specifications detailed in Section 3.

## 6. Conclusions

In this work, we presented a Flexible Aerial / Legged Marsupial Autonomous system architecture, comprising a legged locomotion ground robot and an autonomous hybrid micro tiltrotor, and additionally armed with the capacity for combined docking and recharging. This type of marsupial system-of-systems can be leveraged in long-term wide-area combined ground-and-aerial surveillance missions in unstructured environments, as it offers the ability for repeated aerial system deployments through back-to-back launch and dock-to-recharge cycles. We detailed the critical aspects of the proposed subsystems specifications and their design. Finally, we presented a set of three experimental evaluation sequences, each studying the FALMA system's performance against its core design objectives.

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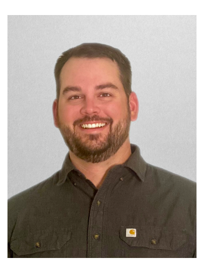
## BIOGRAPHY



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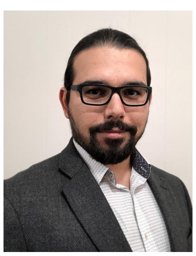

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