Utility of a Sensor Platform Capable of Aerial and Terrestrial Locomotion*

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Abstract – **Homeland security and national defense include many missions that would be served by a multi-sensor platform capable of flying, landing, perching, and walking. Soldiers in an urban environment could obtain near- and medium-field intelligence by deploying the vehicle and landing it on the top of a building. Maritime domain protection would be significantly enhanced by a small aerial vehicle that could 'perch on' (hang from) the high point of a cargo ship during onboard inspection. The surveillance capability of unmanned aerial vehicles (UAVs), which are beginning to enjoy widespread use in military and reconnaissance situations, could be significantly enhanced by a vehicle with sufficient stealth to gain closer approach to the surveillance target without being detected. Finally, long term surveillance could be performed by a vehicle capable of flying, walking, and taking off from the ground. The Morphing Micro Air-Land Vehicle (MMALV) has been developed in response to these opportunities in surveillance and intelligence gathering. MMALV integrates the University of Florida's micro air vehicle (MAV) technology with the terrestrial mobility of Mini-Whegs™. MMALV is capable of flying and walking, and successfully performs the transition from flight to walking. Furthermore, MMALV is currently able to transition from terrestrial to aerial locomotion by walking off the roof of a two story building. A wing retraction mechanism improves the portability of the vehicle, as well as its terrestrial stealth and ability to enter small openings. A tail hook is currently in the design process, to allow for the 'perching' behavior.**

Index Terms* – *multi-mode mobility, micro air vehicle, Mini-Whegs™, morphing, reconnaissance

I. INTRODUCTION

Recent technological advances have made it possible to develop multi-sensory platforms capable of multiple modes of locomotion. The work presented in this paper involves a small vehicle capable of flying, landing, walking, and perching. The small size of the Morphing Micro Air-Land Vehicle (MMALV) provides it with considerable stealth and makes it man-portable. The mechanical technology has also been proven to be scalable, meaning that the vehicle size can be increased as necessary to increase sensory payload.

A platform such as this would be applicable in a wide range of homeland and national security mission scenarios. While some of these mission scenarios would require only a subset of the current capabilities of the vehicle, others would require significant enhancement to the potential of the platform. We present several potential missions here, and discuss the performance requirements for each.

A. Battlefield Situational Awareness

Small military units like Special Operations teams would benefit from a low signature reconnaissance vehicle easily transported and deployed by the unit to provide battlespace awareness along intended movement or at specific target areas. One such vehicle would be a hybrid micro robot capable of 1) being hand launched and flying to a target zone or reconnaissance site, 2) landing stealthily within the targeted zone (e.g. on a rooftop), 3) transforming itself into a highly mobile land vehicle controllable by the team, 4) relocating on demand for best sensor placement – including avoiding or moving over ground obstacles, and 5) transmitting critical data (visual, acoustic, chemical) from its position to the military unit. Ideally, the vehicle would also be capable of re-launching itself to fly to another reconnaissance position or return to its military unit.

This was the original application envisioned for MMALV, to increase near- and medium-field situational awareness for soldiers on the battlefield. In this scenario, a platoon of soldiers would carry several MMALV robots with them. When the need arises for intelligence gathering within a 1-mile range, a MMALV would be deployed with the appropriate sensors. MMALV would fly to the target location, such as the top of a building. Upon landing on the building, the vehicle would reconfigure to maximize terrestrial mobility. After the necessary intelligence has been gathered, MMALV would re-launch by way of walking off of the building roof-top. The vehicle would

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then fly back on the a secondary target, or rendezvous with the launching personnel for recovery.

The critical capabilities for MMALV to possess for the successful completion of this mission are: aerial locomotion; terrestrial locomotion; modular sensor system, so that the platform can be customized to the specific needs of the mission; ability to reconfigure; smallest possible size, to maximize stealth. MMALV may also need the ability to surmount the parapet that is found around most flat roofs.

B. Maritime Domain Protection/Ship Inspection

A required mission area of both the United States Navy and United States Coast Guard to support the Global War on Terror is to conduct Maritime Interdiction Operations (MIO). MIO include locating, intercepting, and boarding ships that have been identified as possible smugglers of terrorist material or personnel. These operations are best conducted as far away from ports as possible and require small teams of sailors to board threat vessels. The boarding teams and their host ship must conduct and maintain surveillance on the threat vessel's main deck and bridge crew before and during the actual boarding. A micro-robotic vehicle that is easily launched from the host ship or by the boarding team, capable of flying to the threat vessel and "perching" on or hanging from a high point to provide visual and other sensory information, could play a significant role in Maritime Interdiction Operations.

The sensing capabilities of the micro-robot could be used to insure compliance from the threat vessel's main deck and bridge crew, track progress of the boarding party, and monitor the threat vessel's "disengaged" side for clandestine cargo dumping. Other terrestrially-mobile flying micro-robots may be used as "advanced parties" to crawl into spaces and obtain sensor readings from cargo holds and containers. As with the previous scenario, the ability to relocate on the ground to best position its onboard sensors and re-launch for additional surveillance would be significant vehicle capabilities in Maritime Domain Protection missions. The perching behavior would also require a retractable tail hook, so that the vehicle can be recovered.

C. UAV Surveillance Capability Expansion

This mission is a variant of the field reconnaissance mission where MMALV launches from another, larger, airborne unmanned aerial vehicle (UAV). In addition to significantly increasing the range of MMALV, this would enhance the UAV's stealthy insertion capability by providing a quiet, low-radar-cross-section mobile sensor in its payload. An example of a military mission utilizing this capability could be over the horizon beach reconnaissance prior to a special operations team insertion or Marine landing. The UAV would be launched from a ship out of the coast's visual and radar range then release multiple MMALVs within a mile of the beach to fly into pre-selected surveillance positions. The UAV would then orbit to provide necessary communications links back to the host ship.

This mission would require a mechanism by which MMALV could be launched from an airborne UAV. A wide range of missions are also conceivable that would benefit from the ability to recover MMALV with the UAV.

D. Long Term Terrestrial Surveillance

This mission represents a combination of several of the previous scenarios. MMALVs would be launched either by strategic reconnaissance special operations teams or UAVs inside enemy territory then fly to a designated surveillance positions to monitor potential enemy movement or a specific target. A critical road intersection, mine warehouse, or missile storage facility are examples of targets that may require longer term surveillance. After landing, the MMALV could use its crawling capability to obtain the optimal vantage point within the surveillance area. After an extended monitoring of the target area, the MMALV could re-launch to another surveillance position, rendezvous with a recovery UAV, or return to its launching ground team.

In addition to the capabilities discussed previously, MMALV would require the ability to launch from the ground, and perform energy recover to enable long term surveillance and communications.

E. Basic MMALV Performance Specifications

MMALV was developed to improve near- and medium-field reconnaissance for ground based military personnel (warfighters). To fulfill its proposed mission [1] MMALV must fly over 1.6km to a target zone and land on a building rooftop. After locomoting to the edge of the roof (to survey adjacent areas) or into the building, MMALV must take-off from the roof and return to the deployment zone. Fig. 1 depicts multiple stages of this scenario.

Design specifications arise from the vehicle's intended function. To enhance stealth and be transportable by a single soldier the platform should be small (wingspan < 30.5cm) and light (weight < 450g). To maximize indoor reconnaissance capabilities, it is also desirable that the vehicle be capable of reconfiguring upon landing, thus decreasing its overall dimensions.

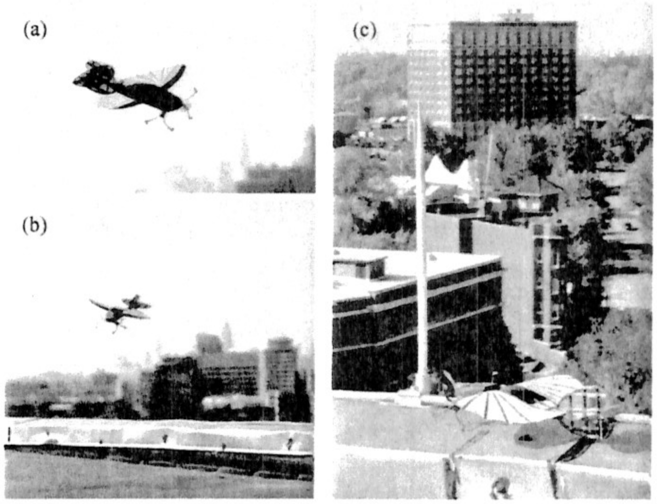

Fig. 1: In the proposed mission, MMALV must (a) fly up to 1.6km from the launch point to the target zone, (b) land on a rooftop within the target zone, and (c) walk to the edge of the building to survey the neighboring area.

The key to MMALV's success is the integration of the proven, highly adaptable UF-MAV and Mini-Whegs™ technologies. Their lightweight, biologically inspired design makes them ideal for integration into a flying/walking vehicle.

The University of Florida's flexible wing design is the basis for MMALV's aerial locomotion capabilities. The flexible wing confers upon the UF-MAV several advantages over similarly sized rigid-wing vehicles [2]. Delayed stall allows the vehicles to operate at lower speeds. Improved aerodynamic efficiency reduces the payload that must be dedicated to energy storage. Passive gust rejection significantly improves stability. The vehicle's carbon fiber construction is both lightweight and highly durable.

MMALV's terrestrial locomotion is based upon the Mini-Whegs™ line of robots, developed at Case Western Reserve University [3]. Over seven Mini-Whegs™ robots have been constructed, including models that are capable of jumping [4]. Mini-Whegs™ displays two characteristics critical to the successful field deployment of MMALV. Use of a single drive motor and diagonal gait coordination lead to a high level of efficiency, and the wheel-leg running gear provides Mini-Whegs™ with excellent terrain mobility.

II. BACKGROUND

A. *The Flexible Wing Micro Air Vehicle*

It has been well established that the aerodynamic efficiency of conventional (smooth, rigid) airfoils is significantly compromised in the Reynolds number (Re) range between 10^4 and 10^6. This Re range corresponds to the class of craft referred to as micro air vehicles [5]. In fact, the ratio of coefficient of lift (C_L) to coefficient of drag (C_D) drops by nearly two orders of magnitude through this range. With smooth, rigid wings in this Re range, the laminar flow that prevails is easily separated, creating large separation bubbles, especially at higher angles of attack [6]. Flow separation leads to sudden increases in drag and loss of efficiency.

The effects of the relationship discussed above can also be observed in nature. Consider, for example, the behaviors of birds of various sizes. Large wingspan birds, which soar at $Re > 10^6$, tend to soar for prolonged periods of time. Medium-sized birds utilize a combination of flapping and coasting, while the smallest birds, which would soar at $Re < 10^4$, must flap continuously and rapidly to stay aloft.

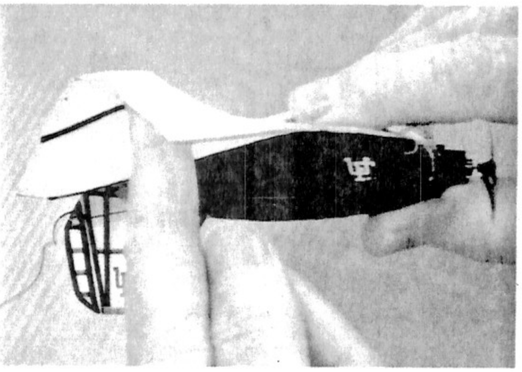

Fig. 2: Demonstrating the flexibility of the wing on the UF-MAV

Other major obstacles exist for flight on this scale [2]. Earth's atmosphere naturally exhibits turbulence with velocities on the scale of MAV flight speeds, and characteristic lengths on the order of MAV wingspans. This can result in significant variations in airspeed from one wing to the other, which in turn leads to unwanted rolling and erratic flight. The small mass moments of inertia of these aircraft also adversely affect the stability and control characteristics of the vehicles. Even minor rolling or pitching moments can result in rapid movements that are difficult to counteract.

Through the mechanism of passive adaptive washout, the flexible wing developed by the UF MAV Lab overcomes many of the difficulties associated with flight on the micro air vehicle scale. Adaptive washout is a behavior of the wing that involves the shape of the wing passively changing to adapt to variations in airflow. For example, an airborne vehicle may encounter a turbulent headwind, such that the airspeed over only the right wing is suddenly increased. The compliant wing structure responds to the instantaneous lift generated by the gust by deforming in a manner similar to Fig. 2, which results in a reduction in the apparent angle of attack, and a subsequent decrease in lifting efficiency, as compared to the left wing. However, because the air velocity over the right wing is higher, it continues to develop a nearly equivalent lifting force as the left wing. Similarly, as the airflow over the wing stabilizes, the wing returns to its original shape. This behavior results in a vehicle that exhibits exceptionally smooth flight, even in gusty conditions.

The success of this design is well documented. At the International Micro Air Vehicle Competition, the UF team has taken 1st Place overall the past six years, and has won the surveillance section for 5 of the past 6 years.

B. *Terrestrial Locomotion*

The real-world deployment of micro terrestrial robots has generally suffered from two primary shortcomings. The relative size of real-world obstacles makes navigation a daunting task for robots less than 45cm in size, and power-source miniaturization has lagged behind other critical technologies, such as actuation, sensing, and computation.

A wide array of vehicles have been constructed that attest to the difficulty of designing field-deployable mobile micro-robotics. Khepera robots have a 5cm wheelbase, onboard power, and considerable sensing capabilities [7]. However, their 1.4cm diameter wheels restrict them to operation on very smooth, flat surfaces. Millibots use tracks, but it is not clear that they offer much advantage because at this small scale it is difficult to implement a modern track suspension [8]. A small hexapod has been developed by Fukui et al. [9] that runs in a tripod gait using piezoelectric actuators. However, small joint excursions limit the vehicle to relatively flat surfaces. Birch et al. [10] developed a 7.5cm long hexapod inspired by the cricket and actuated by McKibben artificial muscles. It walks using 2 bars of air pressure, but the compressor is not onboard the vehicle.

The desired 30cm wingspan of MMALV could incorporate the terrestrial running gear of a larger robot than those described above. Sprawlita [11] is a 16cm long hexapod based upon the cockroach. Using a combination of servomotors and air cylinders, Sprawlita attains a top speed of 4.5 body lengths per second, which is fast compared to existing robots of similar size. However, operating at 6 bars of air pressure, it is unlikely that Sprawlita will ever be autonomous.

The implementation of biological locomotion principles holds considerable promise for terrestrial locomotion [12]. Legged animals exist and thrive at a wide range of sizes, and are capable of overcoming obstacles that are on the order of their own size. While direct biological inspiration tries to mimic the natural model to the greatest extent, this technique often requires new technology be developed in order to reach its full potential. Abstracted biological inspiration, on the other hand, attempts to abstract salient biological principles and implement them using available technology.

Locomotion studies of the cockroach illuminated several critical behaviors that endow the cockroach with its superior mobility [13]. During normal walking, the animal uses a tripod gait, where adjacent legs are 180° out of phase. The roach typically raises it front legs high in front of its body, allowing it to take smaller obstacle in stride. When climbing larger obstacles, the animal moves adjacent legs into phase, thus increasing stability.

The Whegs™ line of robots implement abstracted biological inspiration to accomplish the behaviors outlined above [14]. Torsional compliance allows for a single motor to drive the six three-spoke wheel-leg appendages in such a manner as to accomplish all of the locomotion principles discussed above. The Whegs™ technology is also scalable, with successful robots being developed with body lengths ranging from 89cm down to only 9cm.

Mini-Whegs™ (Fig. 3) robots currently offer the best combination of speed, mobility, durability, autonomy, and payload in a micro robot. With a top speed of 10 body lengths per second, Mini-Whegs™ are significantly faster than most other legged robots [14]. The wheel-leg appendage results in a natural "high stepping" behavior, allowing the robot to surmount relatively large obstacles. The robots have tumbled down concrete stairs and been dropped from heights of over 10 body lengths, without damage. Mini-Whegs™ robots have also carried over twice their body weight in payload [16], ensuring that they will be able to support the UF-MAV airframe.

Fig. 3: Relative sizes of Mini-Whegs™ and *Blaberus giganticus* cockroach

III. RESULTS

A. Target Acquisition and Recognition

The MMALV was able to successfully locate and identify a ground-based target during the the demonstration. Fig. 4 shows a sample of the video data transmitted from the airborne MMALV. Fig. 5 shows that the ground-based target (in this case, a resolution template) is easy to discern on from the on-board video. Also show is the synchronized external video of the vehicle in flight. The gray horizontal bands that appear in the image captures of the on-board video are actually the propeller passing in front of the camera.

Fig. 4: A sample of the video transmitted by MMALV during a field demonstration

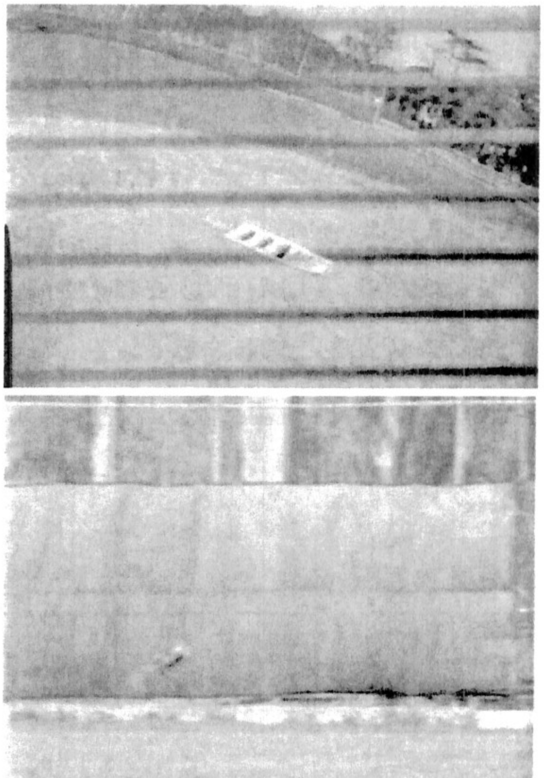

Fig. 5: Top – An image of the ground based target as seen from the vehicles point of view. Bottom – Synchronized external shot of MMALV during the demonstration.

B. Multi-mode Mobility

The vehicle is capable of both aerial and terrestrial locomotion. The small size and light weight of MMALV ensure that it is easy to hand launch. Flight characteristics of the vehicle are slightly compromised as compared to a similarly designed MAV, due to high wing loading. Furthermore, the location of the wheel-legs in front of the wing may increase turbulence over the wing.

MMALV is capable of the transition from flight to walking under most circumstances. When the vehicle lands a significant load is placed on the wheel-legs and drive motors. Occasionally, the nylon hub that attaches the wheel-leg to the motor cracks under this load. This is the primary circumstance that prohibits transition from flight to walking. It was found that incorporating spring steel into the wheel-leg design helped absorb the effect of the impact, thus reducing the likelihood of failure.

Multiple wheel-leg designs were evaluated against a variety of terrain and substrata. It was found that all designs were effective on semi-smooth concrete, dirt, and gravel. It was found that when the vehicle navigated through loose/fibrous materials, the wheg could become entangled, thereby binding the drive motors. This difficulty was more pronounced for those wheel-legs that included "feet".

C. Roof-top Take-off

The vehicle's ability to perform sufficiently at high angle-of-attack and low airspeed conditions resulted in a repeatable, successful take-off capability from atop a building structure. After the vehicle walks off of the roof of the structure, it enters a powered dive, pulled down by both gravity and the propeller. As airspeed builds, the necessary lift is generated to arrest the fall and transition to flight phase.

Two primary modes of failure existed for performing rooftop take-off: 1) insufficient altitude to enter flight phase, and 2) inability to avoid obstacles in the immediate vicinity of the take-off point due to lack of control at low airspeeds.

Each of these modes of failure was found to have a direct correlation to the relative sideslip of the vehicle as it left the structure. Sideslip is a condition in which an aircraft's direction of motion is NOT coincident with the major axis of the fuselage. If the MMALV was able to leave the structure with little or no sideslip, the minimum height for consistent take-off was approximately 20ft, and the vehicle's path was nominally perpendicular to the building. Therefore, if the take-off location was chosen properly (no obstacles directly in front of the vehicle at take-off), successful transition from rooftop walking to flight could be accomplished.

Two potential sources of sideslip were identified, both arising from the possible phasing of the two wheel-leg appendages. Just as the vehicle falls over the edge of the roof, if one wheel-leg is in a position to push off forcefully from the side of the building, but the other is not, a yawing motion will result. Similarly, if the wheel-legs are out of phase as the vehicle leaves the building one wing tip will be lower than the other. Both conditions result in a sideslip situation as the vehicle goes into the power dive phase of the take-off. Two things happen as a result of the sideslip: the downward acceleration is lowered, and the vehicle deviated from its intended course. By the time the vehicle reorients itself, there may be insufficient altitude to pull out of the dive. Similarly, as the vehicle veers off course at low speed, there is insufficient controllability to avoid any impending obstacles.

Both failure modes are minimized by taking-off from a downward sloping surface. The vehicle is able to attain a higher ground speed on the inclined runway than on the flat runway, thereby reducing effect of wheel-leg phasing as the vehicle leaves the building. Therefore, the likelihood of significant yaw and/or wing dip, as well as the associated sideslip condition, is avoided.

D. Wing Reconfiguration

A wing retraction system was developed to allow the vehicle to navigate more easily through complex obstacles. Fabricating the leading edge of the wing in two pieces, and pivoting each piece about an axis at the wing's root allowed for the wing retraction.

By reducing the vehicle width from 30.5cm (12in) to 10.2cm (4in), the wing-retraction system allows the vehicle to enter through smaller openings. Fig. 6 shows a sequence of images, which demonstrate the vehicle's ability. The reconfiguration mechanism was insufficiently robust to attempt flight with the morphing prototype.

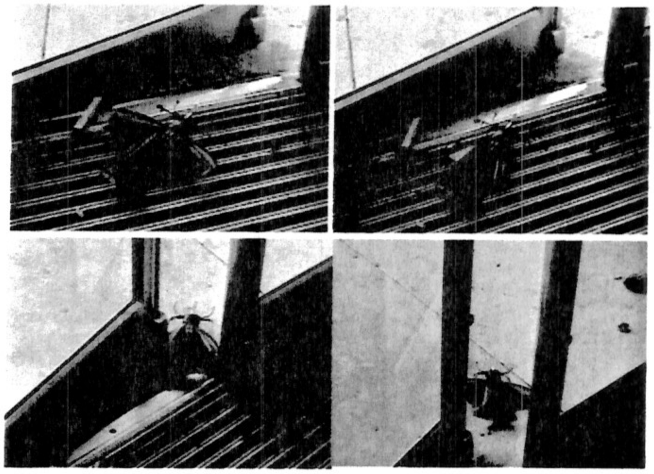

Fig. 6: When (a) MMALV is confronted with a narrow passage, it (b) retracts its wings, (c) negotiates the passage, and (d) redeploys its wings.

IV. DISCUSSION

We believe that all of the failure modes experienced for this prototype MMALV can be mitigated by implementing improvements to the terrestrial locomotion subsystem. The primary changes necessary to overcome most of the difficulties outlined in the Results section are the addition of two rear wheel-legs and the implementation of a more robust drive-train.

Regardless of the terrestrial drive motor used, a more robust drive train is imperative to withstand the impact loads encountered during landing. This capability is critical to the actual field deployment of MMALV.

Roof-top take-off and general terrestrial mobility will be significantly enhanced by the addition of two wheel-legs at the rear of the vehicle. During roof-top take-off, the rear wheel-legs will provide impetus after the front wheel-legs are no longer in contact with the substrate. This will avoid the main source of sideslip during this procedure. Rear wheel-legs will also ensure that the vehicle is able to locomote backwards over obstacles.

In addition to these critical enhancements, several other design implementations would further improve the overall performance and field-ability of MMALV. Several iterations of wheel-leg running gear have been previously tested on the Mini-Whegs™ vehicles, and the preferred design is for each spoke to have a roughly teardrop shape. This was found to reduce the amount of snagging encountered on most substrates, as well as smoothen the body motions during walking.

As well as being an integral part of a robust drive train, a more powerful terrestrial drive motor would endow MMALV with more speed and more torque. The success of roof-top take-off from a slanted surface demonstrates that increased speed at take-off also helps to reduce the chances of failure.

The MMALV described here is operating near the limit of its flight capabilities under a remote operator. While increasing the operating speed would increase the payload, this occurs at the expense of the controllability and efficiency. Two potential solutions present themselves to this problem: increased wingspan and implementation of auto-stabilization hardware. Increasing the wingspan slightly (to, say 35cm) will increase the lift generated by the vehicle. Because of the discrete nature of component size, the increase in vehicle weight will be less than the increase in lift. Implementation of auto-stabilization routines will allow a remote pilot to operate MMALV at higher speeds, which would also result in better lift. Improvements in battery technology would overcome the decreased efficiency associated with operation at higher speeds.

V. CONCLUSIONS

It is a testament to the UF-MAV and Mini-Whegs™ technologies that the prototype described here attained this high level of success. We expect the recommendations outlined in the previous section to fully address the failure modes experienced during testing, and generally enhance the performance and usability of MMALV.

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