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More Than Meets the Eye: A Hybrid-Locomotion Robot with Rotary Flight and Wheel Modes

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Abstract— **Mobility in small ground robots is often improved by novel mechanisms or wheel designs. This can be successful when navigating rough terrain or climbing small obstacles. However, few such robots are capable of scaling obstacles of arbitrary height or traversing all types of terrain. This paper presents a concept for a miniature robot that combines wheeled ground locomotion with rotary-wing flight capabilities, which has the potential to offer the best features of both helicopters and ground vehicles while addressing the aforementioned challenges to mobility.**

A proof-of-concept robot has been designed to test this concept. In its ground mode, it is based loosely on the University of Minnesota's Scout line of robots. It transitions from its ground mode to its flight mode by positioning itself on-end, unfolding rotors from its body, and taking off.

A full prototype of the design has been constructed and the concept has been shown to be feasible, but the design requires refinement before it is fully functional and robust. Test results from a focused ground-mode-only prototype and the miniature helicopter on which the flight mode is based provide estimates of the robot's performance where data could not be obtained from the full prototype. The results show that, while it is capable of the desired functions, more work is required before the concept can reach its full potential.

I. INTRODUCTION

One of the foremost concerns for miniature robots is that of mobility. While smaller robots are frequently desirable in many real-world situations due to their ease of transport and ability to maneuver in tight spaces, the variety of terrains and obstacles that can be navigated or scaled is reduced compared to similar larger robots, giving them limited utility in most circumstances.

The difficulty in improving the mobility of small robots is due to at least two factors. First, the small size imposes energy constraints on the robot by requiring that the energy source be compact and thus have a relatively small energy reserve. Second, any given terrain is more difficult for a smaller robot to navigate (all else being equal), since the effective terrain roughness is inversely related to robot size.

Much work has been done to enable small robots to walk or roll over rough terrain [1], [2], [3]. These solutions, while effective when the local elevation changes in a terrain are small, do not enable a robot to traverse relatively high changes in local elevation, such as, for example, steps taller than the robot. Jumping can give them this ability [4], [5], [6], [7], but, being without powered flight capabilities, jumping mechanisms have built-in altitude limitations imposed by their springs (or analogous energy storage elements), and the random nature of the landing orientation in many cases can make for difficulty achieving directed motion following a jump or wasted energy if the robot ends up tumbling back to its original location. Some jumping robots have been equipped with gliding mechanisms [8], and while this can potentially alleviate issues related to the randomness of jumping, the height is still limited by the jumping mechanism.

One relatively unexplored solution is the addition of a powered flight mode to a ground robot. The attainable altitude for such robots would be limited only by aerodynamics, efficiency, and the robot's total energy reserves, rather than the amount of energy it can put into a jump. This would provide flexibility for the robot, particularly if the immediate objective is to scale an obstacle. With a sufficient energy supply such a robot would have a far greater range of scalable obstacle heights than a comparable jumping robot. For instance, most small robots store enough energy onboard to lift themselves onto the roof of a one-story building. However, few if any are able to do so.

Depending on the flight mode of the robot, it could be used as an efficient means of long-distance travel and/or a way to traverse rough terrain and scale obstacles by simply flying over them. One robot that uses the former approach, the MMALV [9], combines fixed-wing flight with the use of wheel-legs for the ground. However, because the MMALV is not capable of unassisted take-off, the flight mode cannot be used to navigate over rough terrain and obstacles at will.

This paper describes the design of a robot that uses the latter approach, with rotary-wing flight and wheeled ground travel. This type of robot potentially offers several key benefits:

- Un-assisted take off (ability to switch locomotion modes at will),
- Hovering (maintaining position in the air),
- Ability to scale large obstacles and fly over rough terrain,
- Efficient ground-mode travel.

While most of these benefits could be realized with a small helicopter, the fourth item, efficient ground-mode travel, sets this design apart by giving it the ability to conserve energy while still making progress toward its objective if the terrain is smooth enough. Compared to the MMALV,

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which instead achieves fast, efficient travel in its flight mode, the roles of the two modes are essentially reversed. The primary disadvantage of the proposed design is that it is relatively complex mechanically, making it prone to mechanism failures.

In addition to an overview of the design, this paper provides detailed descriptions of the critical subsystems. A full prototype has been built and partially tested and shown to successfully perform its primary functions. Where data from the full prototype is not yet available, estimates of future performance based on data from subsystem prototypes are provided.

II. ROBOT DESIGN

This section discusses several important considerations in the design of the robot, describes the general approach for the robot's design, explains how the locomotion modes are achieved on the robot, and finally provides detailed information on its critical subsystems. CAD renderings of the robot in its ground and flight modes are shown in Figure 1.

A. Approach

One of the most challenging aspects of designing flying robots of such a small size (see dimensions in Table I) is providing enough lift while minimizing the overall weight. The following aspects of the robot's design were selected with this in mind:

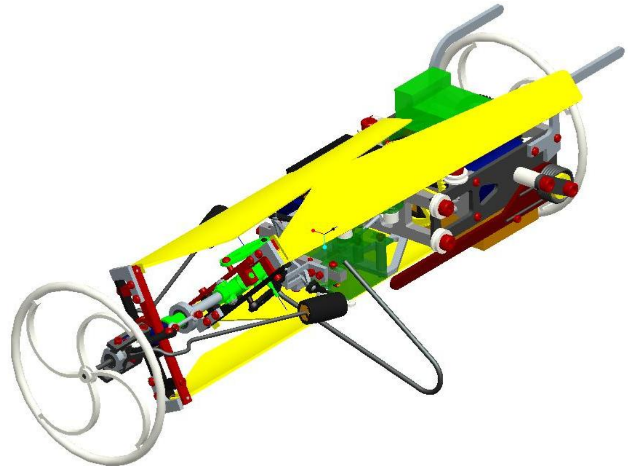
- Dual, counter-rotating, coaxial rotors allow the full power output from the drive motors to contribute to lift. With single-rotor designs, yaw is controlled by a tail rotor, which increases weight and draws energy while driving air horizontally, rather than vertically. In addition to this weight advantage, the coaxial rotor configuration is typically more stable in flight than other configurations, which is particularly important for air vehicles of this size. Much of the flight system in this robot is based a commercially-available radio-controlled (RC) helicopter, the Blade CX2, by E-Flite.
- Wheels driven directly by the rotor shafts require no further gear reduction, and thus no additional weight. While this results in difficulty controlling the robot and limited ground mobility (as discussed in Section III-B), for this proof-of-concept design this trade off was considered acceptable. The ground mode is loosely based on the University of Minnesota's Scout robots.

TABLE I

PHYSICAL SPECIFICATIONS

Metric	Value
Wheel Base	260 mm
Ground mode height	76 mm
Length (Ground mode)	120 mm
Mass	286 g[a]
Rotor Diameter	373 mm

[a] Assumes 2-cell battery. Mass is 301g with a three-cell battery.



(a) The robot in its ground mode.

(b) The robot in its flight mode

Fig. 1. The robot in its ground and flight modes.

The design requirements are simple and reflect the preliminary nature of the design; once the concept is proven, future designs will have much stricter performance requirements. The robot need only be capable of sustained hovering and directed flight in the flight mode (with no altitude requirement), and capable of traversing smooth terrain (e.g. laminate flooring) in its ground mode.

B. General Description

In the robot's ground mode, it drives like most other two-wheeled robots, with one motor driving each wheel, and a tail to provide a counter-torque. Its rotors and stabilizer bar are folded in against the robot's body and disengaged from the motors. This folding-rotor design was selected because it provides protection for the relatively delicate rotor system and allows the robot to reduce its largest dimension in ground mode (the 260mm wheel base) below the diameter of the rotor (373 mm), giving it better maneuverability in small spaces on the ground. It also simplifies the drive system by allowing all drive shafts to be parallel and lie in the same plane.

In order to transition to flight mode, it must undergo a transformation involving two mechanisms which sequentially turn the robot up on its side and engage the rotors with the motors. The rotors, which are hinged near the shaft on pins, then passively unfold from the body of the robot as they start spinning.

The transformation from ground to flight modes begins by extending a pair of arms (called the "moving arms") hinged at the lower end of the robot[1]. The moving arms push on the ground, lifting the upper wheel from the ground and creating a new support polygon defined by points on the lower wheel and each of the moving arms. The moving arms continue to push until the robot is upright, at which point support has been handed off from the lower wheel to a pair of static arms. The robot is shown in Figure 2 in the middle of this process. The two pairs of arms, in this configuration, provide stable support while the robot takes off. Figure 1(b) shows the arms in this configuration, which the robot maintains in flight mode. The center of gravity always remains within the support polygon (when on a flat, level surface), which prevents the robot from tipping over during the transition.

Once the robot is upright, the rotor shafts are engaged. In the process, the stabilizer bar is unfolded. The rotors unfold as they spin up; to keep the rotors from crashing into one another, the upper rotor must be powered first. Once the upper rotor begins to unfold under the centrifugal load, the lower rotor can be powered. The rotor speeds are ramped up until the robot ultimately begins flying. A net yaw-inducing torque must be countered as the upper rotor is spun up in order to keep the robot from spinning (the lower rotor provides the countertorque when it spins up). However, the speed required to raise the rotor and the inertia of the rotor are both small enough that on most surfaces the robot experiences no yaw during this process, as tests have confirmed.

[1]To facilitate further description of the robot as it transitions from its ground to flight modes, the wheels are defined in terms of their positions when the robot is in flight mode. Thus, the upper wheel is near the rotors, and the lower wheel is opposite the upper wheel.

In flight, the robot is controlled like most other miniature RC helicopters. Lift is controlled by adjusting the rotor speeds. Yaw is controlled by adjusting the relative rotation speeds of the rotors. Pitch and roll are controlled by adjusting the cyclic pitch of the lower rotor via a swashplate, which is ultimately controlled by two servo motors. A stabilizer bar linked to the upper rotor helps maintain stability and reject disturbances.

To land and switch back to the ground mode, the actions are reversed. The static arms are designed such that by the time the lower wheel makes contact with the ground, the robot tips to be supported by the moving arms, giving the robot a gentle transformation as the moving arms are retracted.

C. Orientation Adjustment Mechanism Design

The moving arms are hinged to the front and back of the robot, and open toward the ground, as shown in Figure 3. An elastic rope (not shown in the figure) is suspended between them. This holds the rotors against the underside of the robot in the ground mode so that they do not make contact with the ground. The rotors on the opposite side are free to move on their hinges, but stay down under the force of gravity.

Each moving arm is pre-loaded by a torsion spring, which provides the force to reorient the robot. The moving arms are retracted by cables, which run through pulleys to a motor, which wraps the cable up on a spool.

D. Rotor Transmission Design

Each drive motor drives one rotor and one wheel. In the ground mode, because the rotors fold against the robot's body, it is important that they do not spin. The mechanisms involved in engaging and disengaging the rotors are discussed in this section.

To drive the lower rotor, the motor drives an intermediary shaft, which in turn drives the lower wheel and the lower rotor's shaft (also called the outer shaft). The outer shaft

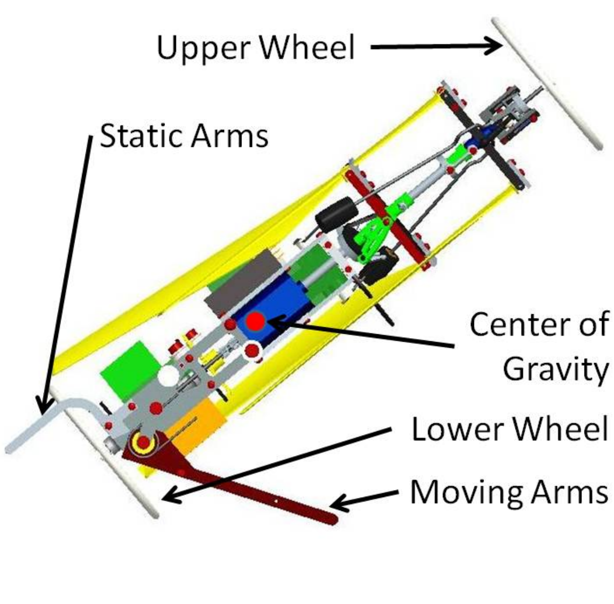


Fig. 2. The robot in the middle of its uprighting action.

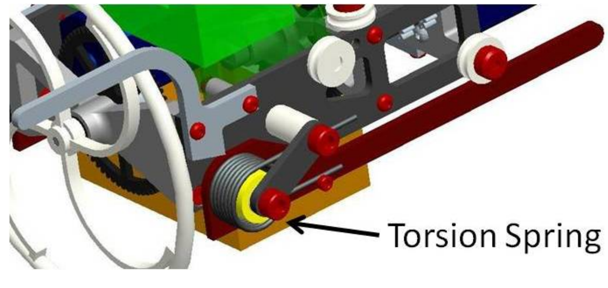


Fig. 3. A close-up view of one of the orientation adjustment arms in its retracted position. Arm retraction cable not shown.

is a hollow tube, through which runs the upper rotor's shaft (inner shaft). The outer shaft is supported by radial bearings, constrained axially only by a servo motor, which can shift the shaft as desired to engage or disengage the outer shaft's gear with its pinion. The transition can be seen in Figure 4.

The upper rotor's motor is permanently coupled to the inner shaft via a gear pair. However, the upper rotor floats freely on the inner shaft, and is constrained axially to move with the outer shaft. When the outer shaft is raised to engage the lower rotor with its motor, it slides the upper rotor upward along the inner shaft, where a dog clutch engages it with the inner shaft.

As the rotors are engaged, the stabilizer bar is unfolded by a four-bar linkage. The stabilizer bar is composed of two halves, hinged in the middle at the top of the robot (just below the upper wheel). It is attached to the inner shaft with a bearing, but is constrained to rotate with the upper rotor by a fork and pin, which allows the parts to translate with respect to one another while maintaining angular orientation. The links that connect the stabilizer bar to the upper rotor force the stabilizer bar to unfold when the outer shaft is raised.

E. Electrical Hardware

The robot can use a standard RC helicopter electronics system, which includes a receiver, signal mixer and electronic speed control for the main motors, and a gyroscope. However, for full functionality this is inadequate. Because rotors normally only spin in one direction, the signal mixer is incapable of reversing the motor directions, which means the robot cannot travel in reverse on the ground. In fact, since the rotors must spin in opposite directions in the air, a separate mechanical switch controlled by the shaft translation servo was installed to reverse the direction of one of the motors in the ground mode. For basic mechanical testing, this is sufficient, but it makes the robot useless for much more, as it cannot move backwards and thus can easily get stuck against a wall.

Significant gains will be achieved with a new control circuit (Figure 5). In addition to making the motors reversible, it will use a microcontroller to allow for some actions to be automated, and to allow for different types of behaviors and control input interpretations for the two different robot modes. The circuit shown assumes that the robot will be teleoperated. It is powered by a 3-cell Lithium-Polymer battery.

III. CURRENT RESULTS

In the prototype, all mechanisms have been tested and work as described, but issues controlling the robot in its flight mode have thus far prevented performance testing. As part of the design process, however, the Blade CX2 was tested and a focused prototype of the ground mode was constructed and tested. Below, results from those tests are presented and used to estimate how the robot will perform when the aforementioned issues are addressed.

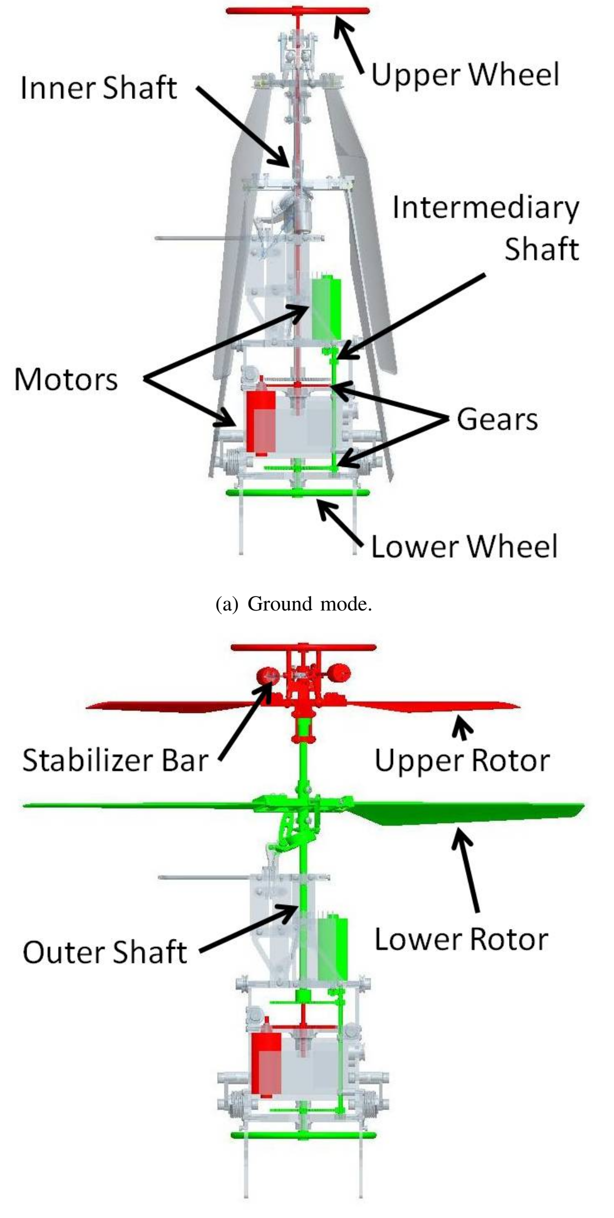


Fig. 4. Views of the robot's transmission in its two modes. Driven components are colored, with the color indicating the driving motor. The outer shaft is shifted upward in the lower figure.

A. Performance Metrics

Given the nature of this concept's potential benefits, several performance metrics are particularly important, and are the measures by which future version of the robot will be evaluated as well. These include:

- Battery life. By comparing the battery life in the two modes, a measure of the benefit of including a ground mode is obtained. While long battery life is desirable for either mode, if the ground-mode battery life is significantly higher, it indicates that hybrid-locomotion robots of this type can be more useful than simply a helicopter in some situations.

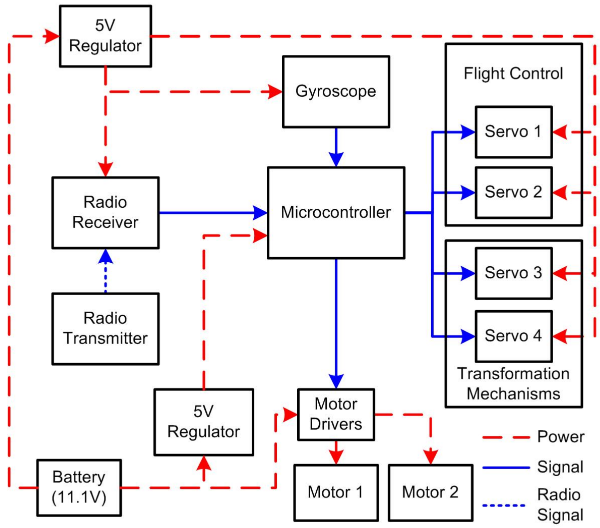


Fig. 5. A block diagram of the proposed control circuit.

- Forward speed. This is another measure of the benefit of combining air and ground locomotion. If the robot is significantly faster on the ground, this compounds with the battery life benefit.
- Attainable hover altitude. This will show the utility of the flight mode for scaling obstacles.
- Roughness of navigable terrain. This will dictate at which point the robot must switch to its flight mode. If the robot is significantly more efficient on the ground, as measured by the first two metrics above, it will be important to keep the robot on the ground as much as possible. The value used here to quantify this metric is the maximum step height that the robot can scale with a running start. For the design presented here, this test is of limited utility because the design requirement was only that the robot be capable of driving over smooth terrain.

B. Focused Prototype

To test the robot's performance in its ground mode, a prototype was constructed with similar dimensions and weight distribution (Figure 6). This prototype uses the standard RC control system mentioned above. All drive system components and their support conditions match those on the actual robot. The focused prototype's body is constructed of three pieces of ABS plastic manufactured via fused deposition modeling.

When tested, the prototype was initially found to be uncontrollable. The wheels' unfavorable gearing caused them to spin excessively fast even in the bottom 15% of the control input range. Because the radio and control components from the Blade CX2 were used, the internal gyroscope created further control difficulties by exaggerating the sudden turns caused by the high sensitivity of the wheel speed. However, with practice, the robot can be driven easily. The performance metrics measured with this prototype are shown along with the expected performance on most of the remaining metrics in Table II.

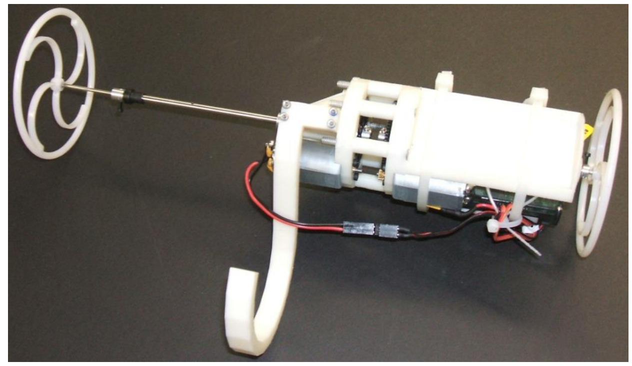


Fig. 6. A photograph of the ground-mode prototype.

Due to the controllability issues, the listed ground-mode forward speed is limited by the skill of the driver, rather than the hardware itself. The ground-mode battery life listed is a worst-case, with the motors spinning at full speed with no load except for the drive train and wheels. Lab tests revealed that during typical use, the current draw was reduced by approximately a factor of 4, so the ground-mode battery life may be as high as 3.5 hours in certain conditions. This is a strong indicator that this concept can be useful.

C. Expected Performance

For the values marked "expected" in Table II, no direct tests have yet been performed. Those values were estimated based on results from tests of the Blade CX2. They assume the use of a two-cell Lithium-Polymer battery with a capacity of 730 mAh, and a total robot mass of 286 grams.

The Blade CX2 was found to have a runtime of approximately 10 minutes maintaining a hover. Using the momentum theory (actuator disk theory), energy consumption can be related to thrust as shown in Equation (1), where L is lift and P is power consumption (under the assumption that power consumption scales linearly with induced power in the airstream).

$$L \propto P^{2/3}. \tag{1}$$

The thrust required to sustain a hover is directly proportional to the mass of the vehicle. Using the 227g measured mass of the Blade CX2 and the 286g expected mass of the robot, the power consumption for the robot is expected to be approximately 40% higher in a sustained hover. If the two-cell battery is used, this gives an expected runtime of

TABLE II
ROBOT PERFORMANCE, TESTED AND EXPECTED

Metric	Value
Ground-mode battery life	52 minutes (minimum)
Air-mode battery life	7 minutes (expected)
Ground-mode forward speed	1.58 m/s
Peak hover altitude	45 cm (expected)
Scalable step height (running start)	1.5 cm

approximately 7 minutes. With a 3-cell battery, the difference can be recovered by the proportional reduction in duty cycle in the drive system.

The peak hover altitude estimation comes from payload tests performed on the Blade CX2, wherein increasing weight was suspended from the helicopter, its throttle was fully engaged, and the elevation of the lowest point on the helicopter was measured. The test was performed indoors over a smooth floor. For high loads, ground effect enabled the helicopter to maintain a hover at a low altitude even if it could not at higher altitudes. The altitude estimate assumes that the battery is fully charged, and is obtained by matching the mass of the robot to the hover altitude of the helicopter at that mass.

The circuit described in Section II-E will enable the use of a three-cell battery to increase the motor power, which will raise the mass to 301 grams but provide significantly more lift. It is useful to consider how the performance might be impacted by such a change. For instance, in order to estimate the motor voltage required to keep performance at the level of the Blade CX2, the momentum theory can be used again to obtain the following approximate relation:

$$L \propto V^{4/3}. \tag{2}$$

Equation (2) relates lift force, L, to the voltage applied to the motors, V, for a given rotary wing vehicle. In accordance with the momentum theory, it assumes the absence of ground effects, along with the assumption mentioned above regarding power. With the move from 2 cells to 3 cells, the battery voltage increases by 50%, which gives a 72% increase in lift.

While the aerodynamics of the differing body shapes and the effects of a slightly larger rotor disk on the robot have not been taken into account, this calculation does suggest that the increased voltage will significantly improve the capabilities of the robot in flight. Since flight capabilities are greatly impacted by the lift:weight ratio, and since the flight hardware has been kept substantially the same in the robot as in the Blade CX2, this suggests that the robot's flight capabilities with a 3-cell battery will be on par with those of the Blade CX2 when the robot weighs approximately 390g, which is far above the robot's estimated weight and suggests that the robot's performance will exceed that of the Blade CX2.

IV. CONCLUSIONS

The design presented here is expected to meet its requirements once the aforementioned issues are addressed. While the expected performance of this design does not reach the potential of the concept it is meant to demonstrate, it shows the basic functions of such designs and shows that the concept is worth pursuing further. In particular, the possibility of extending the lifetime by up to a factor of 30 with respect to a similar helicopter, while retaining the ability to scale tall obstacles and fly over rough terrain, shows that this concept could be very useful.

V. FUTURE WORK

Work is underway to refine the design and address the issues it faces. In addition, the circuit presented above will be added to the robot to give it more functionality. It will allow for the implementation of motion controllers and higher attainable altitudes.

A second version of the robot will have a number of improvements. At least three deficiencies in the current design will be addressed. First, in order to improve controllability and mobility on the ground, the wheels should be geared down further. Second, locking mechanisms should be added for the arm retraction and shaft translation mechanisms to relieve their respective motors of the task of holding the mechanisms in their ground-mode positions, which will improve battery life. Finally, the design is relatively complex and fragile, so future efforts will focus on simplicity and robustness.

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