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Design of an Improved Land/Air Miniature Robot

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Abstract— **Small ground robots remain limited in their locomotion capabilities, often prevented from accessing areas restricted by tall obstacles or rough terrain. This paper presents the improved design of a hybrid-locomotion robot made to address this issue. It uses wheels for ground travel and rotary-wing flight for scaling obstacles and flying over rough terrain.**

The robot's initial design suffered from a number of issues that prevented it from functioning fully, such as overheating motors, inadequate control electronics, and insufficient landing gear. Several improvements have been made to the robot's design to correct these problems.

These obstacles, and the solutions implemented in the improved design, have enabled several design principles to be formulated for miniature hybrid-locomotion robots. It is found that hybrid-locomotion vehicles utilizing rotary-wing flight are most useful when the design is optimized for ground mode performance. Collapsibility is necessary in such vehicles to reduce the impact of the helicopter rotor on the size of the ground mode. Finally, since a large number of actions are necessary to propel and transform the robot, integrating multiple functions into each mechanism can reduce the mass of the robot.

I. INTRODUCTION

Miniature ground robots often encounter impassable obstacles due to a mismatch between the size of the robots and the scale of the objects in their mission environment. For instance, robots operating in urban environments may frequently come across stairs. Robots around the size of a Packbot can typically scale stairs without issue [1], [2], [3], but for robots lower on the size spectrum, similar performance is much more difficult to achieve.

This paper describes improvements to a robot that was developed with obstacle scaling in mind. It is loosely based on the two-wheeled Scout line of robots from the University of Minnesota [4], but with the addition of a rotary-wing flight mode. The robot is primarily meant for use on the ground; the intent of the flight mode is to move the robot over obstacles, across rough terrain, into open windows, etc.

A short summary of prior development on the robot is provided. Next, issues with the original design are described, and solutions are presented. Several empirically-derived design principles discovered in the course of the robot's development are then described and supported by results from the revised design.

A. Related Work

Several concepts have been explored in an effort to enable small robots to scale obstacles. One common approach is to add a jumping mechanism [5], [6], [7]. With jumping, however, the attainable jump height is inherently limited by the amount of energy the robot can put into a jump. The design discussed here uses sustained flight to achieve the same end, eliminating this restriction.

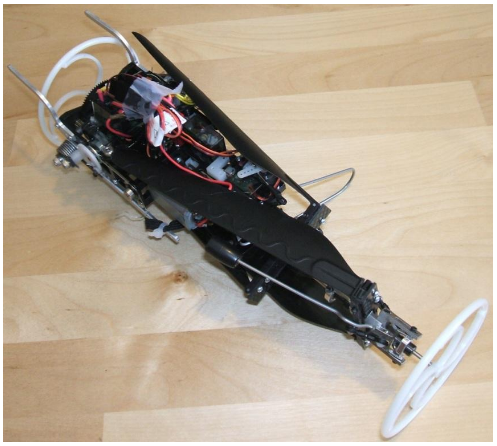
More generally, there are a number of robots capable of multiple modes of locomotion in different environments; these largely consist of amphibious robots [8], [9]. Relatively little work has been done with the combination of terrestrial locomotion and flight. Examples include the MMALV [10], which utilizes fixed-wing flight and wheel-legs, and the Entomopter [11], which uses flapping-wing flight and legs. They are primarily UAVs, with the ability to crawl once they land, whereas the robot discussed in this paper is intended primarily as a ground robot with a flight mode for intermittent use.

B. Summary of the Original Design

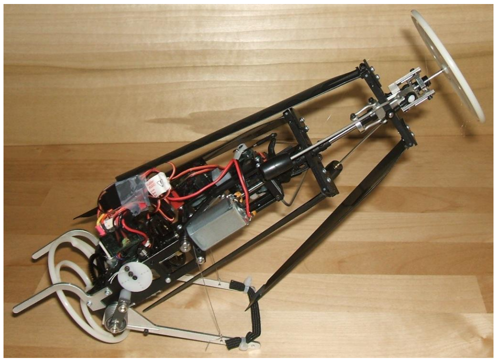
The robot discussed here is a two-wheeled ground robot that transforms into a helicopter. The flight mode utilizes two coaxial, counter-rotating rotors. A stabilizer bar linked to the upper rotor rejects disturbances and improves controllability. Two servo motors control pitch and roll through a swashplate connected to the lower rotor, and yaw is controlled by adjusting the speed differential between the two rotors. The rotors are fixed-pitch, so lift is controlled by rotor speed, rather than by collective pitch as in more advanced rotor systems.

In the ground mode, the rotors and stabilizer bar used for flight are folded down along the length of the robot's body. It transforms into its flight mode by positioning itself on-end, with its long axis oriented vertically rather than horizontally, and unfolding its flight mechanisms. The rotors are attached to the rotor heads close to the drive shafts by passive hinges and thus unfold as the shafts begin to spin.

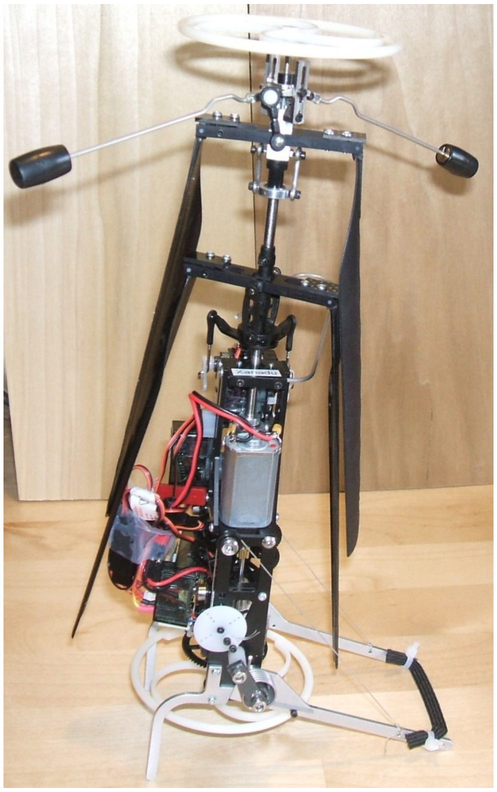
The mechanism that positions the robot on-end uses four legs; two legs are fixed rigidly in position, while the other two are folded on pivots against the body of the robot with a winch. When the winch is released, torque applied by torsion springs at the pivot axes causes the two moving legs to rotate on their pivots, forming what can be modeled as a crank-slider mechanism composed of the robot, the ground, and the moving legs. As the legs extend further, they gradually orient the robot vertically. The full sequence of motions is illustrated in Figure 1.



(a) The robot in its ground mode.



(b) The robot in the middle of its transition from ground mode to flight mode.



(c) The robot in its flight mode before takeoff.

Fig. 1. The robot's transformation sequence. A prototype of the original design is shown.

The robot has two drive motors, each of which drives one rotor and one wheel. The rotors disengage from the drive train when in ground mode, but the wheels are permanently coupled to the two output shafts and thus spin in flight. The wheels are driven at the same gearing as the rotors.

Table I shows the exterior dimensions and masses of the original design and of the revised design. More on the original design can be found in [12].

C. *Issues with the Original Design*

Prototypes revealed several issues with the original design, primarily stemming from design decisions made to reduce the weight of the robot, but also from the use of a commercially-available radio-controlled (RC) helicopter as a basis for the design of the flight mode. These include:

- **Motor failures**: The motors used in the original design are the same as those used in the Blade CX2 from E-Flite, the helicopter upon which the flight mode is based. However, the mass of the robot is approximately 30% higher than that of the Blade CX2, which requires approximately 50% more rotor power in hover (according to the momentum theory of lift). In addition, the robot's drive train is more complex, and thus less efficient, than the Blade CX2's. These factors together resulted in repeated motor failures due to overheating,
- **Inadequate control hardware**: Originally, hobby RC electronics were used to control the robot. The available off-the-shelf components either are not light enough or do not have enough functionality to perform all of the desired tasks with the robot,
- **Inability to transform, unassisted, into the ground mode**: The original rotor containment scheme relied on a band across the orientation adjustment legs to wrap around the rotors on the underside of the robot in the ground mode. However, due to the passive hinges on which the rotors are mounted, by the time the legs were retracted enough to catch the rotors, the rotors had fallen out of reach of the band,
- **Difficulty landing**: The original landing gear design made four points of contact with the ground in a relatively small cluster. This made landing difficult, as small errors in the orientation of the robot could result in it tipping over upon landing, preventing it from making the transformation back into the ground mode. In addition, the original design resulted in the rotor's axis of rotation being approximately 8° off of the vertical when in its take-off configuration (Figure 1(c)), causing undesired horizontal motion even before the robot takes off,
- **Tipping forward during ground locomotion**: The original tail proved to be inadequate, as the robot's center of gravity is nearly on the wheels' axis of rotation, and the robot would easily tip forward.

II. CHANGES IN THE REVISED DESIGN

A number of improvements were made to the design in order to address the aforementioned issues. The motors

Metric	Original Design	Revised
Wheel Base	260 mm	260 mm
Ground Mode Width	290 mm	320 mm
Ground Mode Height	76 mm	83 mm
Ground Mode Length	120 mm	180 mm
Rotor Diameter	373 mm	373 mm
Air Mode Height	290 mm	291 mm
Mass[1]	301 g	318 g

TABLE I

PHYSICAL SPECIFICATIONS

were upgraded, the rotor-containment mechanism was revised, custom electronics replaced the hobby components, the landing gear was scaled up, and a new approach to the tail was implemented. This section describes the rationale behind these changes and the details of their implementation.

A. Motors

As mentioned above, the original motors (model FK-180SH-3240 from Mabuchi Motor) were prone to overheating, with failures manifesting as melted commutator housings after approximately 2.5 minutes of flight. To correct this, brushless motors (model C10 from ELE RC) were substituted. In addition to reducing the mass of the motors from 33g to 8g each, this simplified the drive train by coupling the motor's rotor directly to the shaft it drove. Also, the motor can be driven at a higher power before failure due to all-metal construction and an open-case design that improves cooling.

B. Electronics

In order to expedite the mechanical design and testing of the robot, off-the-shelf hobby RC electronic components were used in the original design. While this achieved its purpose, it left much to be desired. In particular, components that were small enough offered no fine control of the motors and no way to program any autonomous behaviors.

To address this issue and to provide more functionality, a custom circuit board was designed. An off-the-shelf receiver can be plugged into the board for teleoperation, retaining the ability to quickly and easily test the robot. However, on the new board, the signals are fed into a programmable microcontroller for processing before being forwarded to the motors. Onboard gyroscopes and accelerometers enable six-axis inertial measurement. With this configuration, motion controllers can be implemented.

The board was also designed to be used with a Gumstix Overo Fire computer-on-module, which can be used in place of the receiver in a more advanced setup, communicating with the microcontroller over an SPI bus. The Overo enables wireless communication over WiFi or Bluetooth. A camera feeds video to the Overo, which can perform simple vision processing and/or stream it to a remote system. Eventually, the robot could be integrated into the system described in [13] for control augmentation and/or to be used as an experimental platform.

C. Rotor Containment

The original rotor containment system worked properly until the robot needed to switch from its air mode to ground mode. When it made this transition, the rotors escaped the reach of the containment mechanism, as shown in Figure 2. This resulted in the rotors dragging on the ground, causing damage to the rotors and hampering the robot's motion.

Full transformation capability has been achieved in the revised design with two changes to this system. A hook has been added to the lower rotor to catch the upper rotor when it is driven backwards. This holds the upper rotor close to the robot's body, which in turn restricts the lower rotor from unfolding (see Figure 3). These parts work in conjunction with a containment bar attached across the bottom of the retractable legs. Once the robot has tilted over far enough, the rotors are within reach of the containment bar, which holds them against the body for the duration of the robot's time in its ground mode. The containment bar serves the same purpose as the elastic strap used in the original design, but holds the rotors closer to the robot's body as a result of its rigidity.

D. Landing Gear

The containment bar mentioned in Section II-C also assists in stability during take-off and landing. Its addition increases the size of the robot's support polygon (Figure 4), significantly decreasing the likelihood of the robot tipping. In addition, the landing gear has been extended in the other dimension. The landing gear folds up with the retractable legs to reduce the height of the robot in the ground mode (Figure 5), but extends to increase the size of the support polygon for flight mode, greatly improving stability during take-off and landing.

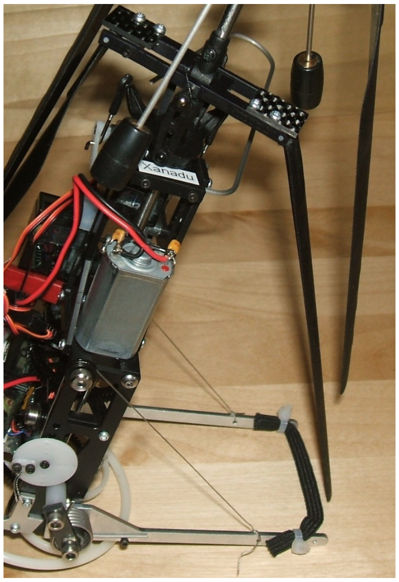


Fig. 2. Rotors escaping their containment mechanism during the air-to-ground transition in the original design.

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[1] For a robot equipped with a 730mAh 3-cell LiPo battery.

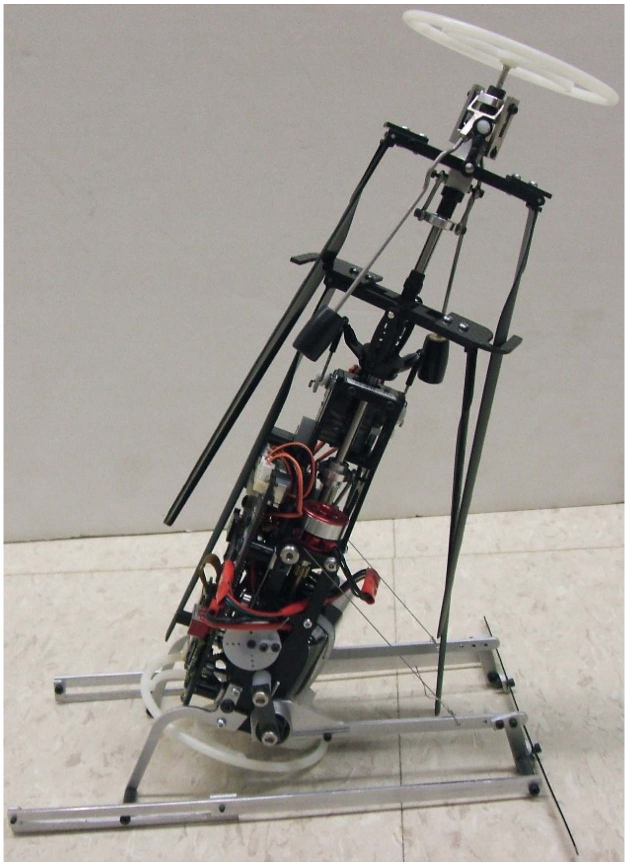

Fig. 3. A prototype of the revised design midway through transformation. The upper rotor is retained close to the robot's body as it tips down, keeping the lower rotor folded as well.

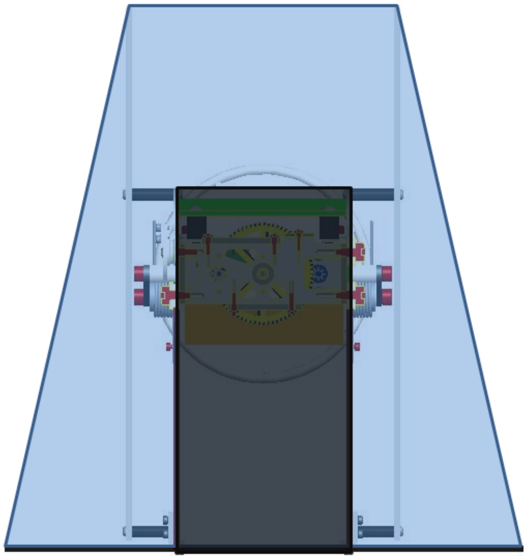

Fig. 4. CAD view, from the bottom of the robot in its flight mode, illustrating landing gear support polygons for the original design (dark shading) and the revised design (light shading).

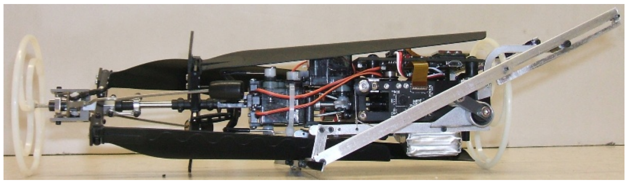

Fig. 5. Front view of the revised design in its ground mode, illustrating the new landing gear mechanism in its folded state.

E. Tail

Originally, the robot had a tail that dragged behind it, much like any other two-wheeled robot. However, it was evident in prototypes that support was necessary in front of the robot as well to prevent it from tipping forward, since the robot's center of gravity is very close to its center axis. This problem was solved by using the rotor containment bar, which extends both forward and backward, as a tail.

III. DESIGN PRINCIPLES

The aforementioned issues and their solutions have contributed to the recognition of several design principles for miniature hybrid-locomotion robots. This section describes those currently identified and justifies them; more are expected to arise as development continues on future designs.

A. Locomotion Focus

A minimal level of mobility in each mode is necessary for a hybrid-locomotion robot to be considered functional, but any additional capabilities can be focused on one of the modes. Such improvements will have a strong interplay with the mass of the robot. Specifically, wheeled robots suffer a much smaller penalty to battery life and maneuverability for a given amount of added mass than helicopters do. A more powerful ground drive train, for instance, may be worth additional mass for a ground-focused robot, but not for an air-focused robot.

The design discussed here is largely air-focused. This is evident from the drive train, which is geared solely for flight and functions poorly on the ground. Also, the wheels were selected purely for their low mass, with little regard for traction or obstacle-climbing capability.

It is instructive to consider the performance of the robot in the context of this principle. Figure 6 shows measurements of the lift and total power consumption of the air mode as a function of rotor speed. It shows that the robot requires approximately 70 W of power to take off (at a rotor speed of nearly 2000 RPM) and maintain a hover with no payload. While this is a high power demand, it is not exceptional compared to typical hobby helicopters; the robot can hover for roughly 4 minutes. It also shows that the robot is capable of taking on a payload of nearly 50% of its weight (though at the expense of maneuverability and flight time). Lift data was collected using a custom-built test stand with a single tensile load cell.

One helpful metric that can be extracted from this data is the ratio of power draw to lift (the inverse of the robot's power loading). In the operating range of the robot (i.e. where the lift exceeds its mass), this ratio is approximately .215 ± .15 watts per gram-force when using non-folding rotors.

Consider that gearing down the wheels in ground mode may add an additional 10 grams of mass (in bearings, gears, etc). This would add approximately 2.15 W of power draw in the flight mode, whereas the change would be negligible in the ground mode, especially considering its significance compared to the electrical overhead (onboard wireless communication devices alone may use a watt or more). If the robot is to spend most of its time in the air, such a change likely is not worth the extra weight. However, the much-improved ground performance would be worth the reduction in flight performance for a ground-focused robot.

Future designs will better reflect the concept of an intermittent-use flight mode. Indeed, for a hybrid-locomotion robot equipped with a rotary-wing flight mode, there is little reason to be air-focused; such a role could be much better served by a regular miniature helicopter. The advantages of the ground mode (stealthy operation, lower energy consumption, and a small size) are largely negated when the robot flies. Thus it is important that the ground mode perform just as well as comparable ground-only robots, or else the flight mode would need to be utilized too often.

B. *Collapsibility*

One design goal for this robot in particular is a small size, especially in the ground mode. The fact that the robot transforms to switch modes, rather than simply having rotors attached to its top, is a result of this. Thus, out of the available rotor configurations (quad-rotor, coaxial, or single-rotor, etc.), the one that can be collapsed into the smallest ground robot for a given level of performance should be used.

The transformation mechanisms and process should also be simple to make it reliable and robust. In terms of drivetrain complexity, perhaps the most easily collapsible rotor configuration is the quad-rotor; rotors could be placed on arms that fold up into the robot's body, and since the rotors are smaller in diameter than in other configurations they would require no additional collapsing. Other rotor configurations require that the rotors themselves be folded down, creating additional design challenges considering that the mechanism for folding them must not interfere with correct operation of the rotors in flight. Tail rotors present a significant challenge, as on a small robot the space for a mechanism to fold up a helicopter tail is extremely limited.

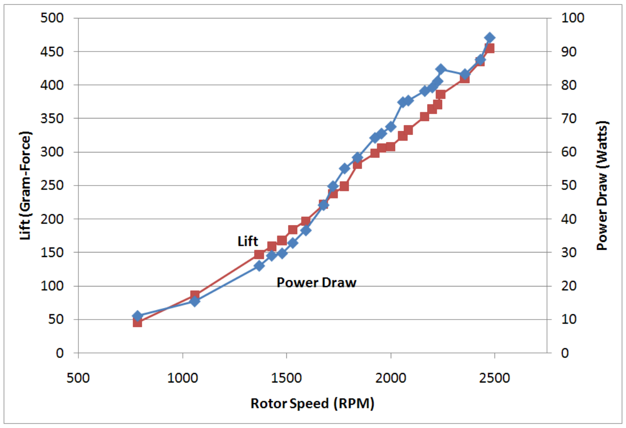

Fig. 6. Power consumption of the robot in flight. Results obtained on a test stand with non-folding rotors.

Compared to single-rotor designs, coaxial rotor configurations offer slightly higher payload capacity for a given rotor diameter. The vertical separation required between the two rotors, however, means that if the rotors fold along the length of the robot's body, a larger single rotor located where the upper rotor would be on a coaxial helicopter could be used for a robot with a given ground mode size; this would allow for a reduction of main drive train complexity, but requires the addition of a tail rotor. Quad-rotor configurations typically have rotor diameters on the order of half the diameter of a similarly-capable single-rotor configuration; in order to improve on a single-rotor design, each of the four rotors would need to fold up as well. On the design presented here, a coaxial configuration was selected for its excellent indoor flight characteristics and the relative ease of collapsibility, since no tail is necessary.

One way to achieve further collapsibility would be to add another hinge to the rotor mid-blade, in addition to hinges on the rotor head. The blade's aerodynamic, mechanical, and size requirements, however, make this infeasible.

Another consideration in collapsibility is that the flight components, which are relatively fragile, should be shielded adequately from contact with the environment. This is achieved on the current design by folding them down within the wheel diameter, so on mostly-flat surfaces there is little chance of the rotors contacting other objects. The shielding is further enhanced by the revised rotor containment system, which holds the rotors closer to the robot's body. We believe that this is an excellent way to achieve a robust robot, as it is based on the premise that wheels can serve as protective elements, which has been demonstrated quite successfully [4]. Additional shielding could be achieved if the blades were stored inside an external shell.

C. *Combination of Functions*

One common theme in the development of this robot has been the necessity for creative uses of its mechanisms for several different functions. As illustrated in Figure 7, each mechanism on the robot serves several functions, each of which is necessary for at least one of the robot's primary actions. The need for multi-purpose components in miniature air vehicles and particularly in hybrid-locomotion designs has been noted before [11]. This helps reduce weight, but also requires a number of interactions between mechanisms, in effect increasing system complexity. Reducing this complexity will be one of the primary aims of future development.

In some cases, this integration has hindered performance. For instance, the tail on the revised design, which has been made part of the landing gear, gives the robot little ground clearance; the robot has scaled steps of only 4 mm with

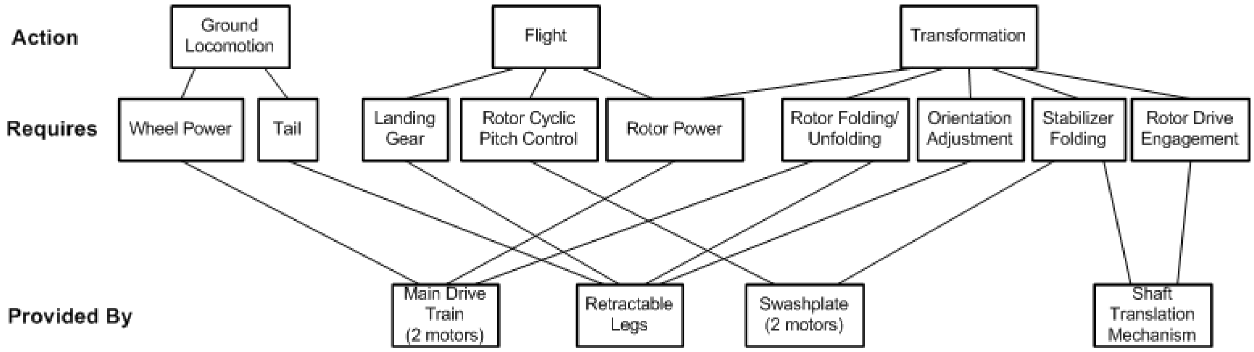

Fig. 7. A diagram illustrating the roles of each mechanism in the function of the robot

the new design, whereas the original design was capable of scaling up to 15 mm with a running start.

IV. CONCLUSIONS

This paper has presented several improvements to the design of a hybrid-locomotion robot. In addition, an initial set of design principles for such robots was presented. Ultimately, the design serves as a starting point for the development of more robust and capable robots utilizing wheels and rotary-wing flight. There is room for improvement, particularly with regard to the ground mode, but the results to date are encouraging, showing that the concept has utility.

V. FUTURE WORK

Work has begun on a new robot, which will have a completely new mechanical design. The primary goals of the new design will be to improve the ground-mode capabilities to allow the robot to drive over rougher terrain, improve the transformation mechanisms to make them more robust and error-tolerant, and ruggedize the robot to give it more utility in real-world scenarios.

VI. ACKNOWLEDGMENTS

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