Design Principles for Miniature Rotary-Wing Hybrid-Locomotion Robots

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

ALEX KOSSETT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

NIKOS PAPANIKOLOPOULOS AND WILLIAM DURFEE

May 2013

ABSTRACT

Hybrid-locomotion robots that utilize wheeled ground locomotion and rotary-wing flight hold great promise for increasing the mobility of miniature robots. Such robots improve upon ground-only robots in that a flight mode is available for use when otherwise impassable terrain or obstacles are encountered.

This thesis presents designs for such robots and formulates principles for the design of similar robots. The design discussed herein is based on a two-wheeled ground robot. The robot tips itself on-end, allowing rotors to unfold from along the length of the robot's body. While the design principles were developed as a result of work on this robot, they are nevertheless applicable to other hybrid-locomotion robots utilizing a rotary-wing flight mode, regardless of the form they take.

A predecessor utilized twin coaxial rotors, while the novel V2 design presented here is equipped with one main rotor and a tail rotor. Both designs use a set of arms, hinged near one side of the robot, to push on the ground, creating a moment about one of the wheels and lifting the other off the ground, ultimately positioning the robot's long axis vertically. Mechanisms for engaging drivetrains, folding/unfolding rotors, and unfolding a tail with a tail rotor (in the V2 design only), complete the transformation; the orientation-adjusting arms then serve as landing gear for the flight mode.

Performance of the novel design improves upon the predecessor, but still leaves much to be desired. With a top speed of 0.3 m/s on flat terrain, a climbing capability of 19mm, and a lifetime of up to 2.5 hours on the ground, terrestrial performance is satisfactory. The flight mode has not been successfully demonstrated, but related testing shows that battery life in flight would be less than 5 minutes.

Such performance metrics lead to the primary design principle: hybrid-locomotion robots with rotary-wing flight modes should have ground-focused designs to enable the terrestrial navigation of all expected environments. Such designs will reserve the flight mode for only unexpected obstacles or terrain, while spending the majority of their time in the much more energy-efficient ground mode.

Four other principles have been formulated:

- Parts should perform as many functions as possible to minimize the quantity and weight of components.

- Drive systems for the two locomotion modes should be separate due to widely disparate requirements.

- The robot's flight hardware will always be much larger than is practical in the ground mode in environments of reasonable complexity, and thus the robot should collapse to a smaller size in the ground mode.
- The robot's flight mode components must be protected from the environment while in the ground mode.

With design principles formulated, design changes can be explored. Impact tolerance of any meaningful amount proves to be infeasible due to the structural requirements of impact-tolerant components. Scaling the designs up is feasible, but significantly reduces the utility of the robot in cluttered and indoor environments. Scaling the designs down is largely impractical due to lack of actuator availability and the complexity of the design. Also, it would render the robot largely useless in outdoor environments, as terrain would be difficult in the ground mode, and wind makes flight at such scales infeasible. Alternate rotor configurations are possible, and a quad-rotor system may be superior to the designs discussed herein.

The work in this thesis represents a first step - a proof of concept. Useful robots will require significantly more mechanical work. In addition, development would be required in both electronics and controls, and the robots could benefit greatly from the development of autonomous behaviors. The results to date have certainly been promising and merit further work.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Miniaturization is a trend in many aspects of engineering, and robotics is no exception. For applications in military, law enforcement, or emergency operations, small robots can be of incredible utility due to their ease of transport and ability to maneuver in small spaces. One of the foremost concerns for such robots is that of mobility; as robots get smaller, terrain gets more challenging. Bumps become hills, smooth terrain becomes progressively rougher, and small steps become impassable barriers. For a given operating environment, this can place a lower limit on the size of a useful ground robot.

As an example, consider a scenario for which the Scout robot [1] was intended: investigating the interior of a building. The Scout robot (and, more specifically, the COTSM Scout robot) has only two 3-inch wheels and weighs about one pound. This small size restricts the robot's options if it encounters stairs: it can go down, but not up. The COTSM Scout is throwable, so it could potentially be deployed to the top level of a building with the expectation that it descend to explore the remaining floors. But this only works if the building is short enough to be able to throw the robot to the top level and has a window to throw into (that may be open or broken), and if the user can throw accurately enough to get it into that window.

Larger robots, on the other hand, don't have such a restriction. Take the Pointman robot [2], for example, which weighs 15 lbs, with dimensions of 6 inches tall, 20 inches wide, and 24 inches long. Even at that size, clever mechanisms must be employed to allow the robot to scale stairs - it pitches its body repeatedly through 360 degrees, climbing a stair with each half turn as its wheel comes around to "step" onto the next stair. Robots must be even larger to be able to climb stairs in a straightforward manner, like the 40-pound Loper [3].

This thesis explores a new form of robot that can work around such issues, enabling smaller robots to work in more challenging environments. To achieve this, a robot is equipped with two modes of locomotion: a rotary-wing flight mode and a wheel-driven ground mode. It offers a unique combination of features: very small size and low weight (one pound, roughly 3.5 x 10 x 8 inches), with the capability to switch to the flight mode at will. In principle, this allows it to traverse difficult terrain and eliminate the special deployment requirements and *a priori* knowledge required to successfully deploy small robots (that is, one must know where to deploy the robot appropriately to avoid obstacles - the new concept may simply fly over them when encountered). Small size and low weight are critical for easy transportation and deployment, while the new capabilities can expand mission profiles.

To summarize, the objective of this design is to greatly broaden the accessible areas of an operating environment without increasing size or weight significantly compared to robots with similar ground locomotion capabilities.

The thesis will address this design concept by showing the feasibility of its mechanical design. Based on the development and analysis of two designs, a set of design principles for such robots is then presented.

This thesis focuses primarily on the mechanical aspects of a proof-of-concept design called Hybrid V2. It does not address detailed aerodynamic considerations or motion control, and addresses electronics only briefly.

The thesis is organized as follows:

- The remainder of Chapter 1 covers related work, provides motivation for the topic, and gives a short overview of helicopter operation.
- Chapter 2 describes the design of Hybrid V2.
- In Chapter 3, design principles for miniature hybrid-locomotion robots are presented.
- In Chapter 4, the effects of several possible design changes are investigated.
- Chapter 5 offers a final discussion of the design and analyses presented in the thesis.
- For reference, Appendix B briefly describes a preliminary design, called Hybrid V1, that was covered extensively by previous publications [4, 5, 6].

1.1 Related Work

The subject of this thesis does not fit neatly into any well-established categories, so in determining what is relevant related work, it is instructive to consider the purpose of the design. The intent of including the flight mode is to allow a robot *primarily intended for the ground* to circumvent otherwise impassable obstacles by flying around them (the reasons for treating the robot primarily as a ground robot are described in detail in Section 3.1). With regard to this function, there are three major categories of related work: ground mode enhancements, jumping robots, and climbing robots.

Other related work pertains to the combination of multiple locomotion modes, even if they are used for other reasons. Such hybrid-locomotion robots form another category, covered below.

The related work presented here is not intended as a comprehensive overview, but more as a summary of the types of solutions currently available and used in robotics for mobility enhancement.

1.1.1 Ground Mode Enhancement

Robots in this category use wheels other than the standard round shape. While such wheels are often promoted as offering improvements to mobility over rough terrain, they offer obstacle scaling benefits as well.

Whegs [7] and DAGSI Whegs [8] are two robots that use a “wheel-leg” type wheel. In essence, they use several specially-shaped spokes that protrude radially from the hub. As the name implies, this offers the simple operation of wheels with much of the benefits of legged motion, allowing the robot to “step” onto objects that would be too high for a round wheel to climb. Many variations on the whegs concept exist. DAGSI Whegs uses whegs as well, but it has a two-part articulated body. This allows it to climb an object by “riding” up the side of it with the front two whegs while the other four whegs remain on the ground to push. When the front two whegs reach the top of the object, they begin to pull the rest of the robot up.

RHex [9] uses a concept similar to the Wheg. However, instead of three spokes, it uses only one spoke per axle, in an attempt to mimic a cockroach’s locomotion.

The Loper [3] is a robot designed to climb stairs, and it does so very effectively. It uses a “tri-lobe” type wheel that essentially walks up one step per $^1/_3$ revolution of the wheel.

With wheeled robots (even those with specially-shaped wheels), the disadvantage for obstacle scaling is that the sizes of the obstacles it can climb are directly proportional to the size of the robot. The upper limit on a wheeled robot’s climbing capability is at most the length of the robot, and in most designs much lower. What novel wheel designs typically do best is allow better mobility over difficult terrain with relatively small local changes in height. Of course, for a 3-inch-tall robot facing stairs, novel wheel designs are not helpful unless the robot is very long, in which case it can ”climb” up the front of the step with its front wheels; such a body shape is contrary to the goal of keeping the robot small.

Perhaps the most common type of robot available commercially in military, explosive ordnance disposal, and search and rescue, is the tracked robot. While tracked robots can typically achieve good mobility on most terrain, they still suffer from the same scale-dependence as wheeled robots and can be difficult to control on stairs [10].

1.1.2 Jumping Robots

One important distinction between jumping and flying robots is that, while both spend time in the air, flying robots are capable of maintaining an altitude and controlling their motion in the air, whereas jumping robots are in a state of free fall as soon as they leave the ground. Thus, the height of the obstacles jumping robots can scale is limited by the amount of energy delivered by the jumping mechanism at take-off. With flight, a robot is not restricted by initial energy storage in a mechanism, but instead by the total energy stored in its power source. This would, potentially, allow for much taller obstacles to be scaled.

Various jumping robots have been developed, and the goal of each is typically to increase the jump height/robot height ratio, or the jump height/robot weight ratio. However, the greatest shortfall of most of these robots is that the act of jumping is relatively uncontrolled; an initial direction may be set, but the robot may, for example, end up landing in a problematic orientation, which ultimately will cause it to roll off its target landing location or render it immobile. Some jumping robots have been equipped with gliding mechanisms [11], and while this can potentially alleviate issues related to the randomness of jumping, the height is still limited by the jumping mechanism.

The smallest jumping robot is likely a grasshopper-inspired robot that can jump up to 27 times its height vertically [12]. It uses a spring-loaded four-bar linkage as a jumping mechanism, which can be manually adjusted for jumping force, take-off angle, and force profile during jumping. Adding a righting mechanism to the robot in the form of a spherical shell increases the mass by 40% and reduces its jump height/size ratio to 6.3 [13].

The Scout [14] is, in a way, a predecessor to the robots described in this thesis. It uses a two-wheel drive system for ground locomotion. Because it is self-righting, it is capable of multiple jumps. It uses a winch to retract a spring-steel tail, then orients itself for the correct trajectory using a gyroscope and its wheel motors. This robot is capable of jumping vertically approximately 3.5 times its height.

Similarly, the Jumping Mini-Whegs robot [15] uses a spring-loaded mechanism and is capable of jumps up to 2.2 times its height. This robot also uses whegs, as described above.

Leg-in-Rotor [16] is a robot that uses a pneumatic cylinder to jump. This gives it more flexibility in terms of the jump profile it can perform, as it can jump while rolling, which gives it an established horizontal velocity as it leaves the ground. However, at 1700 grams, it is relatively large.

Similarly, the Precision Urban Hopper [17] can jump while driving to achieve an adjustable jump angle. It utilizes a combustion process to provide the jumping energy, allowing it to jump up to 25 feet.

1.1.3 Climbing Robots

Climbing could achieve obstacle-scaling in a more energy-efficient manner than rotary-wing flight. Currently, however, climbing robots typically work only on regular or at least well-known surfaces, such as interior walls or a tree trunk, and they move slowly. RiSE [18] is a hexapedal robot that uses a compliant, spined foot design to grip walls. Stickybot [19] is a derivative of the RiSE platform and utilizes adhesion to stick to surfaces. Climbing Mini-Whegs [20] is based on the Whegs platform and uses adhesive pads.

Climbing robots, however, can still face similar issues to ground robots. Though they can climb vertically, their performance is highly dependent on the surface being climbed. A flying vehicle has little concern for the terrain it is flying over. In terms of obstacle scaling, this is the prime advantage that hybrid designs have over climbing.

1.1.4 Other Approaches

Snake robots, such as the active cord mechanism [21], maneuver their bodies like snakes to reach higher places. This can be helpful in some situations, but with the length of the robot at least as long as the obstacle is tall, it is not a weight- or size-efficient way to climb.

Tumbling robots, such as the Adelopod [22], use their bodies as wheels, rolling them along by pushing the ground with arms that trail behind them. By using their bodies as wheels, they achieve the same theoretical limitation as wheeled robots (that the scalable obstacle height is limited by body length), but practically are much more capable over difficult terrain. However, they are inefficient over long distances and difficult to control.

Reconfigurable robots, such as the ckBot [23], have the potential to be adept at scaling obstacles. However, at this point in time their development is just beginning. Essentially, small modules could work together to scale an obstacle, possibly stacking themselves to reach the top. Once the top is reached, one of the modules could anchor itself and pull the others up. This is interesting, because it uses several smaller modules together, but relatively inefficient, because the primary means of motion is through reconfiguring the modules into different shapes.

1.1.5 Hybrid-Locomotion Robots

One relatively unexplored solution, and the subject of this thesis, 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 size of its body or 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. Most small robots store enough energy onboard to lift themselves onto the roof of a one-story building. They lack the capability, however, to expend enough of it at once to scale a building.

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 [24], combines fixed-wing flight with the use of wheel-legs for the ground. However, because the MMALV is not capable of unassisted take-off (it must be thrown or driven off a building to start flying), the flight mode cannot be used to navigate over rough terrain and obstacles at will.

A cousin of the grasshopper-inspired jumping robot discussed above has been developed that serves as a microglider after a jump [11]. Essentially, it is a glider with a jumping mechanism on its underside. The jumping platform throws the glider into the air, where it can perform directed gliding to move toward an objective. Since it jumps, this system is still limited by the energy stored in a mechanism. However, it is capable of directed motion in the air.

Two similar robots, the BOLT [25] and its predecessor DASH+Wings [26], incorporate very simple legged motion with flapping-wing flight. An interesting benefit is available with these robots: the flight mode can assist the ground mode on the ground, greatly increasing the top speed. While they can achieve very impressive speeds on flat terrain (approximately a meter per second from 20cm robots), they lack locomotion capability on rougher terrains and lack significant capacity for payloads of interest. Also, to date, the experimental platforms lack the locomotive capability to do more than drive the robots forward (e.g. they cannot turn or control motion in the air).

The Entomopter [27] is a hybrid-locomotion robot using flapping-wing flight and articulated leg locomotion modes. Work to date has focused on the propulsion system for the robot and no known results of an integrated hybrid robot have been published.

Finally, the HyTAQ robot [28] employs the same two modes that are the focus of this thesis - wheeled ground locomotion and rotary-wing flight. This design has a rotating cage that doubles both as a wheel and a protective covering. As will be further explained in Chapter 3, this design helps reinforce several of the design principles presented herein. While it excels at remaining lightweight and can make synergistic use of its two locomotion modes, its ground mode is quite limited.

1.2 The Need for Hybrid-Locomotion Robots

Of the environments that are of interest to humans, most contain objects on a human-sized scale. Stairs are made for humans to climb, doors for humans to open, and tables for humans to sit at. Man-made environments, for the most part, are created specifically to be accessible to humans. On the other hand, for ground robots, there is always a limit to the scalable step height (the maximum height of an obstacle that it can climb over[1]), and as the robots are miniaturized the step height scales proportionally. Essentially, small ground robots operating in human environments are limited due to a mismatch in scale between the robot and the environment.

The benefits of giving a robot two modes of locomotion are derived from the capability of one to make up for drawbacks of the other, or from a certain mission profile requiring two or more distinct actions not attainable by a single mode. For example, a robot may utilize a balloon for extended observation of an area, identify an object of interest, deflate its balloon, and then crawl to its target for a closer view.

There are numerous combinations of locomotion modes that could be used, and the utility of each will depend on the type of mission the robot is to perform. Flight modes include the following:

- Buoyant flight (utilized by balloons and blimps),
- Fixed-wing flight (airplanes),
- Rotary-wing flight (helicopters, autogyros),
- Flapping-wing flight (ornithopters), and
- Gliding.

Ground modes are numerous but can largely be distilled into the following categories or hybrids thereof (examples of each were described in Section 1.1):

- Wheeled,
- Tracked,
- Legged (either crawling or walking),
- Snake-like (many forms of snake locomotion exist), and
- Tumbling (powered by rotating arms or internal weight-shifting).

Clearly, an enormous array of locomotion combinations could be created for various specific purposes. For this thesis, however, the focus is on improving the mobility of a ground robot. Namely, a robot with rotary-wing flight and wheeled ground travel potentially offers a combination of benefits, ideal for urban environments, not available with any other combination of modes:

[1] While obstacles can vary in shape and thus no single value can describe the locomotive capability of a ground robot, this scalable step height is used as a simple metric to aid discussion. It is defined as the height of the largest step that a robot can climb.

- 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,
- Relatively high payload capability, and
- A very compact form.

While most of these benefits could be realized with a small helicopter, the fourth item, efficient ground-mode travel, improves upon a helicopter by giving the robot the ability to conserve energy while still moving toward its objective if the terrain allows. Compared to the MMALV, which instead achieves fast, efficient travel in its flight mode, the roles of the two modes are essentially reversed. The Entomopter similarly uses flight as its primary locomotion mode (though its winged flight makes it more agile and less efficient over distance than the MMALV, and its legged ground locomotion would make it relatively slow on the ground). The primary disadvantage of the proposed design is that it is relatively complex mechanically, making it prone to mechanism failures.

1.3 An Overview of Helicopter Operation

To facilitate the discussions of the flight mode in this thesis, this section will explain how radio-controlled helicopters work.

Helicopters operate in a six-degree of freedom space, but, like most other vehicles, are under-actuated (i.e. they cannot directly control motion in all degrees of freedom). The three rotational degrees of freedom are termed pitch (tilting forward/back), roll (tilting left/right), and yaw (turning left/right) (see Figure 1.1).

As drawn in Figure 1.1, lift is shown as equivalent to thrust. While this is usually a close approximation, a distinction is important because the rotor's plane of rotation is seldom purely horizontal. Lift is the portion of the forces acting on the helicopter in the upward direction. The rotor's thrust, however, is directed normal to its plane of rotation[2]. In the rotor systems found on full-size helicopters and advanced RC helicopters, the helicopters are controlled by adjusting this plane of rotation to control the transverse components of this thrust. However, the rotor tilts involved are small enough that the lift is still approximately equal to the thrust force.

[2]The rotor never actually lies in a plane; rather, the blades trace the surface of a cone centered roughly on the shaft and opening upward. The "plane of rotation" is really the plane that best fits the path of the rotor blade tips throughout a revolution. Thrust is very nearly directed perpendicular to this plane.

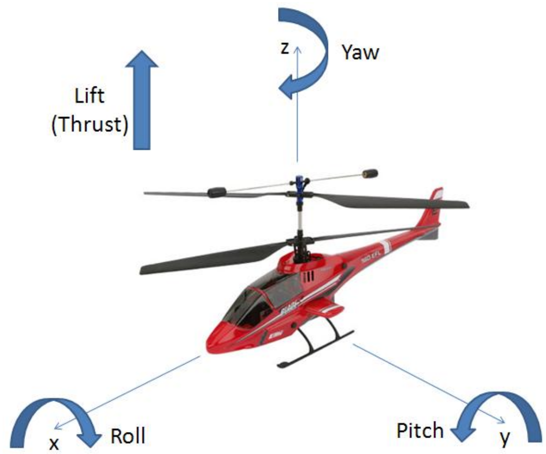


Figure 1.1: The controllable motions on most helicopters.

For simple motion from one point to another, a helicopter must have at least two controllable degrees of freedom: one for lift so that it can control its altitude to take off and land, and one for yaw so that it can turn and direct its motion. In such a case, the helicopter would need to have a tilt built into its rotor to force the helicopter to translate, and it would need to be stable about its pitch and roll axes. Some small toys operate in this manner.

If three degrees of freedom are controllable, they may take the form of "blimp steering," as used on some other toy helicopters. In such a case, yaw and forward translation are controlled by two variable-speed fans placed on the left and right side of the helicopter, while a third actuator controls lift. A second option would be to control pitch, roll, and lift, though this comes at the expense of not being able to control the direction the helicopter faces. Thirdly, lift, yaw, and pitch could be controlled, though to the author's knowledge there is no commercial example of this.

A fourth degree would allow the helicopter to control lift and all three rotational degrees of freedom, which is how most helicopters, either RC or "real," operate.

A number of rotor configurations exist to achieve four actuated degrees of freedom, but most have at least one main rotor with blade pitch controlled via a swashplate, which adjusts the pitch of the rotor blades continuously throughout each revolution. The most common configuration is the "single-rotor" configuration, in which a large main rotor, rotating in a plane above the body of the helicopter, provides lift, and a smaller rotor mounted on a tail provides yaw control and a torque to counter that from the main rotor (some more exotic single-rotor helicopters use ducted fans or aerodynamic effects for the same purpose). Dual-rotor configurations eliminate the tail rotor by using two main rotors spinning in opposite directions; normally there is no net torque on the helicopter body, but to induce a yaw motion the torque to one of the rotors is increased or decreased. Dual rotors can be configured coaxially or with offset (tandem) axes.

Finally, some RC helicopters utilize a quad-rotor configuration, which have no swashplate but control the speeds of four rotors placed in a square shape to control the helicopter's motion through differential lift forces.

For those helicopters with swashplates, either fixed-pitch or collective-pitch rotors can be used. With fixed-pitch rotors, the rotor is essentially a rigid assembly that pivots on a feathering hinge whose axis lies along the length of the rotor. In this way, through the swashplate, the rotor can be tilted up or down throughout a turn of the main shaft to vary the angle of attack as a function of the angle of the rotor shaft. This, in turn, changes the direction of the thrust applied by the rotor by shifting its effective plane of rotation. With fixed-pitch rotors, the rotor head speed must be changed to control the lift.

Collective-pitch rotors systems alter the angle of attack of each rotor blade separately. This enables a constant (with respect to shaft angle) increase or decrease in the angle of attack throughout the rotation of the rotor, which is used to control thrust. Throttle typically is increased with the angle of attack to keep the rotor speed as constant as possible. A collective pitch system is advantageous because rotor pitch can be changed much more quickly than rotor head speed, making it much more responsive. However, it does require one additional actuator. Collective pitch rotors are the standard for full-sized helicopters and for RC helicopters with rotors of about 400 mm diameter or greater.

And excellent reference for further detail on swashplate operation is J. Seddon's *Basic Helicopter Aerodynamics* [29].

Chapter 2

The Hybrid V2 Design

Following the limited success of Hybrid V1, and with the lessons learned from its development, a second design was created - Hybrid V2. This chapter will describe this design in detail. The objectives of the design are first described, followed by a comparison with Hybrid V1 and a thorough description of Hybrid V2's design and operation. Finally, the design and a prototype of the robot are evaluated.

Through the prototyping process, significant challenges were encountered and a number of changes were tested in an attempt to get the prototype operating as desired. These changes, and their motivation, are discussed in the Design Evaluation section at the end of this chapter. The design described below, however, is as the robot was originally designed. It is presented in this manner to allow for a centralized evaluation of the design.

2.1 Objectives

For Hybrid V2, the objective was to create a robot with a similar form factor, but that better reflects its operational role - the robot is best suited for use as a ground vehicle, using the flight mode only when the ground mode fails, rather than a helicopter (see Section 3.1 for further discussion on this topic). This meant that it should be much more ground-focused, with capabilities similar to other ground robots on the same scale.

The robot also needed to be less fragile both structurally and operationally. Hybrid V1 was largely open to the environment, and in the ground mode the long shaft that drove the right wheel was susceptible to bending. It also relied on a fragile sequence of operations to transform, particularly in the air-to-ground direction.

2.2 Design

Following is a list of the major differences between the V1 and V2 designs.

- Single-rotor design - Using a single rotor allows the top wheel (the wheel near the rotors) to be much closer to the body of the robot, improving structural integrity in the ground mode. This is because, unlike coaxial designs where a rotor shaft must span the distance between the two rotors unsupported, bearings can be placed immediately below the rotor. This is further improved by the fact that the rotor head (which contains the top wheel) locks onto the robot's chassis in the ground mode, providing better support for the wheel.
- No flybar (a device linked to the rotor that aids stability due to a gyroscopic effect) - Using a flybarless design eliminates one component that needed to be folded down in V1.
- Larger rotor - The use of a single rotor allows a larger rotor diameter to be used in the robot for the same ground-mode size. This is a consequence of using a single-rotor design, and the lack of a flybar further contributes to the ability to use a larger rotor.
- Complete separation of flight and ground drive systems - The ground mode is driven by its own motors, allowing it to be functionally isolated from the flight hardware. This is beneficial because it eliminates transmission concerns and removes drive train components from the body of the robot, freeing up space. It also allows the drive systems for each mode to be optimized independently.
- A much improved wheel design. The wheel's treads were modeled after the COTS-M Scout's wheel treads to ensure comparable terrain performance.
- Tail rotor - Because the robot uses a single-rotor design, a tail rotor is necessary for counter-torque. The tail rotor is mounted on a tail boom that partially folds up and doubles as the ground-mode tail.
- Collective-pitch rotor control - In principle, this allows the robot to be much more responsive in the flight mode, improving controllability and potentially reducing the time required for aerial maneuvers. In practice, this improvement was never demonstrated (as will be discussed in Secion 2.3).
- Completely redesigned chassis - The chassis consists of six hexagonally-patterned rods and two end blocks, enabling the entire interior space to be utilized for functional components. The rods double as rails for the linear motion necessary for transformation. The chassis design is much more rigid in bending than the previous design's.
- Single transformation actuator - Using only a single actuator eliminates the coordination that was necessary between the transformation actuators in V1.

- Better mass distribution - The mass in the V1 design was centered near the lower end of the robot, causing one side to get better traction in the ground mode.

- Active rotor folding - Active rotor folding ensures that the rotors go where they should be in the ground mode.

2.2.1 Locomotion Configuration

Since one of the biggest structural issues with V1 was the long unsupported rotor shafts, a new rotor configuration was necessary for V2.

A variety of rotor configurations exist, but only two were found to be feasible: quad-rotors and single-rotor with a tail rotor. A single-rotor design would use the same basic set of actions as Hybrid V1 to achieve its transformation. A quad-rotor design, however, could fold its rotor supports into the body without a change in orientation, effectively eliminating one of the mechanisms (but requiring multiples of the rotor-retraction mechanism). Both designs could benefit from the lack of a flybar; the quad-rotor design is naturally much more stable, and recent advances in RC helicopter control systems have allowed flybarless designs to work just as well as their flybarred counterparts.

Ultimately the single-rotor design was selected due to its better agility, but a quad-rotor design may be worth further investigation in the future as it likely will prove to be simpler to implement. The V2 design is shown in Figures 2.1 and 2.2.

2.2.2 Size

Like with V1, a commercial RC helicopter was used as the basis for the flight mode of V2, which allows for some of the flight hardware to be purchased off-the-shelf, speeds up the design process, and allows a representative flight mode to be tested early in the design process.

The Hurricane 200 FES, from Gaui, was selected as the basis of the flight mode because it is the smallest off-the-shelf flybarless helicopter, with a rotor diameter of 430 mm and a nominal mass of 300 g. With the helicopter base design selected, a number of lower bounds on the size can be defined: the rotor blades put a lower limit on the robot's width due to their requirement to fold down (with 200 mm rotor blades, the ground mode could be approximately the same width as V1); the actuator placement requirements would dictate a minimum body diameter (see Figure 2.3); the extended tail length should be equal to that on the Hurricane and thus would dictate the robot's length in either mode (see Section 2.2.5), and the wheel diameter must of course be as large as the body diameter, but was chosen to be 90mm to maintain rough proportionality with the COTSM Scout [1].

A flybarless helicopter with a tail rotor requires five actuators: a main drive motor, three swashplate control servos, and a tail pitch control servo. The most compact way to mount

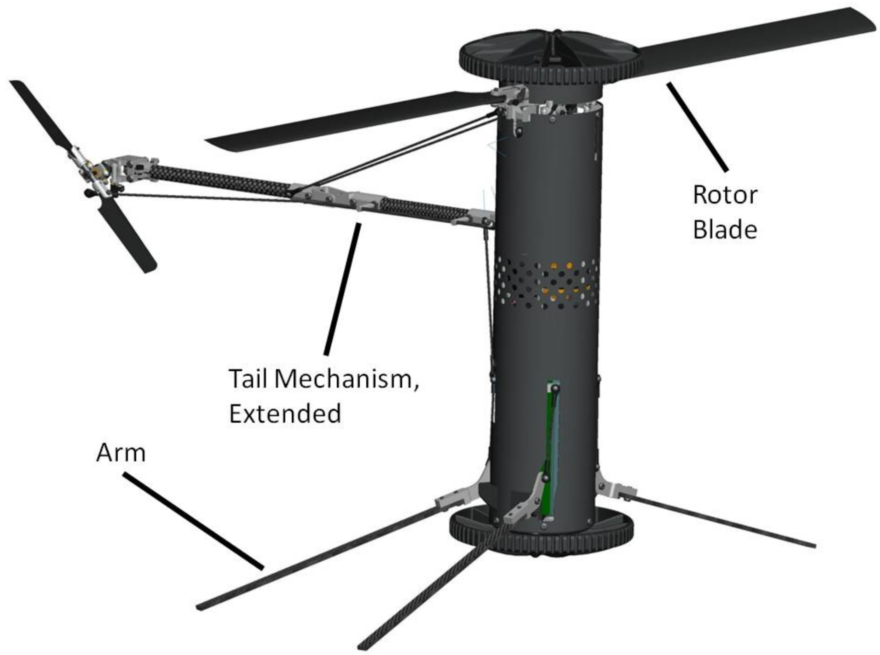


Figure 2.1: Hybrid V2 in flight mode.

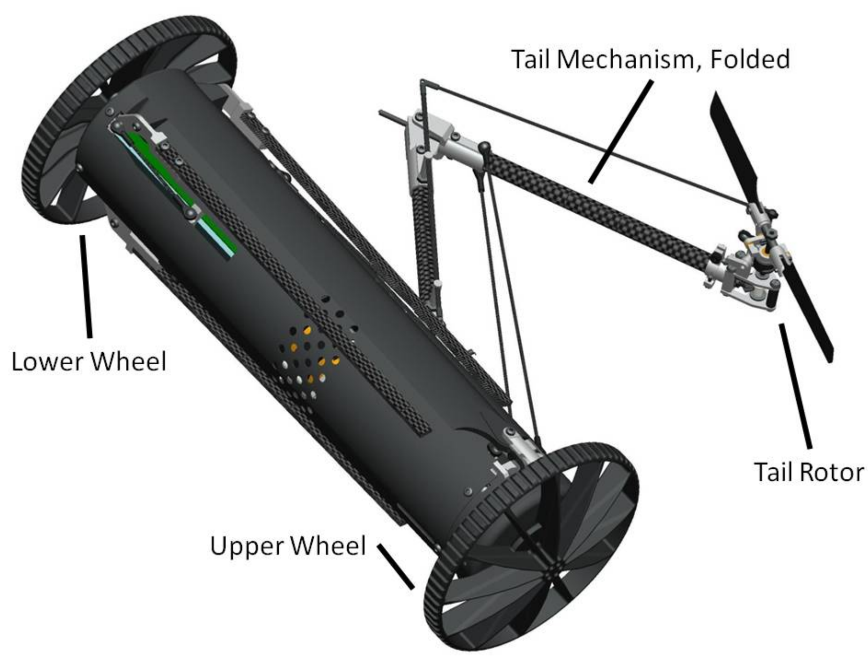


Figure 2.2: Hybrid V2 in ground mode.

the three swashplate servos was to place them in a triangle shape (Fig. 2.3). The smallest commercially-available hobby servo motors with suitable power, torque, and speed are approximately 22x11x20mm, which dictated that the robot have a body diameter of at least 50 mm.

With some extra effort, the design could be scaled up or down. The implications of such changes are discussed in Section 4.2.

2.2.3 The Flight Chassis

One critical aspect of this design is that, in the ground mode, the flight system is protected from the environment and isolated from the robot's structure. This is done by building the flight portion of the robot (Fig. 2.4) on an independent structure that is mobile within the robot, and which locks onto the robot's main chassis only at the output (that is, at the rotor head, which is relatively oversized to contain the upper wheel's geartrain and provides cover for the rotor components). This is an important improvement over V1, in which the outer rotor shaft served as a structural member in the flight mode, and the inner shaft directly coupled to the wheel.

The rotor head is clamped rigidly to the chassis in the ground mode (Figure 2.5). In this way, all drive components, control linkages, and actuators are prevented from contact with the environment. The upper wheel is attached to an axle held within the rotor head, which is driven by a gear pair. A dog clutch couples the pinion's shaft to a motor (mounted on the main chassis) in the ground mode. There are two possible orientations of the rotor head when it is clamped, so the rotor head contains two such pinion, shaft, and dog clutch assemblies.

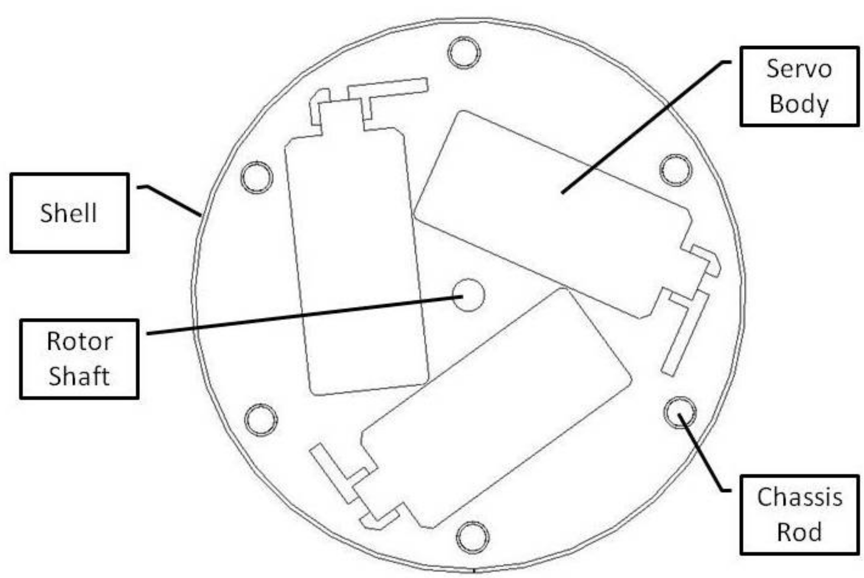


Figure 2.3: Cross-section view of the servo arrangement in the V2 design.

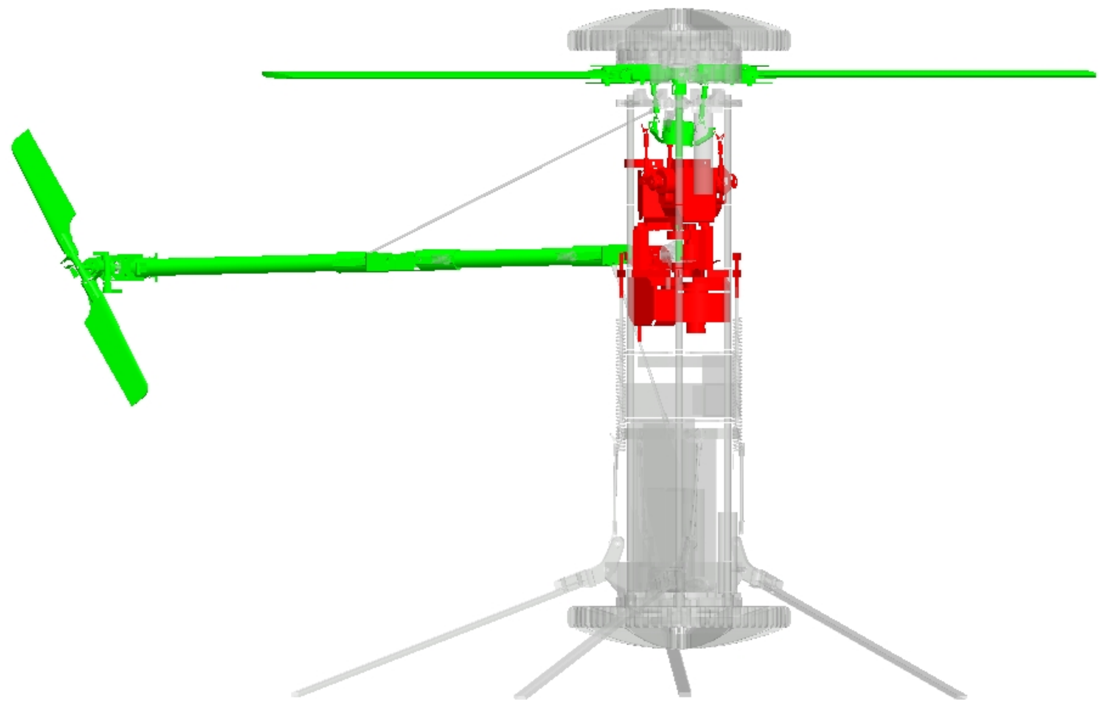


Figure 2.4: The flight chassis (red) and associated systems (rotor system and tail, green). The flight chassis incorporates all actuators necessary to fly the robot, and is mobile on the robot's structural rods.

The rotor head is clamped during the last stage of the flight-to-ground transformation. The force is transmitted by the actuator first through the force amplification springs, then through the shaft pull bar, which pulls on the rotor shaft, which finally pulls on the rotor head (this force path is illustrated in Figure 2.6). The clamping force, then, is equivalent to the force amplification spring's load when the actuator is fully retracted, minus the forces required to hold against the chassis preload springs and the rotor folding springs.

2.2.4 Overview of the Transformation Process

The transformation process involves a number of mechanisms. This section will describe their operation; a description of their design and an analysis of the interactions between the mechanisms is provided in subsequent sections.

The mechanisms involved in transformation are the following:

- An orientation adjustment mechanism, which tips the robot up on its end when transforming into flight mode and tips it back to its horizontal orientation when transforming back. The orientation adjustment mechanism also serves as landing gear (See Fig. 2.1).

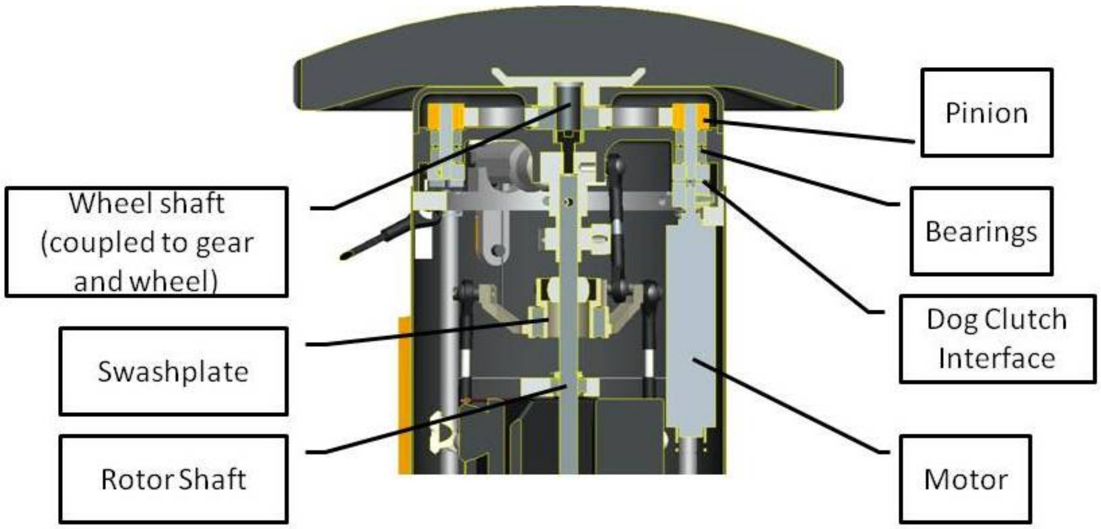


Figure 2.5: A cross-section of the robot's upper portion in the ground mode. Note that a second pinion is included opposite that driven by the motor; this is due to the fact that the rotor head can be oriented into two positions.

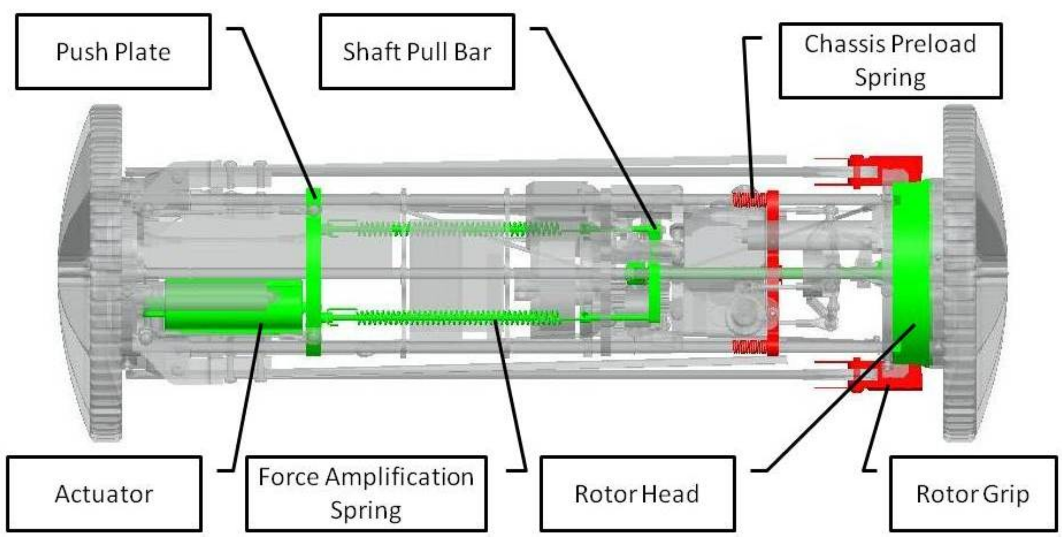


Figure 2.6: An illustration of the force path that transmits clamping force from the actuator (at left) to the rotor head (right). Parts in green pull on the rotor head, while parts in red resist the force and result in reduced clamping force.

- A tail extension/retraction mechanism, which extends the tail boom for flight mode and retracts it for the ground mode to reduce the length of the robot (see Fig. 2.2). Moving the tail rotor further from the robot's body is necessary to reduce the required tail rotor thrust and aerodynamic interactions between the main rotor and tail rotor.

- A rotor head retraction mechanism which, when transforming into ground mode, serves to correctly orient the rotor head and clamp it to the body of the robot to isolate the flight components from the environment (Fig. 2.13).

- A rotor folding mechanism, which folds the rotors against the side of the robot's body (Figure 2.15).

All of the mechanisms are driven by a single linear actuator through a "push plate" that acts as an interface between the single actuator rod and the multiple mechanisms by providing mounting locations for a number of links and rods.

Orientation Adjustment Mechanism Operation

The orientation adjustment mechanism serves the same purpose in V2 as it did in V1: it changes the orientation of the body so that it is vertical, rather than horizontal, and acts as the landing gear for the flight mode. It also operates in a similar manner (with arms that push on the ground; see Figure 2.7), though the mechanism design is significantly different.

There are two key differences between the two versions. First, there are four moving arms, rather than 2 moving and 2 fixed, so that in the ground mode the entire mechanism can be retained within the diameter of the wheels. Second, it uses a four-bar mechanism that is not back-driveable in either direction under the expected loading (that is, the rated back-drive force of the actuator is higher than the load it must sustain), which eliminates the quiescent current draw that was an issue in V1 (the mechanism is shown in Figure 2.8).

Each of the four arms pivots near the lower end of the robot's body. One link connects each arm to the push plate, forming a four-bar slider-crank linkage. Over the full travel of the actuator, the arms start out next to and parallel with the body of the robot when the actuator is fully retracted, to a position displaced approximately 102 degrees when fully extended. As the arms rotate, the two on the underside of the robot contact the ground, forming essentially a tripod support comprising the two arms and the lower wheel. As the arms rotate further, the upper wheel lifts off the ground and the body begins to tip up, until eventually the body is vertical and the other two arms also contact the ground. The arms rotate still further and lift the robot fully off the ground, so that the only contact the robot has with the ground is the ends of the four arms. In this position, the arms serve as the landing gear for the flight mode.

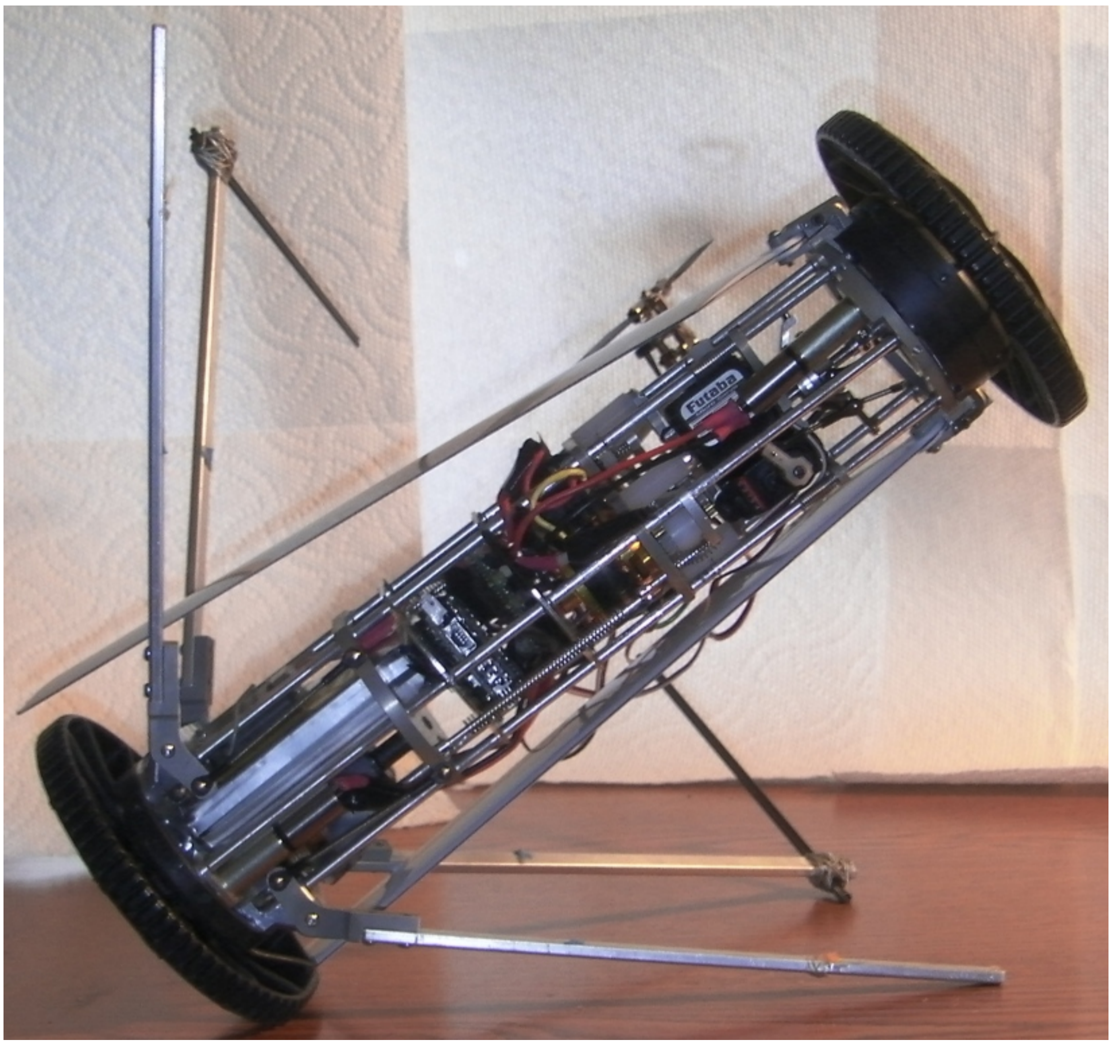


Figure 2.7: A photo of the prototype in the middle of a transformation. Note the four arms, and the two black protrusions from the rear arms that were added to increase the landing gear's stability.

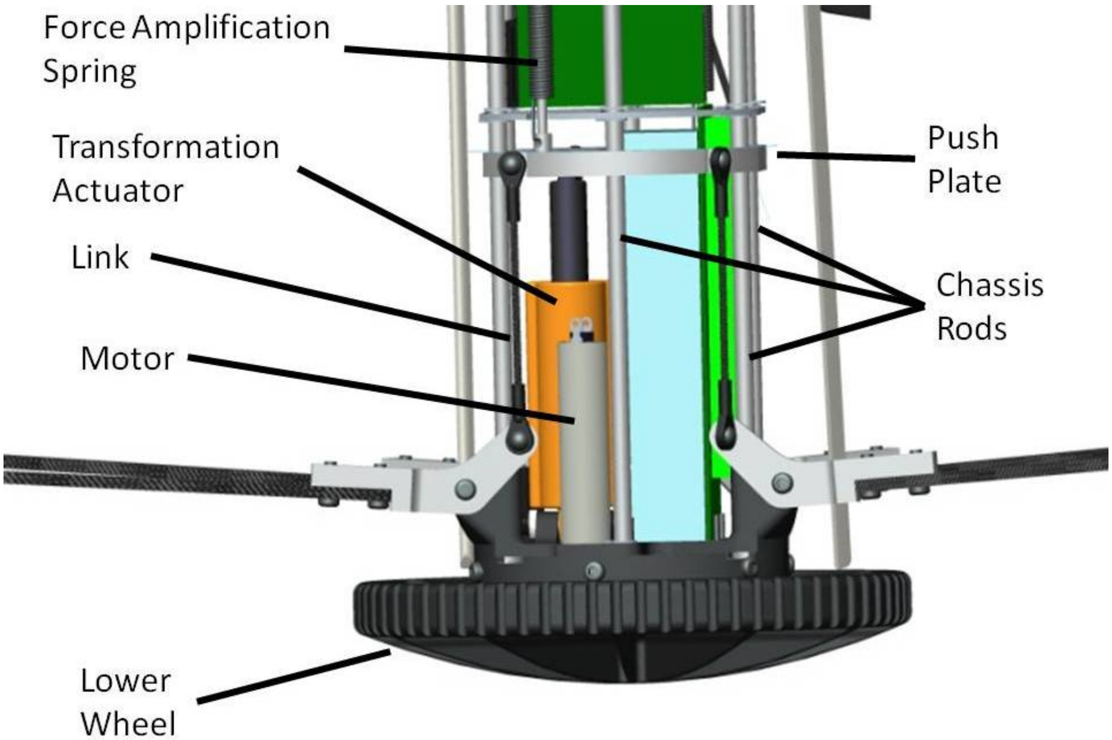


Figure 2.8: The V2 design's orientation adjustment mechanism.

Tail Mechanism Operation

The purpose of the tail mechanism is to reduce the length of the robot in the ground mode while still enabling the tail rotor to be at a reasonable position in the flight mode. In the flight mode, the further the tail rotor is from the main rotor shaft, the lower the thrust it must produce to counter the main rotor torque, and thus the lower power it will consume. However, if the tail were to remain the same length in the ground mode, it would be detrimental to the small size goal of the robot. The tail mechanism retracts the tail approximately 140 mm to a total length of about 200 mm; were the tail left extended, the overall length of the robot in the ground mode would be approximately 345 mm, or roughly 70% longer. The tail operation is illustrated in Figures 2.9, 2.10, 2.11, 2.12.

Like the orientation adjustment mechanism, the tail mechanism operates over the full length of the transformation actuator's travel. It is most simply viewed as a six-bar Watt II linkage driven by a slider, but due to some small movements at what would be the ground pivots, this is not strictly true; more accurately it is a seven-bar, 2-DoF linkage with two slider inputs (this is addressed in more detail in the design section below).

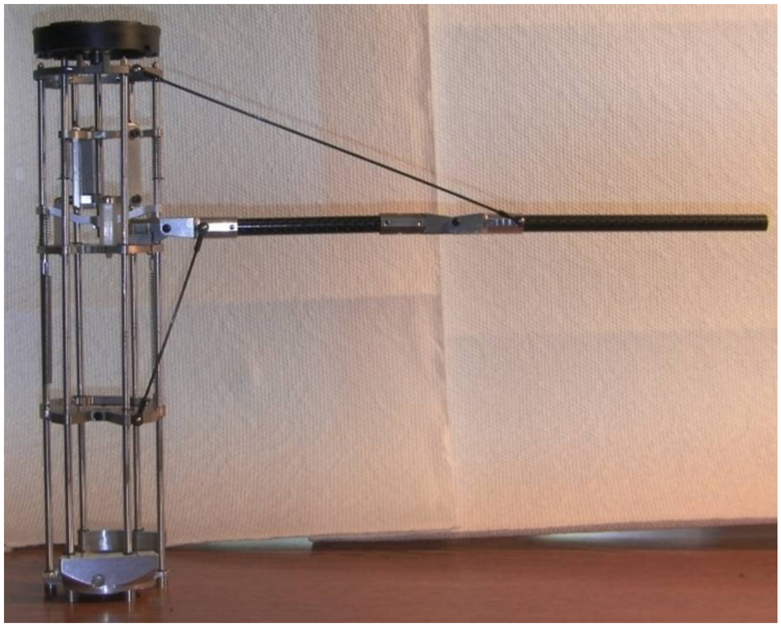


Figure 2.9: A partial prototype fully transformed into flight mode.

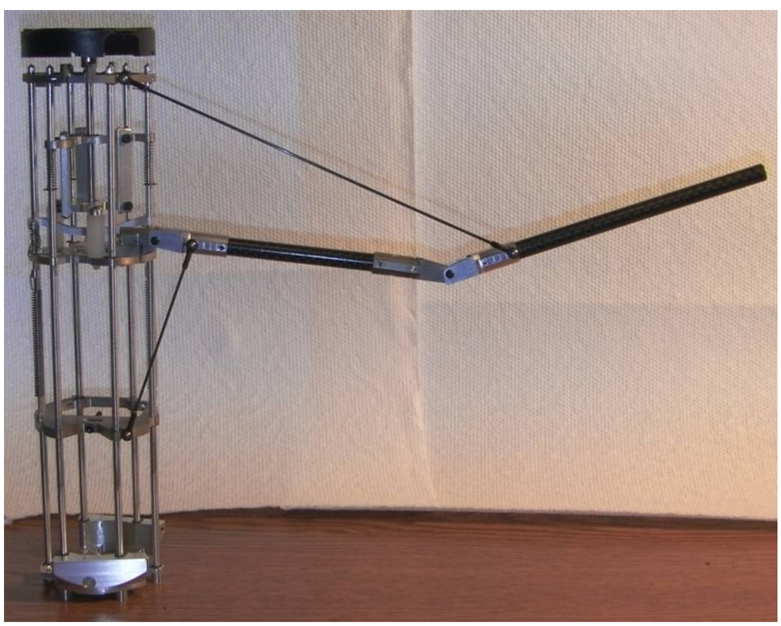


Figure 2.10: A partial prototype with the pull bar starting to contact the rotor shaft cross-pin.

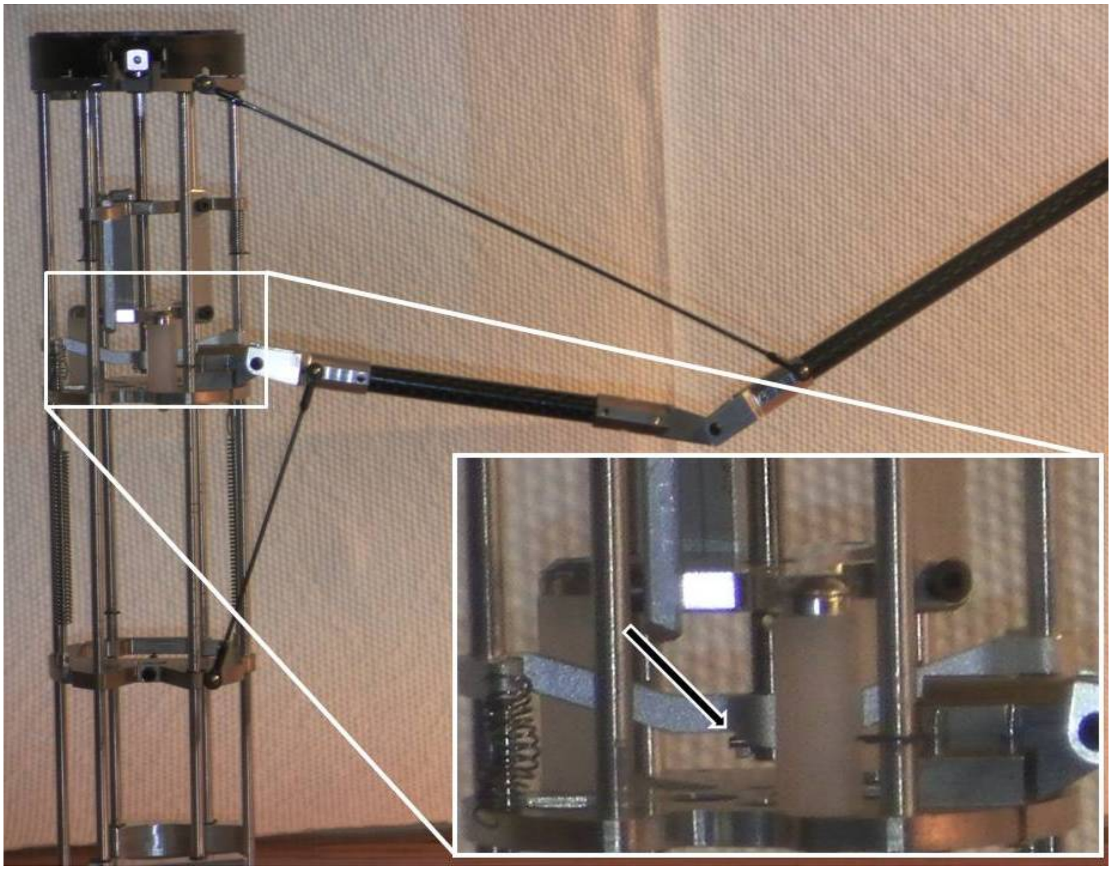


Figure 2.11: A partial prototype with its rotor head clamped to the main chassis. Note that the rotor head has rotated from the previous figure due to the shaft pull bar's cam action. Inset: the rotor shaft cross-pin can be seen fully seated in the helical cam surface, which is further described below.

When extended, two of the links (called the "boom links") serve as the tail boom, while the others serve as supports. The tail rotor is driven by a set of shafts that draw power from the main rotor's drivetrain. To enable the two boom links to pivot relative to each other, each link has its own shaft supported by ball bearings; these shafts are linked to each other with a flexible shaft portion, which is essentially a long torsion spring (a flexible shaft portion also connects the first shaft to a shaft in the body of the robot). When the links fold, the torsion springs buckle.

Similarly, a multi-part control link is used to control the tail rotor swashplate with a servo mounted on the robot's body.

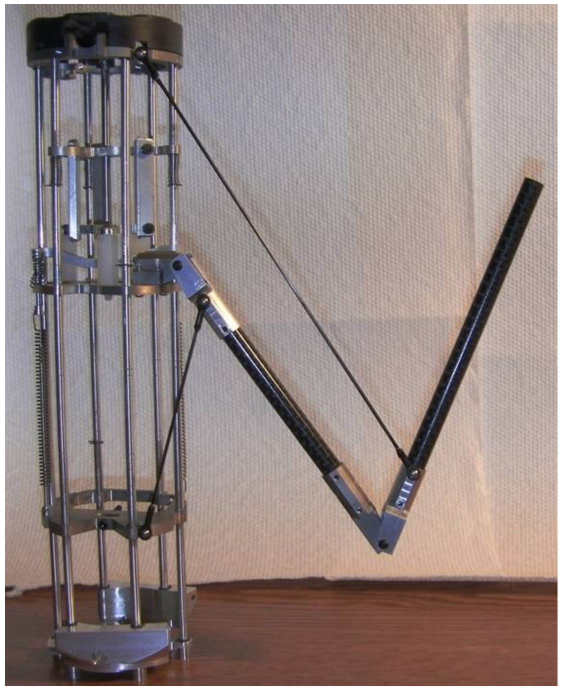


Figure 2.12: A partial prototype in the ground configuration.

Rotor Head Retraction Mechanism Operation

The rotor head retraction mechanism serves two primary purposes, most readily described during a transition from flight mode to ground mode: it lines up the rotor in the z-axis (i.e. around the main rotor axis) and then clamps the rotor head to the body, which essentially isolates the flight system from any direct contact with the environment. For the reverse transformation, the mechanism releases the rotor from the orientation lock, and raises the rotor head sufficiently to clear the robot's body and allow it to spin. The translation of this mechanism also drives the rotor folding mechanism.

Unlike the previous two mechanisms, this one does not have continuous motion of all parts during the transformation. Instead, it goes through several distinct steps, the timing of which is controlled by two sets of springs with prescribed spring rates and preloads, and several mechanical stops.

In the first phase, which occurs during the first 15% of the actuator travel (moving from fully extended to retracted; see Figure 2.10), a cross-bar with a helical surface (Fig. 2.13) in its center is pulled toward the bottom of the robot. This bar, called the shaft pull bar, does not touch the rotor shaft in flight mode, but during this retraction the helical surface contacts a cross-pin in the rotor shaft. A set of preloaded compression springs resist translation, keeping the shaft in place axially while it rotates along the helical groove as the cross-bar is retracted. Once the shaft is rotated to the correct location, the pin bottoms out on the surface and the cross-bar begins pulling directly against the compression springs, ultimately causing translation of the flight chassis.

Once this motion starts, roughly the next 30% of actuator travel pulls the flight chassis into the robot body and clamps the rotor head to the chassis (Figures 2.11 and 2.14). During this phase, the rotor folding mechanism works to fold the rotors against the robot's body (Fig. 2.15), while the dog clutch that drives the output pinion (Fig. 2.16)is simultaneously engaged.

Once the rotor head is clamped to the body, the actuator's only interaction with this mechanism is the extension of a set of springs, called the force amplification springs. Up until this point, these springs were clamping two rods together axially, essentially forming a single pull rod, as the actuation forces up to this point were not sufficient to pull those pieces apart against the force of the springs. The actuator pulls on one side of this assembly, and since the other side is attached to the flight chassis and thus not moving at this point, the springs get extended. The spring set provides the clamping force for the rotor head, and more importantly stores energy to assist the transformation actuator in the reverse (ground-to-air) transformation. This set of springs is covered in more detail in Section 2.2.6.

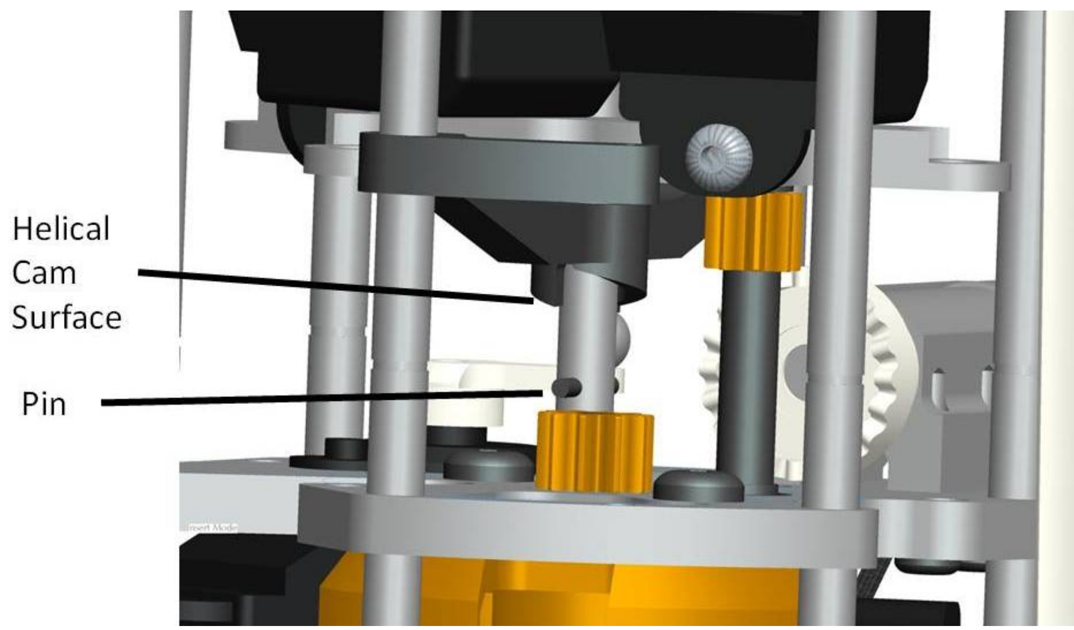


Figure 2.13: The V2 design's shaft pull bar, used for rotor orientation and retraction.

Figure 2.14: The V2 design's rotor head clamped to the robot chassis.

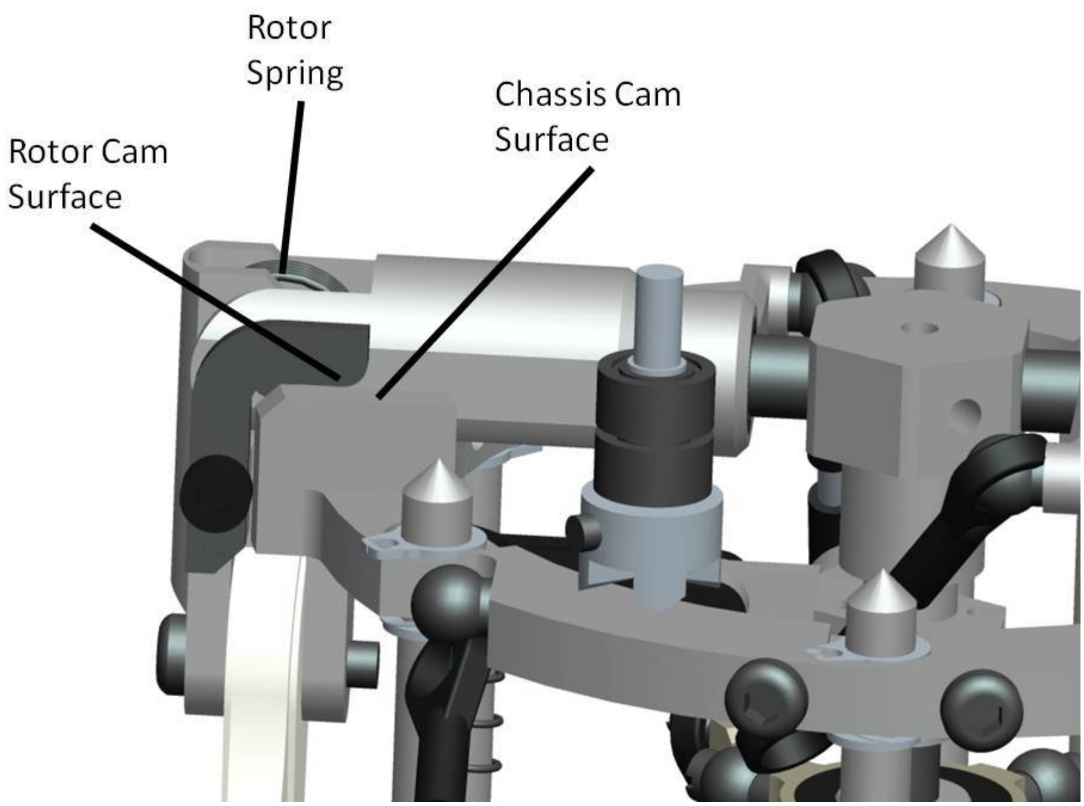


Figure 2.15: The V2 design's rotor folding mechanism.

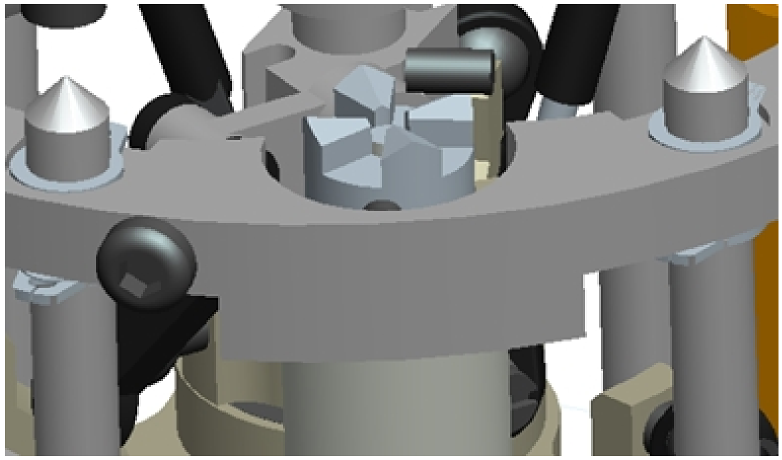


Figure 2.16: The dog clutch.

Rotor Folding Mechanism Operation

In V1, the passive rotor folding scheme ended up allowing the rotors to scrape on the ground and did not reliably allow the rotors to spin up. In addition, the tail on the V2 design would make a passive folding scheme impractical, since, upon takeoff, the rotor would hit the tail before it had a chance to spin up.

Instead, an active rotor folding system is employed. The rotor blades are spring-loaded with torsion springs so that they are normally in their extended position. After the rotors are oriented in the correct position, as the flight system begins to retract into the body of the robot, the rotor position is known. It is then possible to place a cam surface at the top of the body which will mate with a follower attached to the rotor blade grip. Over a total translation of 6 mm, this cam-follower interaction causes the rotor to fold down 90 degrees.

2.2.5 Transformation Mechanism Design

In Section 2.2.4, the transformation process was described. This section will cover in detail the designs of the mechanisms which execute those processes.

Orientation Adjustment Mechanism

The orientation adjustment mechanism consists of the push plate (which drives all transformation mechanisms), four arms attached at pivot points arranged around the circumference of the robot's body near the bottom wheel, and a link for each arm that connects to the push plate. The arms in this design are formed by a base piece and a replaceable, longer end piece. The links are attached with ball-and-socket joints, while the pivot points are formed by brass

Figure 2.17: Photos of the prototype's rotor folding mechanism in the fully extended (left) and fully retracted positions. This prototype is equipped with heavier rotor blades than the mechanism was designed for, so they "droop" somewhat even when fully extended. This aids the function of the folding mechanism by improving its pressure angle at the early stage of operation. Centrifugal force extends the rotors fully when the rotor head is spun up.

bushings.

The arms are arranged in an irregular pattern. Two arms are on the bottom of the robot (in ground mode), while two are on top in a pattern mirroring the bottom two. The arms do not project radially, but rather are angled to favor the robot's somewhat rearward center-of-gravity and to avoid impacting other components as they move (see Figure 2.18). The arms, upon transformation into flight mode, serve as the landing gear.

For purposes of force analysis in the ground-to-air transformation, the orientation adjustment linkages are modeled as a crank-slider mechanism in series with another slider-crank mechanism. The slider in the first mechanism is the arm dragging on the ground, while in the second mechanism it is the push plate (pushed by the transformation actuator). The crank in the second mechanism is the arm itself. In effect, this forms a Watt I mechanism for function generation (the robot's orientation as a function of the actuator displacement). The crank and the robot's body act as the ternary links, while the sliding motion of the arm on the ground, the sliding of the push plate, and the coupling between the push plate and arm form the three binary links (along with the ground, of course).

Because of the angles at which the arms extend from the robot, a simplified model is used to greatly reduce the complexity of the analysis: the mechanism is modeled as a *projection* of the mechanism, with dimensions as they are projected in the folded state (that is, the projected mechanism's dimensions remain the same throughout the motion, despite the fact that in the real mechanism, out-of-plane motions will shorten some of the projected dimensions). The projection plane is the plane of motion in which the orientation adjustment occurs. This is a conservative simplification (i.e. the forces calculated are higher than the actual forces) due to the fact that in the real mechanism the moment arm of the orientation adjustment arms effectively decreases

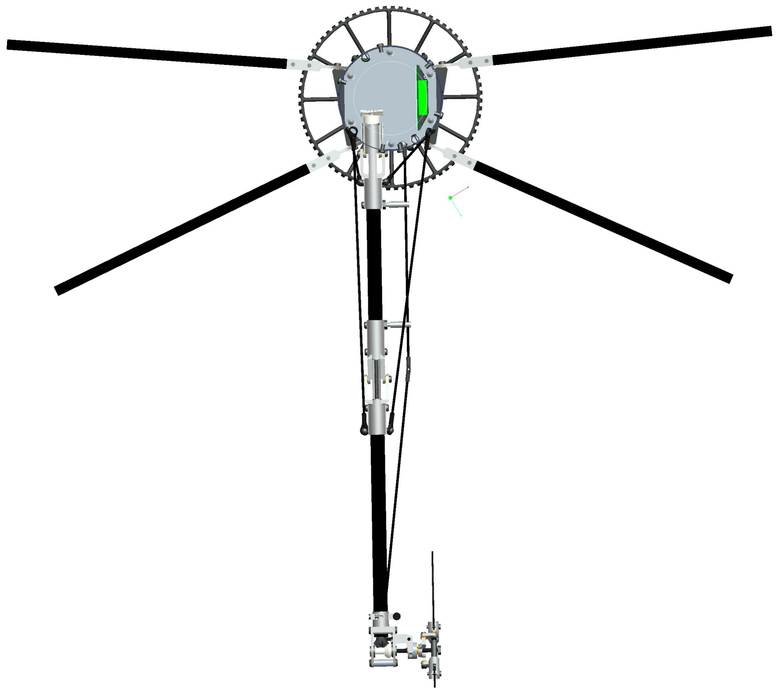


Figure 2.18: A view of the V2 design's transformation arms in flight mode from the top. Some parts are hidden for clarity.

throughout the motion, resulting in a higher mechanical advantage in the *real* mechanism.

These two mechanisms can be analyzed serially, first by determining the crank torque in the first mechanism, then by determining the force required of the slider in the second mechanism to provide that torque. Friction is ignored. The torque requirement in this case reduces to that for the V1 design, covered in [4] (though with appropriate parameters substituted for the new design). Determining the required actuator force is then simply a matter of determining the moment arm for the crank. The results of this analysis can be seen in Section 2.2.6, which covers actuation requirements.

Tail Mechanism

Ideally, the tail boom would fold up completely within the wheel diameter in the ground mode. However, after several attempts at numerical and computer-assisted graphical synthesis, no acceptable mechanism was found. This constraint was consequently loosened to require only that the tail be shorter in the ground mode than in the flight mode, and for the tail to serve as the anti-torque member in the ground mode as well.

The tail mechanism essentially performs a two-precision-position path generation task. The orientation of the output link is important only in the flight mode, though the overall length of the mechanism is desired to be small in the ground mode. Because a suitable driving mechanism (the linear actuator) was already in use for the other transformation tasks, it was used again to drive the tail mechanism.

One interesting aspect of this mechanism is that the tail rotor is driven by the rotor motor, which actually translates along the long axis of the body during the transformation. Thus, the first of the two links containing the drive system must move with the rotor motor. The displacement is approximately 6mm, but it is driven by the 20mm displacement of the transformation actuator.

Graphical synthesis was employed to identify the correct locations for the joints, and the resulting topology is shown in Figure 2.19. To achieve sufficient torque in the flight mode from the tail rotor, the tail boom length was chosen to be the same as that on the Hurricane 200 (the helicopter model on which the flight mode is based). Through trial and error, a two-joint boom was found to have an acceptable compromise between complexity and compactness; the sum of these link lengths was set to match the desired extended boom length.

The push plate start and end positions were constrained by the other mechanisms, but the location of the pivots on the push plate were not. Pivot points on the tail boom sections for the follower and driving links were chosen to lie on the tail boom's axis for simplicity in component geometry. The location of the follower link's ground pivot was free to choose, but localized in a relatively small area due to the motion required. Finally, the "ground" pivot for the first tail boom link (the pivot which actually translates 6 mm) had to be placed in accordance with the gearing and shaft requirements, and thus was fixed.

The graphical synthesis employed Pro/ENGINEER's sketching capability, and the constraints assignable within it. After assigning relevant constraints, the free choices could be "dragged" as necessary to find acceptable solutions. The objective in narrowing down the free choices was to maximize transmission angles while reducing the length of the mechanism in the ground mode.

The worst-case transmission angle in the selected design is 22.5 degrees (between the second tail boom link and its follower), which is not ideal. However, in this case the low transmission angle is acceptable for a number of reasons: the driving dyad at that point in the motion has a high transmission angle (71 degrees), which means that it can compensate for the low angle on the tail boom link; the extension motion is aided by the buckling torsion springs (described below), which assist the motion by adding a torque between the tail boom links; and the link itself is the only load, meaning that while the force transmission is poor at that point, the

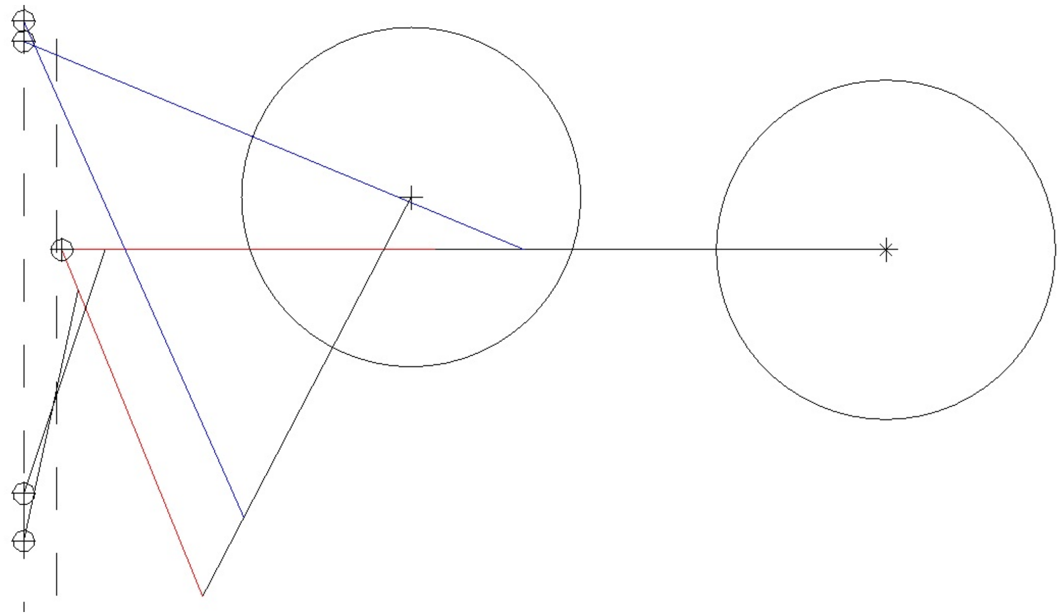


Figure 2.19: Schematic of the V2 design's tail mechanism. The large circles represent the tail rotors in the extended and retracted positions. The small circles near the left indicate the positions of the ground pivot and of the endpoints of the input sliders' motion.

required force is low.

To drive the tail rotor through two joints, flexible shaft members were used (Figures 2.20 and 2.21). Each tail link, and a short segment on the robot's body, contains a shaft constrained by ball bearings. Connecting these shafts are torsion springs, which buckle to allow the tail to fold. The springs were designed with small diameters to reduce the bending stiffness while increasing torsional stiffness. Still, under full load, the two springs may have a displacement of about 250 degrees each. However, with tail rotor speeds up to 15000 rpm, this is relatively insignificant.

At the end of the tail mechanism is a right-angle gearbox which drives the tail rotor directly. The tail rotor has its own small swashplate, controlled by a folding link rod (hinged coaxially with the tail boom sections), which links back to a servomotor on the robot's body. This system uses sliding links to translate linear motion in the flight mode, but the links are connected by pivots to allow them to fold up (this folding joint is visible just behind the flexible shaft segments in Figures 2.20 and 2.21).

Rotor Orienting Mechanism

During the transformation from the flight mode to the ground mode, the rotors fold down and the rotor head is clamped to the robot's body; the rotor head must be oriented in a particular orientation as the first step in the transformation. The rotors must be in such a location that

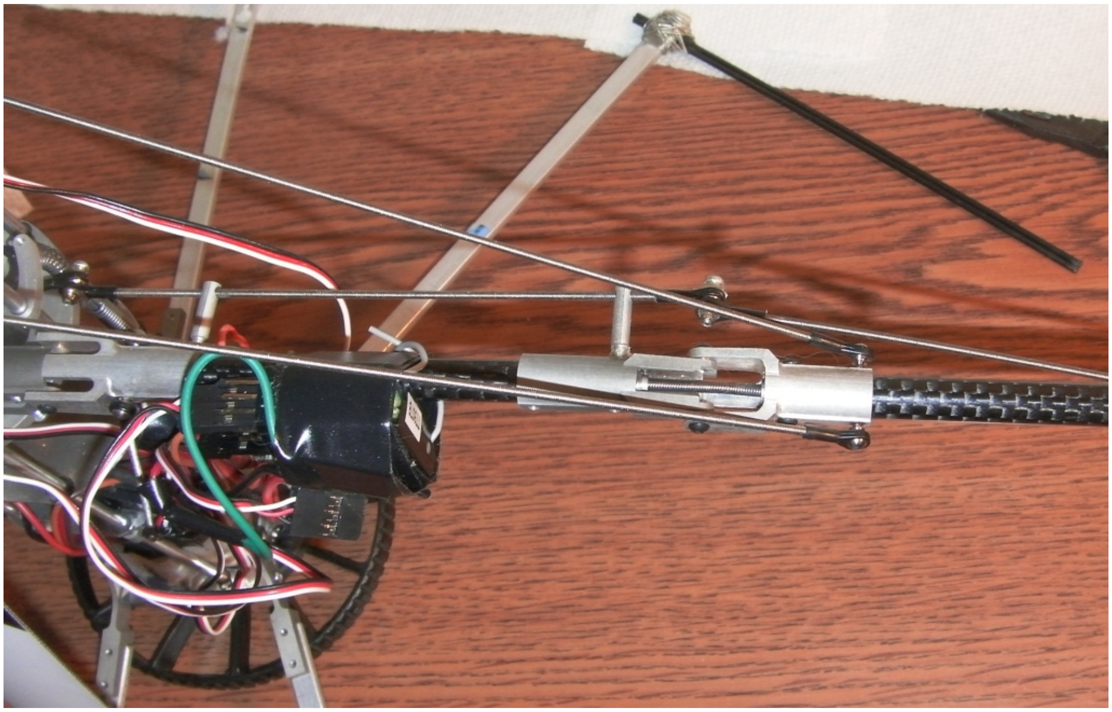


Figure 2.20: The flexible tail drive shaft, housed between the two hinged blocks, in its straight configuration. Adjacent to the hinge blocks are the hinged tail swashplate control links. In the background, the black rod protruding at a right angle from the orientation adjustment arm is an addition to help stability the robot's landing gear.

they do not interfere with the robot's sensing or its other transformation mechanisms, and the rotor head must be oriented correctly to meet with its mating features correctly. It is also essential for operation of the rotor folding mechanism, because features on the robot's body push on the rotors to make them fold, so the rotors must line up with these features.

To achieve this, a helical cam mechanism (Figure 2.13) is employed that disengages while the robot is in flight mode. The cam surface is a helical ramp on the shaft pull bar, and the follower is a cross-pin in the rotor shaft. In flight mode, the shaft pull bar sits high enough that the cam surface is held above and away from the cross pin, enabling the rotor shaft to spin freely.

Prior to the transformation into ground mode, the force amplification springs are fully retracted and the rods to which they attach are in contact, forming a mechanical stop and allowing the shaft pull bar to move in unison with the push plate. The springs remain retracted throughout the rotor orienting process because the rotor orientation force does not exceed their preload.

As the transformation actuator retracts (again, in unison with the shaft pull bar), the helical cam surface eventually contacts the cross pin. The cam action causes the rotor shaft to turn in the "forward" direction, such that the drivetrain freewheels in a one-way bearing, so motor

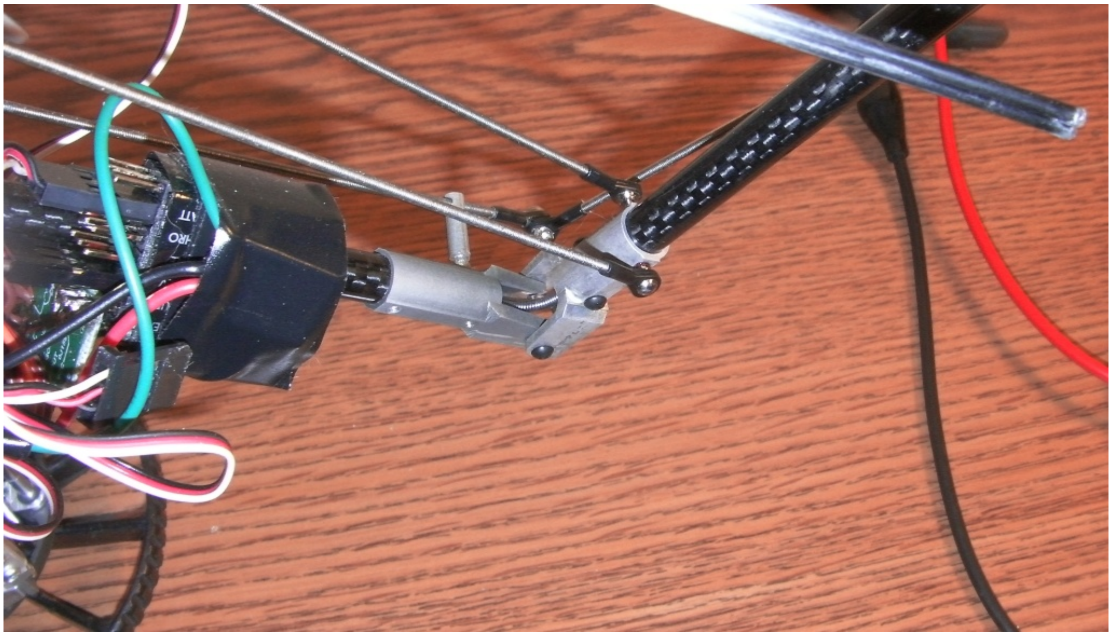


Figure 2.21: The flexible tail drive shaft in its bent configuration. Note that the tail swashplate control links are folded as well.

cogging torque does not need to be overcome, and the tail rotor will not turn. Thus the force required to orient the rotor head is based on the ramp angle of the helix, the friction between the cam and follower surface, and the torque required to rotate the rotor shaft (i.e. to overcome friction in that portion of the drivetrain).

Using the Hurricane 200 helicopter, upon which the drivetrain is based, rotor turning torque in the freewheel direction was measured to be 2.94 mNm. The mean radius of the helical surface is 2.5 mm, which means that a tangential force of 1.2 N is required to rotate the rotor head. The ramp angle is 15° (this was based on the required clearance in the flight mode and the limited travel available), so neglecting friction on the cam surface (assumed to be negligible due to the application of grease), the necessary axial force (applied by the shaft pull bar on the cross pin) to correctly orient the rotor head is $1.2N/\tan 15° = 4.5N$.

This 4.5N requirement, in turn, was used to define the necessary preload in the flight chassis preload springs. Using a safety factor of 2, this was chosen to be 9N (when compressed to the ground state they reach 12N). This ensures that the rotor head is properly oriented before it begins moving, so that once it does translate it will be ensured to clamp properly. There is a balance to maintain between the preload spring and the rotor head clamping force: the preload must be high enough to ensure that this happens, but in the clamped state the spring load must be low enough to allow for sufficient clamping force. This calls for a very low spring rate. Even so, the clamping force is only 14N out of a maximum possible 36N (the peak actuator force), due to the chassis preload spring and the rotor springs.

Rotor Folding Mechanism

A view of the rotor folding mechanism in its folded state is shown in Figure 2.15. The mechanism is actuated as the rotor head is retracted, and thus the force required to fold the rotors is of interest because the transformation actuator will ultimately need to supply it. As the rotor head retracts, the cam arm on the rotor contacts a flat wall on the robot's chassis. The contact point is slightly offset horizontally from the rotor hinge, which allows a couple to form once contact is made. A model of this mechanism is shown in Figure 2.22.

The model is drawn, and will be explained, for the act of folding (rather than unfolding) the rotor, as in this action the actuator must work against the torsion spring built into the hinge, making folding the more demanding action. Note that while it is called the "cam mechanism" due to the way the components interact, it can be reduced to the double-slider mechanism modeled in Figure 2.22; this is due to the constant radius of the follower portion (attached to the rotor grip) and the flat geometry of the surface against which it slides.

As shown in the model, F_y is the vertical force applied to the hinge by the transformation actuator, F_x is the friction force between the rotor's cam arm and the robot's chassis, and T_s is the spring torque. The range of motion is $-18.5° \leq \alpha \leq 71.5°$ (shown at 71.5°). The spring is

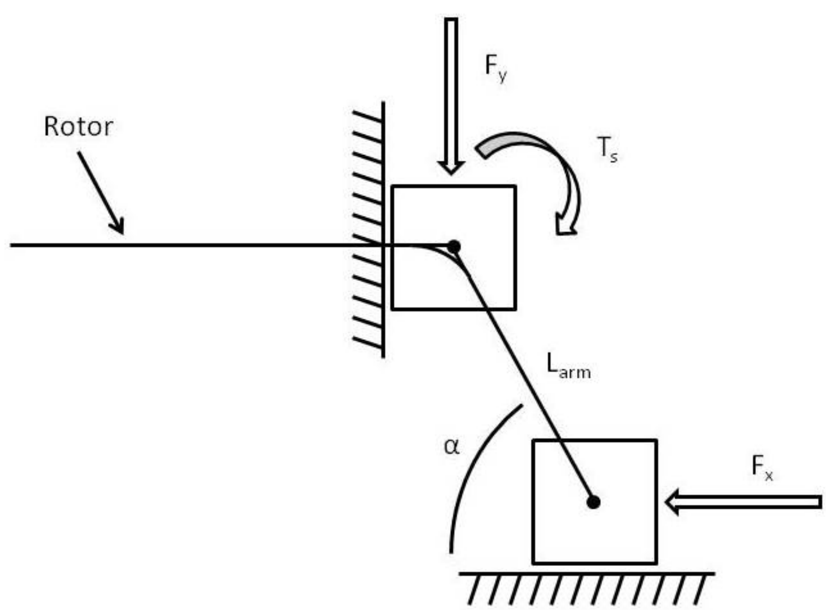


Figure 2.22: A model of the V2 design's rotor fold mechanism

pre-loaded to 180° in the position shown (the free position is reached when $\alpha = 251.5$, though this is outside of the mechanism's range of motion); this pre-load allows the rotors to unfold completely, against the weight of the rotors, purely with the aid of the torsion spring.

Conservatively, the rotor weight is not considered in the mechanism analysis in order to simplify calculations. In reality, rotor weight will assist in the transformation, with its contribution to the force balance changing as the robot's orientation changes (this contribution, as a function of the actuator travel, is exceedingly complex, and so is omitted for simplicity as well as to be conservative). The quasi-static moment balance about the lower "pivot" is thus

$$\begin{aligned}
F_y L_{arm} \cos\alpha &= T_s + F_x L_{arm} \sin|\alpha| && (2.1)\\
&= \kappa(251.5 - \alpha) + F_y \mu L_{arm} \sin|\alpha| && (2.2)\\
F_y L_{arm}(\cos\alpha - \mu \sin|\alpha|) &= \kappa(251.5 - \alpha) && (2.3)\\
F_y &= \frac{\kappa(251.5 - \alpha)}{L_{arm}(\cos\alpha - \mu \sin|\alpha|)} && (2.4)
\end{aligned}$$

where κ is the spring rate, μ is the coefficient of friction between the cam arm and the chassis wall, and the $\sin|\alpha|$ is an absolute value because F_x is a friction force and switches directions when α crosses 0 (note that F_x is a component of the equation because, though the moment is calculated about the lower pivot where it is applied, an equal normal force opposes it on the upper "pivot"). F_y is shown as a function of α for several values of μ in Figure 2.23. The graph shows the force required for a single rotor, so two rotors require double the force shown. In this design, $L_{arm} = 3.16$ mm and $\kappa = .055$ mNm/°.

Note that, as the rotor approaches its full extension (α approaches 72.5 degrees), the force requirement increases considerably with relatively little friction, as can be predicted from the transmission angle at that point. To counteract this, the prototype used a PTFE tape to reduce friction. However, even so, the prototype was unable to initiate the motion unassisted with a fully-extended rotor. When heavier rotors were eventually installed (since the lighter ones the design was intended for were no longer available), the rotors "drooped" a small amount (roughly 5 degrees - see Figure 2.15), which enable this mechanism to work as intended.

As detailed below, a set of compression springs act against the actuator as the flight chassis is retracted; this detracts from the force available for rotor folding. However, the transformation arms act to assist the actuator, as they support the weight of the robot and, through the transformation mechanism, the forces involved ultimately work to retract the rotor head. The set of compression springs apply a total force ranging between 9 and 12 N (conservatively assumed to be a constant 12N hereon for simplicity), while the arms supply slightly more than 20 N at the point where the rotor cam arm just begins to contact the robot chassis. This limits the allowable coefficient of friction in the cam; the peak force exceeds 24 N (which is the actuator

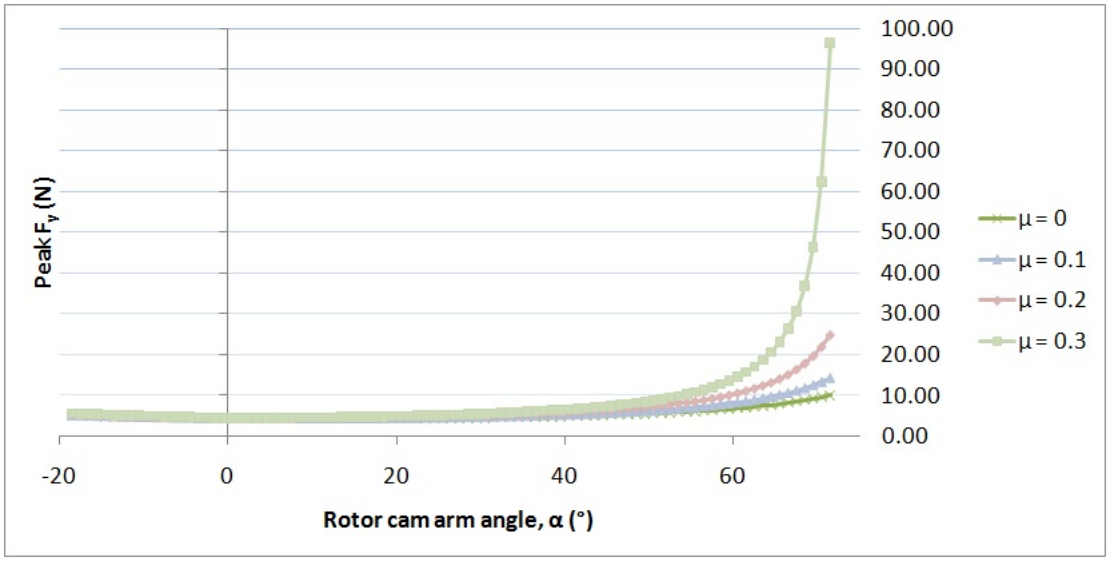


Figure 2.23: A graph of the V2 design's rotor folding force as a function of cam arm angle. The force is for a single rotor, so the force required for the full mechanism is twice what is shown.

stall force, plus the arm force, minus the compression spring force, split between two rotors) at $\mu = 0.2$; more conservatively, if the contribution from the arms is neglected, the maximum allowable friction is $\mu = 0.1$. Thus, maintaining good lubrication at this interface is critical (applying a film of a low-friction material, e.g. PTFE, would also help).

2.2.6 Actuation

On this version there are a total of 8 actuators: 2 ground-mode motors, 1 transformation actuator, 1 flight mode drive motor, 3 flight mode swashplate control motors, and 1 flight mode tail pitch control motor. This section will describe their selection.

Ground Motors

The primary selection criteria for the ground motors were mass and power output. Keeping mass low is critical to reduce the rotor power required in flight mode, and power output dictates the obstacle scaling capacity and top speed.

To maximize the available space on the interior of the robot, the motors are as close as possible to the outer shell. A gear pair is then used to couple the motor to the output shaft. The center distance of the gear pair is thus fixed and, because the pinion should not extend outside the body diameter, dictates that the gear be much larger than the pinion.

A variety of motors and gearheads were found (from vendors such as MicroMo [30], Maxon

Motors [31], and Namiki [32]) and a model was developed to allow a detailed comparison for the selection. Both top speed in the ground mode and obstacle scaling capacity were considered. Targets were for a top speed of .5 m/s and enough output torque to scale a step equal to the wheel radius.

The motors considered were in the 6-10mm diameter range. Brushed motors below 8mm were found to be inadequate, and motor mass increases quickly with diameter. Sensorless brushless motors at a 6mm diameter are available, and the entire motor assembly would be 2g lighter per motor. However, sensorless brushless motors rely on a high motor speed to achieve commutation; at low speeds, the required back-EMF (used to measure rotor position) is too small to sense. The motor controller must resort to a highly inefficient commutation mode to apply a torque. Operating at low speeds typically is only done at startup for sensorless motors, making this a transient condition. However, since operation near stall is required for ground robots (climbing and rough terrain can require high torques and a robot can frequently get blocked, stalling the motors), sensorless brushless motors are not a good option.

An 8mm brushed motor from MicroMo (part number 0816 D 003 S), along with a 51.2:1 gearhead (part number 08/2k 51.2:1) were selected. Output gearing (the gearhead drives a gear pair) was selected to be 7:1. This combination, though rated for only 3 volts, was estimated to allow the robot to drive at .48 m/s even at the low battery voltage of 7V (which is almost fully depleted). Also, it would be capable of providing short bursts of torque up to approximately .35 Nm, more than double the amount necessary to lift the robot over an obstacle half its height (though, admittedly, this is unlikely to happen in most circumstances with the current wheel design, due to lack of grip). Motor lifetime under these operating conditions is uncertain, however, as the operating parameters significantly exceed the ratings for the parts.

Flight Motors

Because much of the flight system for this design is based on a commercially-available helicopter, actuator selection for the flight mode was relatively simple.

For the main drive motor, the lightest-weight motor with the highest power rating at the battery pack's voltage was selected. This was found to be the Scorpion Power System HK-2206-5300KV brushless motor. However, in the RC market, while extremely high power densities can be found, performance details are scarce. For example, the HK-2206 is rated for 130 W power input, but no efficiency or load-speed curve is provided. Thus, better options likely remain. One helpful factor in motor selection is that the Hurricane 200 (upon which the flight mode is based) is designed for stunt flying; thus the motor size used is capable of delivering the high powers required for stunts. This high power capability can instead be used to carry a high payload.

The pitch control servos were similarly selected based on low weight and high power output. The flybarless rotor head is particularly demanding on servo motors; with a typical flybarred helicopter the torque required to maintain the rotor blades' pitch is provided by the flybar, which acts as a force multiplier. With no such mechanism in a flybarless helicopter, torque requirements are higher. The selected servo is the Futaba S3154, which had the best torque output in its size class at the time of selection.

Transformation Actuator

In both the V1 and V2 designs, springs are used liberally to aid in actuation. In V1, however, the transformation actuator was not capable of holding a position against the force of the spring without considerable current draw. The new design relieves this issue by using an actuator with a high back-drive force.

The actuator was selected based on the expected transformation force requirements (detailed in section 2.2.6), with a requirement of 20 seconds maximum for transformation time (the details of the several transformation mechanisms were designed simultaneously, which allowed for some adjustment for mechanical advantage and more variety in actuator selection).

Early in the design process, however, it was found that the initial stages of transformation required very high forces. A high-force actuator would be required, but it would be underutilized as the transformation progressed. Additionally, such actuators were excessively large. Instead, a smaller actuator was selected (model PQ12 from Firgelli Technologies), and was given assistance by the force amplification spring. Among other things, this spring stores energy from the flight-to-ground transformation for use in the reverse transformation, which reduces the burden on the actuator.

Transformation Force Balancing

The complexity involved in the usage of a single actuator for all of the transformation actions merits special consideration. In particular, the force requirements of the different mechanisms at different times during the transformation make actuator selection a difficult task. Here it is shown how the forces balance throughout the transformation process with a quasi-static force analysis.

Since all the transformation actions can be traced to the motion of a push plate which is fixed to the end of the linear actuator, a force balance will be done on the push plate. Since the plate is restricted to move along the actuator's line of action, transverse forces are not considered. For brevity, only the transformation from ground to air mode is considered, as this is the more demanding direction (working against gravity). The force balance is done as a function of x, the actuator displacement, where the actuator is fully retracted (and the robot is in ground mode) at $x = 0$. Modeling the robot with a point mass located at its ground-mode center of gravity and otherwise neglecting the masses of the individual components, the forces (calculated) are the following:

- $F_A(x)$, The actuator force, which can be *up to* the actuator's stall force (39 N) in either direction at any position.

- $F_{amp}(x)$, The force amplification spring force, which is always directed in the actuator's extension direction. This force supplements the actuator force when transforming into flight mode, and resists the actuator when transforming into ground mode. The force ranges linearly with actuator displacement from 36 N at $x = 0$ (maximum spring extension) to 24 N at $x = 11$, where the push plate bottoms out on (or, in other words, makes direct contact with) the flight chassis and F_{amp} then becomes a function of the forces applied to the flight chassis (rather than a direct function of the actuator displacement).

- $F_{orient}(x)$, The force from the orientation adjustment arms. The force is highest at the beginning of the orientation adjustment, starting at approximately 50 N at $x = 3.9$.

These forces are shown graphically throughout the transformation in Figure 2.24.

Further, the force amplification spring's other end attaches to the flight chassis, which itself merits a force balance, the result of which can be substituted in for the force amplification spring in the first balance when the amplification spring reaches its stop, allowing the determination of F_{amp} for $x > 11$. The forces here are from:

- $F_{amp}(x)$, The force amplification spring,

- $F_{clamp}(x)$, Chassis clamping, which is the residual force from the amplification spring once the folding and preload forces are covered. This force peaks at 14 N when the actuator is

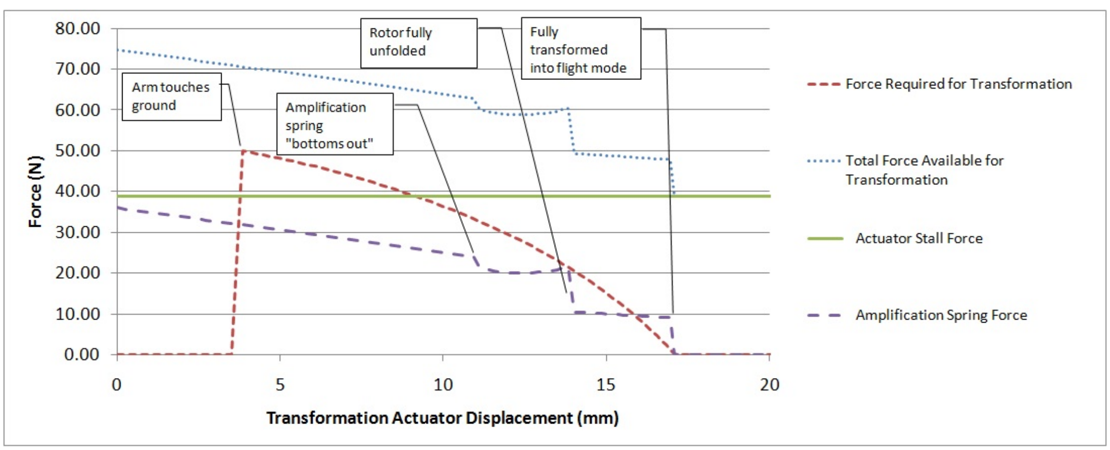


Figure 2.24: Graph of the force supply and need in the V2 design's ground-to-air transition. The total force available is the sum of the actuator force and the amplification spring force. The region between 4 and 9 mm of travel is where the amplification spring is necessary, as the required for exceeds that available from the actuator.

fully retracted,

- $F_{fold}(x)$, The rotor folding spring, which transmits its torque through a moment arm as a force, ranging between 8.5 and 13 N when engaged (neglecting friction),
- $F_{preload}(x)$, The flight chassis preload spring, which both ensures that the flight chassis is in the correct position in the flight mode and enables the rotor orientation to take place before the rotors are retracted. The force ranges from 9 to 12 N.

These forces are shown in Figure 2.25.

The transformation occurs in several distinct stages, visibly separated by discontinuities in Figures 2.24 and 2.25. These are caused by hard stops acting on the flight chassis, the rotor head, and the force amplification spring.

First, with 11mm of actuator travel, the push plate engages a hard stop on shaft pull bar, to which the other end of the amplification spring is attached. This eliminates the force from the amplification spring except for what it transmits from the flight chassis - that is, the amplification spring must apply a force to the push plate equivalent to what the other springs apply to the flight chassis to maintain force balance; the excess force from the amplification spring's extension is taken up by the hard stop between the push plate and pull bar. When that hard stop is reached, the flight chassis begins to move, disengaging the rotor head from the chassis and reducing the clamping force to 0. At 14mm of travel, the rotor blade folding levers disengage from the chassis, removing the rotor folding spring force. The next stage, starting at 17mm of travel, is marked by the flight chassis engaging a hard stop on the chassis, eliminating the force from the preload spring. Finally, the last 3 mm of travel is used purely to move the shaft pull bar away from the pin on the rotor shaft.

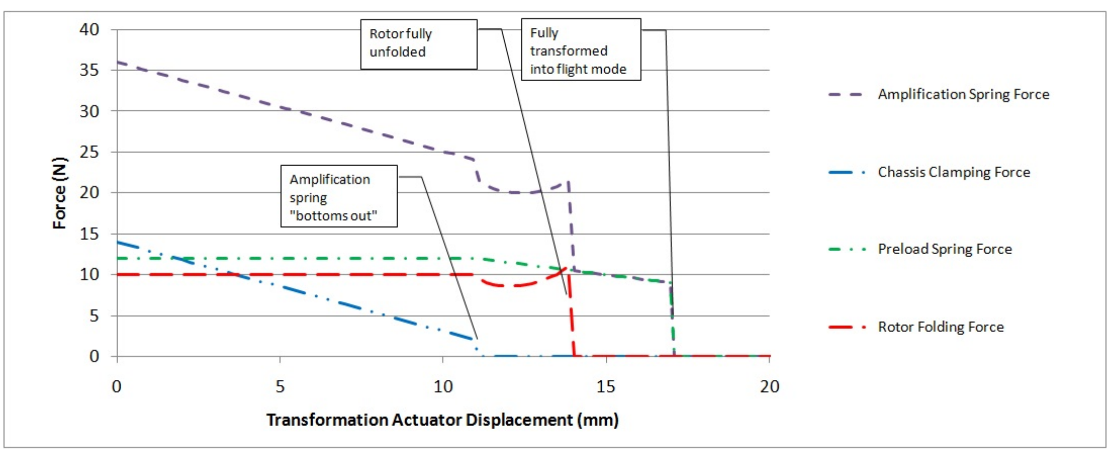


Figure 2.25: Graph of the amplification spring force in the V2 design. The amplification spring force is equal to the sum of the other components shown on the graph.

2.2.7 Avionics and Electronics

Development of V1's electronics and controls system was not smooth, and never fully completed. There are numerous options available in the hobby RC market for brushless motor drivers and helicopter control systems that have advanced features that would take months to implement on a custom system. While the mass may be higher than necessary, it was nevertheless decided to go with a mostly off-the-shelf electronics and controls system to begin with for the V2 design. A block diagram of the system is shown in Figure 2.26.

The battery feeds directly into an ESC (electronic speed controller - the hobby market name for a brushless motor driver), which has an integrated BEC (battery eliminator circuit - the hobby market name for a voltage regulator intended to power devices at 5V). The ESC drives the flight motor (which drives the main rotor) based on a signal from the SK720 flybarless control unit, which includes inertial sensors and executes a control loop to maintain flight stability. The SK720 also controls the three swashplate servos and the tail servo. The SK720 receives control input from a receiver dedicated to the flight mode, which has a paired controller (the Air Transmitter).

The ground mode similarly has its own dedicated receiver and transmitter. This enables the ground transmitter to turn off the SK720 when the robot is in the ground mode with a switch; this is necessary because the SK720 may otherwise attempt to adjust the control servos, which would be damaging to the robot's mechanisms. The ground receiver is always on, and sends commands to the two wheel motor drivers and the transformation actuator driver.

The motor drivers originally were intended to operate from the battery voltage as shown in the block diagram, but for the sake of expediency these were implemented by using servo circuit boards, which require a 5V regulated input. Had the motor drivers been powered with the battery voltage, the motors would have been able to run faster (resulting in a faster robot), and the transformation actuator would have been more powerful and faster.

2.3 Design Evaluation

For a quantitative evaluation of the design, performance metrics must be identified and defined. Since the design was done to explore the possibilities for combining locomotion modes, locomotion metrics are of the highest interest. For hybrid-locomotion robots, the same performance metrics as are used for ground robots and helicopters can both be used. Transformation performance must also be considered.

Important performance measures include the following (though this is not an exhaustive list):

- Driving speed over various terrain,

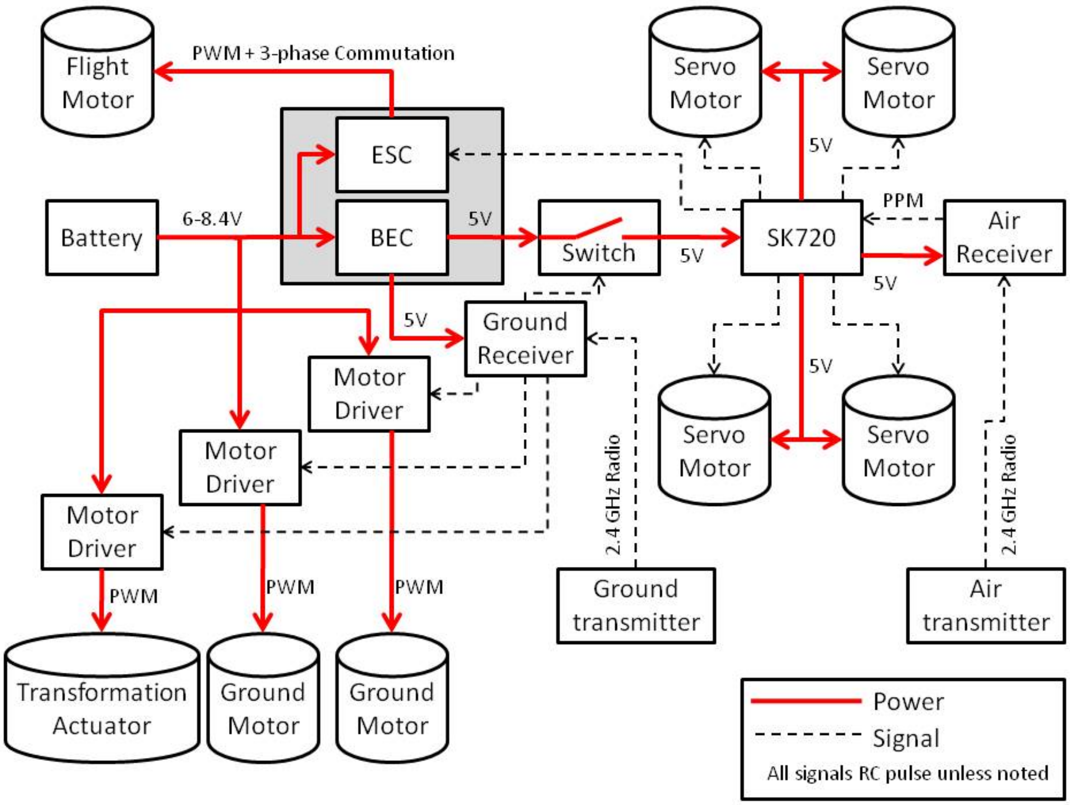


Figure 2.26: A block diagram of the V2 design's electrical system.

- Maximum navigable terrain roughness,
- Scalable obstacle height,
- Battery life in various scenarios (ground mode and flight mode),
- Average cost of transport in both modes, which is a computed quantity measuring locomotion efficiency on a distance-traveled basis,
- Take-off and landing times,
- Maximum forward speed in flight,
- Controllability of the robot in flight,
- Transformation time,
- Transformation mechanism robustness,

Of particular interest for hybrid-locomotion designs are the costs of transport in the flight and ground modes. This dictates the relative benefits of the two modes, and in an advanced autonomous system could determine the point at which a mode transition occurs. If take-off/landing and transformation costs are low, the robot could transition between modes whenever a lower cost of transport can be achieved.

If a future effort is made to create a more practical version of the robot, environmental performance also should be taken into account. This would include resistance to dust and water, humidity, extreme temperatures, impacts, and other environmental hazards. This design, however, is not hardened against any environmental factors.

Table 2.1 covers a number of performance capabilities of the V2 design. Many useful measures are omitted due to the fact that the flight mode was not successfully demonstrated (the reasons for this are discussed below).

Metric	**Value**
Speed on flat ground	0.3 m/s
Scalable step height	19 mm
Battery life, ground mode	2.5 hours
Battery life, flight mode	Less than 5 minutes
Transformation time	15 seconds
Average cost of transport on flat ground	2.4

Table 2.1: Performance of the V2 design

Several notes on the metrics are merited. First, an attempt at designing a motor driver capable of driving the motors at the full battery voltage failed; as a fall-back, a servo motor control board was used instead, which runs at only 5 volts. Had 7 volts been available, the 0.3 m/s speed would instead be closer to 0.4 m/s. Increased current draw would be only slight; the gearing is such that the motor operates near no-load anyway.

Second, the linear actuator also relied on a servo motor control board, which consumed a significant amount of power due to the way it was hacked. Improving this control system could reduce battery draw enough to increase ground mode battery life above 4 hours.

Third, though the speed measured is significantly slower, and the scalable step height not significantly higher than in V1, the drivetrain is nonetheless much improved. V1 was incapable of traversing extremely minor steps (¡5mm) without a running start; this design has no issue. Such a capability (that is, the capability to move slowly) is desirable for any teleoperated machine.

Finally, each of these factors result in an overestimated average cost of transport, reflective more of the prototyping sacrifices than the design itself. With the improvements identified here, we may expect the cost of transport to be closer to 1.3 in the ground mode.

Aside from the limited quantitative evaluation provided above, several additional issues exist with the design:

- Many of the joints are quite loose. This is particularly evident in the transformation arms, which have significant play on their 2mm diameter hinges. This effectively reduces the stability of the robot while transforming, since the weight distribution can more easily tip the robot in an unfavorable direction. Further, it was impossible to achieve a level stature in preparation for flight, which contributed to the failure to get the prototype flying. A design change was attempted that replaced the nylon base piece with an aluminum one, which was expected to provide a better joint, but which was ultimately inadequate. A better design may rely on larger pivot points, which would reduce the sensitivity to the radial clearance in the joint.

- The interactions between the rotor head and the rotor body are very dependent on tight tolerances, which were not achieved on the prototype, resulting in poorly functioning rotor folding mechanisms and poor locking of the dog clutch used to drive the top wheel. The rotor folding mechanisms were further hampered by the rotor orientation mechanism, which worked poorly; a higher helix angle would greatly improve performance, but would require more travel in the actuator to allow for the same sequencing of motions.

- Due to the loading on the push plate, it tilts somewhat, reducing the precision of the transformation motions. The push plate has three sources of eccentric forces: the tail boom links are only on one side of the plate, the orientation adjustment arms are loaded asymmetrically, and the actuator itself is offset from center. This caused the push plate not to remain level, which introduces error in the mechanism motion. This manifested as a further exacerbation of the loose orientation adjustment arm joints. An improved design would ensure that everything on the push plate moves in tandem.

- The retaining rings used to constrain all of the parts along the six chassis rods make assembly and repair very difficult. Parts need to be assembled in a particular order. A particularly difficult assembly step is that of assembling the flight chassis, which has two parallel plates, and three springs, which each need their own set of retaining rings.

- Since the tail only partially collapses, it is at a high risk for damage. A better design would have the tail fully collapse within the wheel diameter, and possibly close a cover over it when collapsed. This would greatly improve protection of the tail boom in the ground mode, which is critical because the flight mode cannot function without a working tail rotor. However, a counter-torque tail is necessary for any two-wheeled robot and this purpose is served by the tail boom in this design, so this likely would not offer significant reduction of the robot's size in the ground mode. Such a design was attempted here, but no solution was found, so the partially-folding design was chosen.

- Further improving the transformation process would greatly improve the real-world utility. In particular, this design's transformation process is tenuous even on flat terrain. It should be improved to operate even on uneven terrain, but currently it is not clear exactly how this can be achieved.

- Through the V2 prototype's development, the helicopter on which it was based became obsolete. It thus became impossible to obtain the parts that were originally designed into the robot. In particular, the lack of its lightweight rotor blades meant that the rotor unfolding springs were not strong enough to fully lift replacements; fortunately, the centrifugal effect of the rotor spinning compensated for this when the rotor had a suitable initial position. A future design should make use of more-available parts from better-established products.

- There were excessive vibrations in the robot that the control system was unable to handle. The origin of these vibrations is partially traceable to poor balance in the rotor head, and partially to the overall structure of the robot being inadequately stiff.

- The landing gear on the robot was inadequate, which led to two separate attempts to expand the robot's support polygon. The first involved adding offshots at the end of the back arms at a right angle; these were compatible with the robot's transformation mechanisms. They could not compensate for the loose mechanisms, however, and eventually a six-point "training gear" set was added, which made transformation impossible (Figure 2.27).

This large set of design problems meant that the robot never achieved sustained flight; the most it was able to do was skip across the ground, no more than a few centimeters in altitude each time.

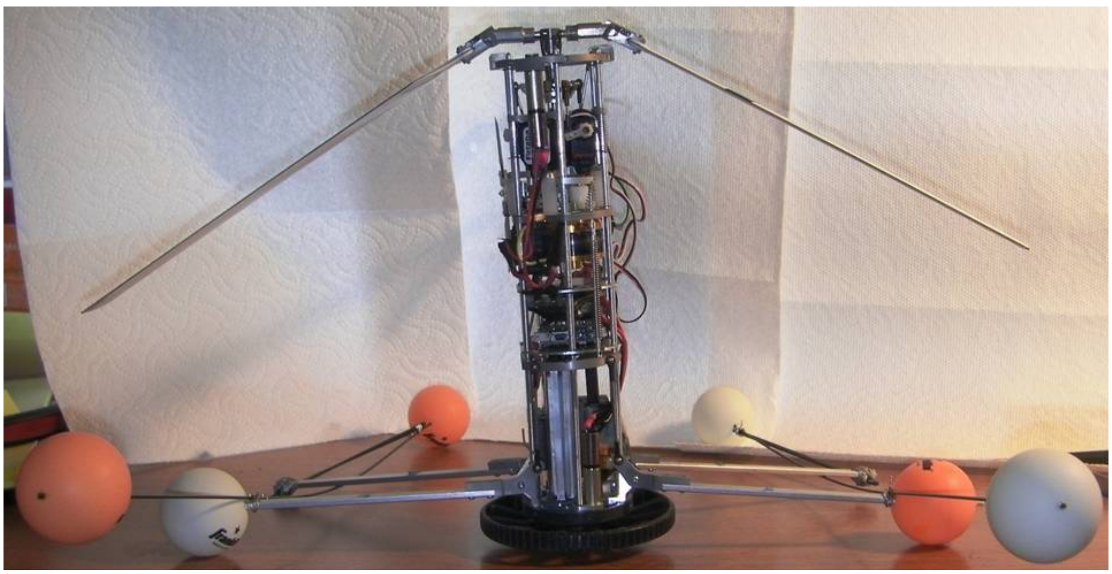


Figure 2.27: A photo of the prototype showing its landing gear. The upper wheel's gearbox assembly is removed, revealing the folding rotor grips.

Chapter 3

Design Principles for Miniature Hybrid-Locomotion Robots

This chapter covers a set of design principles for miniature hybrid-locomotion robots; these are elements that are necessary (but not sufficient on their own) to create an optimal design, and are drawn from the lessons learned in the development of the robots presented herein, and from the form taken by other similar robots. In short, they are:

- Hybrid-locomotion robots with a rotary-wing flight mode should have ground-focused designs.
- Flight and ground-mode drive systems should be functionally separate.
- As much as possible, parts and mechanisms should serve multiple roles.
- The flight mode should collapse in the ground mode to minimize size.
- Flight mode components should be protected as much as possible from the environment.

The applicability of these principles to other hybrid designs varies. In particular, the first principle (locomotion focus) does not hold up for other combinations of modes, particularly those including fixed-wing flight, as it depends on the mission profile and relative efficiencies of the two modes. The second principle listed is applicable wherever a propeller or rotor is used on a small robot due to the disparity in requirements between the drivetrains of the two locomotion modes; however, it may not scale well if size proportions are altered (e.g. if wheels get relatively smaller as the robot and rotor get bigger). For principles three through five, no specifics of a design or mission will affect the soundness of their application, so they are applicable to all hybrid designs with varying degrees of usefulness.

3.1 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 or performance improvements can be focused on one of the modes. For instance, additional weight or space can be used for more powerful motors; a ground-focused approach would use the space to improve ground locomotion speed or torque, while an air-focused approach would improve flight agility or speed.

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, then, may be worth additional mass for a ground-focused robot, but not for an air-focused robot.

V1 is very air-focused. This is evident from the drive train, which is geared solely for flight and therefore functions poorly on the ground. Also, the wheels were selected purely for their low mass, with little regard for traction or obstacle-climbing capability.

In the V2 design, a large effort was made to improve the ground mode. Indeed, it is capable of ground locomotion over a much wider variety of terrain, reducing the need for the flight mode, which enables a longer runtime.

It is instructive to consider the performance of the robots in the context of this principle. Figure 3.1 shows measurements of the lift and total power consumption of V1's air mode as a function of rotor speed, taken on a test stand (Fig. 3.2). It shows that the robot, with a mass of 300g, 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 battery can sustain this for roughly 4 minutes; a hobby helicopter may last up to 10 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.

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, which is a characteristic often quoted for helicopters - the inverse is used here as it is more directly applicable to the analysis). In the operating range of the robot (i.e. where the lift exceeds its mass), this ratio is approximately $.215 \pm .15$ watts per gram-force when using non-folding rotors.

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 (roughly 20 mW). This increase in power in the ground mode is especially insignificant considering the power demands outside of locomotion ("overhead" devices alone, such as onboard wireless communication devices, 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

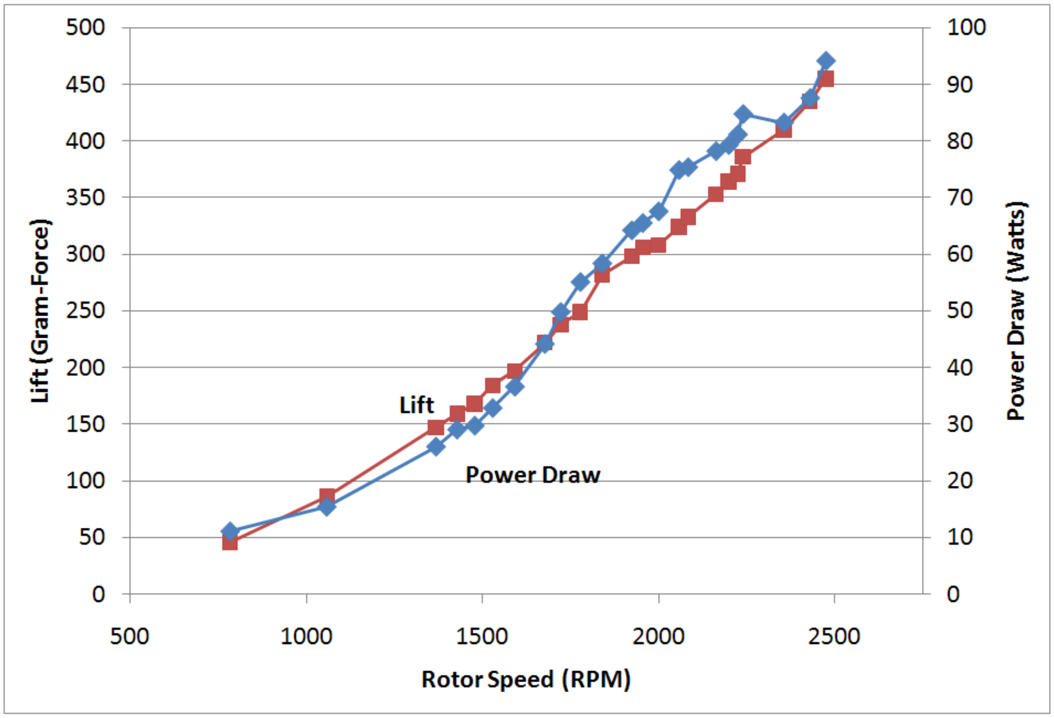


Figure 3.1: Power consumption of Hybrid V1 in flight. Results obtained on a test stand with non-folding rotors.

the reduction in flight performance and runtime for a ground-focused robot. In fact, there are two benefits: improved ground-mode performance, and the resulting reduction in unnavigable terrain (meaning the flight mode is needed less often).

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 without the added overhead of the flight mode. The advantages of the ground mode (stealthy operation, lower energy consumption, and a small size) are absent 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. In other words, the flight mode should be seen as a supplemental capability for an already-capable ground robot.

One interesting design to consider in this context is the HyTAQ robot [28]. This robot simultaneously drives both its flight and ground systems simultaneously, which results in the flight mode aiding the ground mode. While its ground mode alone is quite limited in much the same way as the V1 design presented in the appendix, its rotors can help boost it over obstacles seamlessly. Because of this, it cannot really be considered to ever be in a “ground” or “air” mode - it is in both simultaneously. Of course, this comes with significant cost to battery life,

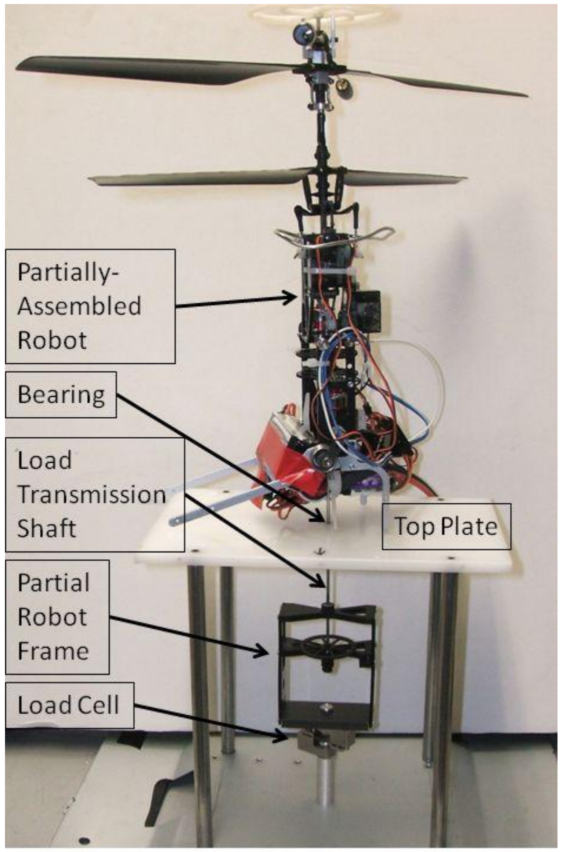


Figure 3.2: A picture of the test stand used for Hybrid V1 thrust measurement.

and the HyTAQ would benefit from the capability to selectively enable its flight mode.

3.2 Separation of Drive Systems

Today's hobby market provides sensorless brushless motors with extremely high power densities (4 watts or more per gram), which serves the flight mode while minimizing weight (notably, as mentioned above, RC components typically are not specified in enough detail to get a full performance picture, so while this power density does not fully describe the motor, it does show the order of magnitude that the motors are rated for). However, high-power motors tend to have relatively high no-load currents that can result in losses of 10W or more even if the robot only needs 1W of power in the ground mode.

Even with a suitable drivetrain and even if no-load currents are equivalent to smaller motors, though, such a motor is itself a poor choice for the ground mode; in stall conditions, which may frequently be encountered when maneuvering over difficult terrain in the ground mode, these high-speed motors draw enormous amounts of power, destroying themselves and the drive electronics in the process.

This can be prevented with current limiting, but operating near stall is still difficult for sensorless brushless motors, which require a large back-EMF (and thus, a high motor speed) to function properly. At stall conditions, the lack of commutation feedback requires the use of "forced commutation," which only drives the right coil 1/3 of the time, resulting in 1/3 of the expected torque output.

Rotor position sensors can be added to brushless motors to allow the right coils to be driven at all times, thereby reducing inefficiencies at low speeds. However, motors designed for high power output typically have relatively large no-load current draw, which can easily exceed the work-producing current in the ground mode (which has relatively low power output requirements), meaning that these motors are still surprisingly inefficient for ground travel.

A transmission for such a system causes problems as well: in V1, the transmission took up all of the interior space in the robot, forcing electronics and other actuators to be placed outside of them. In the V2 design, a much more efficient use of space was possible because the only thing necessary to distribute throughout the robot was electrical wiring, which is much more compact and routable. This enabled significant space for electronics within the robot itself (though, when prototyped, some components still had to be mounted on the exterior due to the use of hobby parts. Future designs could work with custom-built circuit boards that would save significant space).

3.3 Combination of Functions

One common theme in the development of these robots has been the necessity for creative uses of its mechanisms for several different functions. As illustrated in Figure 3.3, each mechanism in the V1 design serves several functions, each of which is necessary for at least one of the robot's primary actions. Ground locomotion requires wheel power and a counter-torque tail, which are served by the main drive train and the retractable arms, respectively. Flight requires landing gear, rotor cyclic control, and rotor power, which are served by the legs, swashplate, and drive train, respectively. Finally, transformation requires rotor power (to orient the rotors correctly at the start of transformation), rotor folding and unfolding (which are served by the legs constraining the rotors as they fold, and by the main rotor spinning them up to unfold), orientation adjustment (served by the legs), stabilizer folding (requiring a flat swashplate and shaft translation), and control over the rotor drive engagement (provided by shaft translation and a dog clutch).

It is tempting to extend the "combination of functions" principle to the drivetrains of the two modes; indeed, this is what drove the drivetrain structure in the Hybrid V1 design and the HyTAQ robot. However, this has proven to be counterproductive: the needs of the ground mode are irreconcilable with those of the flight mode, as described above. Typically the flight mode requires high speeds and low torques, whereas the ground mode requires high torques and relatively low speeds, and the power requirements are at least an order of magnitude higher in the flight mode. For this reason, V2's drive systems for each mode are entirely separate both from one another and from the transformation process.

The need for multi-purpose components in miniature air vehicles and particularly in hybrid-locomotion designs has been noted before [27]. In at least one case [26], the robot's flight mode was chosen largely based on the ability to integrate it with its ground mode, using common mechanisms. This helps reduce weight, but also requires a number of interactions between mechanisms, increasing system complexity. The HyTAQ robot similarly uses a common drive-train (which limits it, as noted above); further, its wheel doubles as a rotor-protecting cage.

In some cases, this has hindered performance. For instance, the tail in V1.1, which is part of the landing gear, gives the robot little ground clearance; the robot has scaled steps of only 4 mm. On the other hand, integrating functions has simplified operation in some cases. For example, the links connecting the upper rotor to the stabilizer bar in V1 serve two functions with no compromise necessary: first, they transmit the stabilizer bar's motion to the upper rotor while flying, and second, they fold/unfold the stabilizer bar during transformation. Separating these functions would have required considerably more complex mechanisms. Another case that benefits substantially from function combination is the force amplification spring scheme, wherein the springs both clamp the rotor head onto the robot and assist the ground-to-air transformation.

The most striking example in the V2 design is the transformation mechanism, which affects every aspect of the robot's design and operation, yet is driven by a single actuator with control required only of the limits of motion. This actuator drives the orientation adjustment (the arms of which turn into landing gear), tail extension (the tail providing countertorque in both the ground and flight modes), and rotor head retraction, which in turn folds the rotors, engages the top wheel motor, and modifies the robot's chassis. This combination of functions makes sense, and is not contrived like that of V1's drivetrain - the single transformation actuator is, after all, still performing only a single task. Using this single actuator eliminates a significant amount of overhead that would be involved if separate actuators were used for each action - each actuator needs a housing, mounting points, and drive electronics. If the mechanisms can be designed such that they each require high forces at different times, even greater savings can be had because the actuator can be relatively smaller.

Combination of functions must be done smartly, with performance tradeoffs duly considered. It is a powerful principle, but as shown above, if applied incorrectly it can be detrimental.

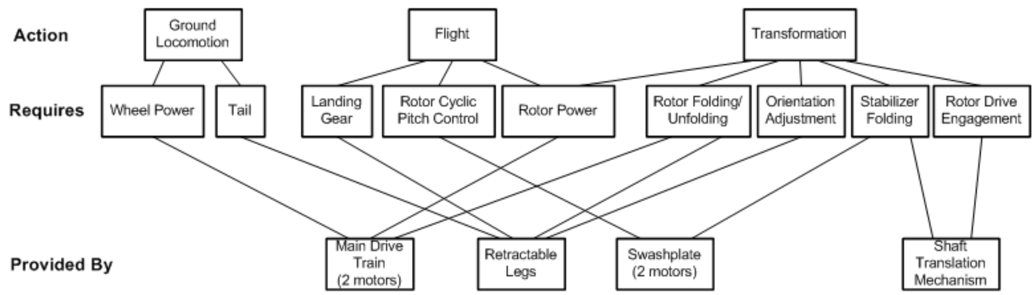


Figure 3.3: A diagram illustrating the roles of each mechanism in Hybrid V1

3.4 Collapsibility

One design goal for these robots 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.

In the case of rotary-wing flight, a higher efficiency can be achieved with a larger rotor diameter. Figure 3.4 shows the trend in power draw for a fixed thrust as a function of rotor diameter. This graph shows that collapsing rotary-wing designs is essential for efficiency in the flight mode; in the V2 design, for instance, using a rotor the same size as the robot's ground width would increase power demands by 2/3.

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 folding. 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.

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 can be used for a robot with a given ground mode size (Figure 3.5); this allows for a reduction of main drive train complexity, but requires the addition of a tail rotor. Indeed, Hybrid V2, with a single main rotor, has a (25%) larger diameter than V1, despite having (14%) *less* spacing between the wheels. This is effectively a 45% increase in rotor diameter (scaled to the robot

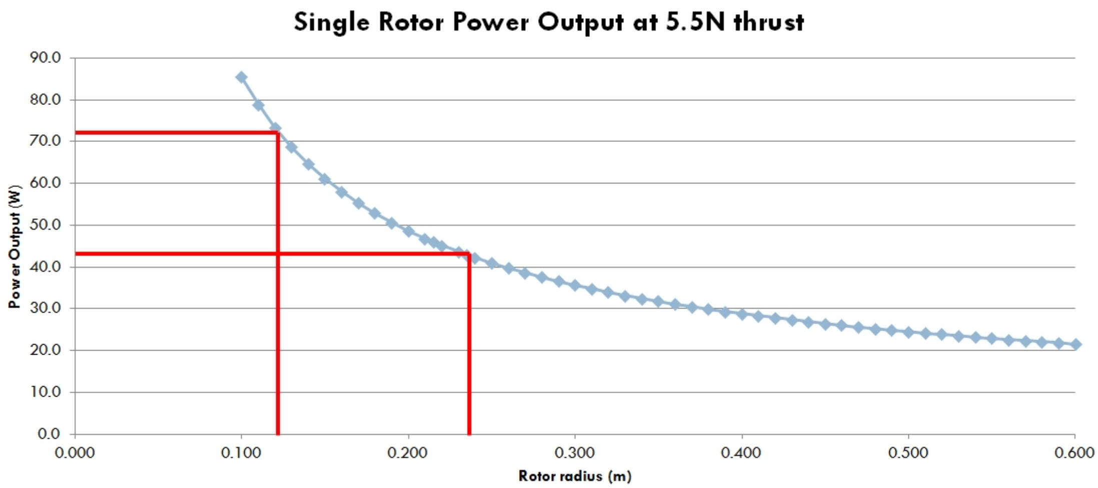


Figure 3.4: A graph of power draw vs. radius for a fixed rotor thrust. The highlighted data points indicate rotor diameters of half- and full-size for the Hybrid V2 design, respectively.

size). 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 at a small scale.

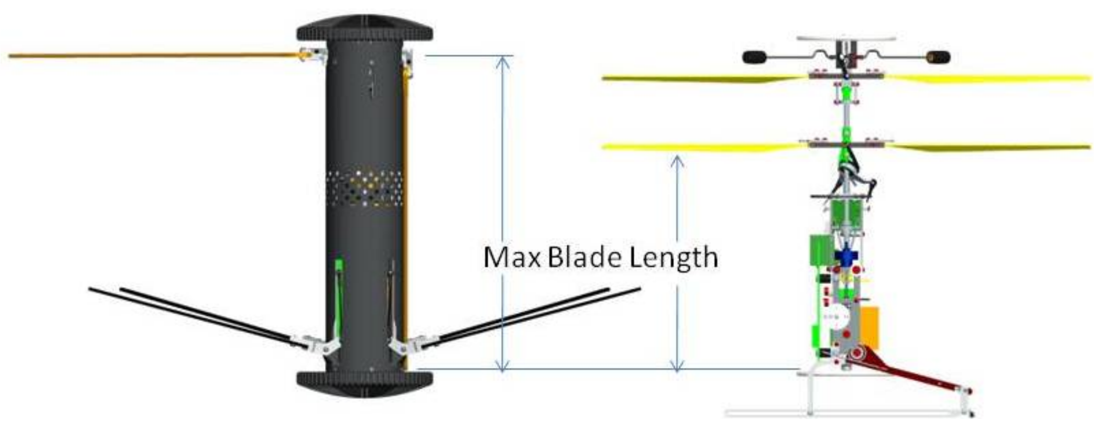


Figure 3.5: Comparison of maximum blade lengths between the two designs. Robots are not shown at actual scale; they are scaled to match the distance between the wheels.

3.5 Protection of Flight Mode Components

One of the critical aspects of any ground robot is its robustness to rough conditions in its operating environment. Such robustness is critical purely due to the fact that a ground robot moves by interacting with the rigid environment on the ground. Rotor blades, however, are relatively fragile - their only intended interaction is with air.

Thus it is necessary to protect the exposed flight mode components when in the ground mode, or risk debilitation of the robot. As mentioned above, this latest design employs the strategy used on the University of Minnesota's Scout robots, wherein as much as possible the robot's components are contained within the wheel diameter [1]. The HyTAQ follows this same principle and method, with its wheel doubling as a rotor-protecting cage.

This principles ties in closely to the collapsibility principle; the flight components, which are relatively fragile, should be shielded adequately from contact with the environment, and collapsing provides an elegant way to achieve this protection. This is achieved on the designs presented here by folding them down within the wheel diameter, so on mostly-flat surfaces there is little chance of the rotors contacting other objects. Additional shielding could be achieved if the blades were stored inside an external shell.

Of course, neither of these designs fully conforms to this principle - the tail on the V2 design, for instance, is not fully collapsing. This is a very challenging principle to follow.

Chapter 4

Alternative Design Possibilities

While the designs presented herein are intended to display the primary features of hybrid-locomotion robots, there are many mission profiles for which they would not be suitable. Of interest, then, is the effect that adapting such robots for other scenarios and requirements would have on their design and performance. This chapter discusses several changes.

4.1 Impact Tolerance

Impact tolerance may be highly desirable in a hybrid wheeled/rotorcraft robot for several reasons. One intriguing possibility, discussed below, is that of landing by simply dropping out of the sky. Among other things, first and foremost this would require an impact-resistant design. Another is that impacts may be expected to occur during the course of any robot's operation, as real-world scenarios contain many unknowns that are difficult to react to for autonomous systems, and even for teleoperators. Finally, certain scenarios may benefit from deployment by throw.

A particularly relevant example of an impact-tolerant robot is the COTSM Scout [1]. The robot has two large, impact-absorbing wheels and a compact body which the wheels protect. In many ways the COTSM Scout is a predecessor to the hybrid-locomotion robots described in this thesis.

The designers of the COTSM Scout articulated several principles for the design of impact-tolerant robots. Among them are:

- For angle-invariant impact design, spherical symmetry is ideal. When not possible, radial symmetry is the next best.
- A monolithic chassis is preferable to a piecemeal chassis.

- Those portions of the robot not protected by shock-absorbing elements must have minimum exposure to the environment to minimize the chance of impacting protrusions (e.g. a step).
- Strength properties (fracture toughness, yield strength, etc.) must be evaluated on a mass basis, since loading in an impact is dependent on mass.
- In urban environments, impact surfaces must be assumed to be perfectly rigid.

The designs presented herein largely conform to three of the first four principles; the chassis, however, is far from monolithic due to the complexity required of it. The fifth principle pertains more to analysis of the impact tolerance than the design itself.

Also, while the bulk of their bodies are contained within the wheel diameter and thus somewhat protected from the environment, they nonetheless have portions extending outside the wheel diameter that would be highly vulnerable in the case of an impact.

Consider also that in order to attain a drop rating onto concrete of 30 feet, the COTSM scout devotes 180g of its 468 g mass (38%) to shock-absorbing wheels, while a titanium shell and aluminum chassis (to which all internal components are fixed rigidly) protect the internal components from damage.

With the V2 hybrid design weighing only 450 g, and with eight actuators and associated moving parts (compared to two on the COTSM), very little remains for shock absorption in the wheels or chassis without severely hampering flight behavior. Further complication arises from the mere presence of numerous moving parts, as they cannot be securely fastened down as in the COTSM.

These issues suggest that impact-tolerance hybrid-locomotion robots would be, to say the least, very challenging to implement, and perhaps even impossible to achieve if one uses the COTSM's 30-foot drop as a benchmark.

4.1.1 Quick-Land Capability

If impact tolerance were achievable, one interesting application would be in the landing of the robot. If the robot could simply drop out of the air, it could save considerable energy that would otherwise be used in searching for a suitable landing zone and performing a suitable descent.

Such an action would require an extremly quick transformation into the impact-resistant state. This state would require that all components of the robot requiring protection be located in the "safe zone" near the wheel axis (e.g. on the COTSM Scout this is a 1.5" diameter shell within its 3" wheels). A higher drop height would increase impact energy but allow for more time to transform. As a worst case, neglecting drag, the time to fall is related to the drop height as $t = \sqrt{2h/g}$. For 30 feet, it takes 1.37 seconds, and for 10 feet, .79 seconds.

Fast transformations require high forces at high speeds. Neither of the designs presented herein are good at quickly retracting their landing mechanisms. This is because space efficiency demanded that the retraction transformation be assisted by the force of gravity (which is unavailable in free-fall) in the air-to-ground transformation (i.e. when the landing gear retracts).

To take the V2 design as an example: as shown in Figure 2.24, the major force required for retraction *when the arms are not in contact with the ground* is that required to extend the force amplification spring. Over the 20mm travel of the actuator, the spring requires a total of 0.326 J of energy to extend. To achieve this over a 16-foot drop (where the time to impact is very nearly 1 second) would require approximately 0.326 W of average output power, neglecting the inertia of the mechanisms (which may be significant and will push this value higher). The actuator used in the design, though (the Firgelli PQ12), can output only one third of this (0.108 W) at peak power output (and its output would vary widely from the peak throughout the transformation). Another design may use the larger L12 actuator, with a higher gear ratio, to achieve transformation without an amplification spring (peak force is 63 N vs. 35 N, with a peak force demand of 50 N for transformation). However, even this design would be inadequate as it has a no-load speed of 5 mm/s, and must travel 20mm to fully transform. And this analysis takes no consideration for the time to ramp down the rotor speed, which will significantly reduce the time available to transform.

In summary, a "quick-land" capable robot would require a significantly more powerful transformation actuator (along with its increased size), a much more collapsible flight system, and a much more robust structure to survive the impact. In turn, the weight required for these changes (particularly for the impact tolerance features and more powerful actuator) would necessitate a more powerful rotor motor, which could easily negate any energy savings achieved by landing quickly.

4.2 Size Scaling

While the bulk of this thesis focuses on miniature robots intended to be operable indoors, it may be beneficial to use larger robots in more open environments, or to miniaturize the design further. Such scaling would affect the robot's capabilities, such as flight time, payload, and ease of control. It would also affect the chassis design, actuator selection, and power source. By far, the most challenging portion to scale correctly is the flight portion, so the analysis will start and focus on the flight portion.

This section will look at each portion of the robot in turn, and then consider the overall implications of scaling. The focus will be on the V2 design. Any such scaled design will be highly dependent on the requirements placed on it (after all, the reason for scaling is to allow the robot to pursue different mission profiles), and as such this section will only provide a glimpse into the issue of scaling.

It is worth considering the benefits and drawbacks of scaling the design. Ultimately, the ideal scale depends entirely on the use case, and there are reasons to scale the robot either way.

Scaling the design down would give the robot proportionally more clearance in confined spaces in either mode. In open spaces, air currents would significantly hamper the utility of smaller robots. In cases where the robot is delivered to a location that it must explore, it would also enable more robots to be deployed for a given size/space constraint (that is, more robots could fit into a truck, for instance), and subsequently they may be able to explore a space more quickly due to having more "eyes" on the scene. However, smaller robots will suffer from shortened battery life, and will have lower payload limits.

Scaling the design up would only be useful for outdoor environments; the design as is currently is just small enough to fit through a doorway, so anything bigger will not be very maneuverable indoors. Outdoors, such a robot may be more useful for getting a temporary "bids-eye view" of a scene, rather than for scaling obstacles. In any case, though, a larger robot would be able to weather air currents much better, making it ideal for outdoors.

4.2.1 Thrust and Rotor Speed

Helicopter design and analysis involves countless variables, and thus the size scaling will be considered only to a first approximation. As a simplifying assumption, the robot's overall mass (M) is assumed to scale as the third power of scale (L):

$$M = cL^3 \tag{4.1}$$

where c is a constant equal to the mass in the non-scaled design. This assumption holds if every linear dimension in the robot's design is scaled by L, where $L = 1$ is the original scaling (this is admittedly not possible to achieve for arbitrary scales with electronics and off-the-shelf components).

In addition, the ideal thrust coefficient (C_t) of the rotor is assumed to be constant. The thrust coefficient is defined as [33]

$$C_t \equiv \frac{T}{\rho A \Omega^2 R^2} = \frac{bcg}{\rho A \Omega^2 R^2} = \frac{bcL^3 g}{\rho A_L \Omega_L^2 R_L^2} \tag{4.2}$$

where Ω is the angular velocity of the rotor, T is the rotor thrust, R is the rotor radius, ρ is the air density, g is gravitational acceleration, b is a constant indicating the desired amount of thrust overhead (this constant allows the scaled and non-scaled helicopters to have the same performance in terms of thrust and, consequently, acceleration), and A is the area of the rotor disk, equivalent to πR^2. The subscript $_L$ indicates that the quantities are for the scaled version.

Simplifying yields

$$L^3 = \frac{\Omega_L^2 R_L^4}{\Omega^2 R^4} \tag{4.3}$$

However, one more substitution is available: for a pure scaling, the rotor radius will scale as well, so that $R_L/R = L$.

$$L\Omega_L^2 = \Omega^2 \tag{4.4}$$

which shows that, for this type of scaling under the stated assumptions, the rotation speed will scale with $1/\sqrt{L}$. This results in a rotor tip speed ΩR scaling with $\sqrt{L}$. This can only scale so far, however, as high tip speeds produce noise and can result in losses due to compressibility effects in the air. Airfoil drag increases dramatically beyond a Mach number of approximately .7 [33], and for helicopters the Mach number of the advancing blade tip is determined by the rotor speed, forward velocity, and altitude.

To determine the rotor torque, it is further assumed for simplicity that non-ideal effects on rotor power are negligible or scale identically to the ideal equations of Rankine-Froude momentum theory [33]. Momentum theory shows that the ideal rotor power in hover is

$$P = \frac{T^{3/2}}{\sqrt{2\rho A}} \propto \frac{L^{3^{3/2}}}{\sqrt{L^2}} = L^{7/2} \tag{4.5}$$

Using the relation $P = \tau\Omega$, where τ is the rotor torque, the torque scaling relationship can then be derived:

$$\tau = \frac{P}{\Omega} \propto \frac{L^{7/2}}{1/\sqrt{L}} = L^4 \tag{4.6}$$

Other scales for rotor behavior may serve better in some circumstances, particularly when a more detailed analysis of the design parameters are considered (e.g. mass scales with L^2, or maintaining constant disk loading, etc). However, for simplicity and brevity, and particularly because the details of any scaled designs are not known, the analysis will continue with the existing assumptions.

4.2.2 Structural Components

One limitation in both designs is fabrication process feasibility at prototype volumes and the availability of common material stock shapes. For instance, small-diameter tubing in magnesium is difficult to obtain; it is not commonly manufactured in extruded form, and machining long tubes out of rod stock is difficult if not impossible at the necessary diameters. If such material were available, the chassis rods used in the V2 design may have been designed to be lighter, since the driving forces in their design were space limitations, weight restrictions, and bending strength. Tube stock would have allowed similar bending strength with significant weight reductions.

These difficulties intensify as the design is scaled down, but as it is scaled up more options are available. However, while it may be possible to construct a robot structure with efficient cross-sections at larger sizes, it is difficult to say exactly what could be used without making a significant step toward the design of such a robot. For the sake of this discussion, it is assumed that the design is simply scaled appropriately, with no change in cross-section. This is consistent with the assumption above that the mass scales with L^3.

To scale the structure here, it is assumed that the design can be based solely on the need to support the robot similarly to the design presented here. External forces are not considered, since the robot was not designed to endure any particular external forces. However, the effects of mass changes on impact force were touched upon briefly in Section 4.1.

With the assumption of a lack of external forces (aside from gravity), the load in all cases is based on the mass and geometry of the robot. In the ground mode, the structure is subjected primarily to shear and bending from the weight of the body suspended between the two wheels. In the flight mode, it is subjected primarily to the tension of the body hanging below the rotor and to the rotor torque (which is countered by the tail thrust).

The worst-case model for ground mode loading puts all weight at the center of the robot, giving a maximum bending moment of $K_{max} = MgB/2$, where K_{max} is the maximum moment, Mg is the robot's total weight, and B is the spacing between the wheels. An approximate bending moment of inertia is $Q = 4\pi R_{rods}^2 sin^2(60°)r^2$, where Q is the moment of inertia, R_{rods} is the radius at which the structural rods lie, and r is the radius of the rods themselves; this equation is derived from 4 rods spaced $R_{rods} sin(60°)$ from the neutral axis, with the other rods placed on the neutral axis, and ignoring smaller terms (e.g. the contribution from the rods on the neutral axis). Overall, the bending stress is then

$$\sigma_{bend,max} = \frac{K_{max} y}{Q} = \frac{MgBR_{rods} sin(60°)}{8\pi R_{rods}^2 sin^2(60°)r^2} = \frac{MgB}{4\sqrt{3}\pi R_{rods} r^2} \tag{4.7}$$

As above, M scales with L^3, while the linear dimensions scale with L. This gives

$$\sigma_{bend,max} \propto L \tag{4.8}$$

Using equation 4.7, with $M = 0.450$kg, $B = .23$m, $r = 0.0015$m, and $R_{rods} = 0.0225$m, $\sigma_{bend,max} = 0.9$ MPa. The AZ31B magnesium alloy used in the chassis rods has a minimum yield strength of 200 MPa. Even under this worst-case model, the scale L would need to exceed 200 to cause yielding; this would be a robot with a mass of 3600 metric tons, a 100 meter rotor diameter, 50 meter ground width, and 18 meter wheel diameter. Clearly, chassis bending is not an issue in the ground mode. Indeed, the chassis may be over-engineered in this design according to this analysis, though the analysis ignores external forces.

Displacement under the bending load may be relevant at higher scales, but it is inherently non-critical in the ground mode, as the critical gearboxes are both very near the wheels where any bending will have very little influence.

Shear loading is even less significant:

$$\tau_{max,shear} = \frac{Mg}{12\pi r^2} \propto L \tag{4.9}$$

With $L = 1$ (i.e. the design as shown here), $\tau_{max,shear} = 52kPa$.

4.2.3 Actuators and Drivetrain

For the rotor drivetrain, torque will scale as calculated above (Equation 4.6). Degree of twist is not critical for the rotor drivetrain, but stress is. Peak torsional stress (σ_τ, indicated as such to distinguish it from the torque τ) is

$$\sigma_\tau = \frac{\tau r}{J} \propto \frac{L^4 L}{L^4} = L \tag{4.10}$$

where J is the polar moment of inertia of the torsion member (which, here, is a solid round shaft). Clearly, with the previous assumptions, maintaining a safety factor will become an issue as the design is scaled up unless other changes are made. These could include material changes or shaft radius increases (though the latter option violates the assumption of identical scaling of all components).

For the ground drivetrain, assuming that speed is desired to scale linearly with the robot size, the wheel scaling alone accomplishes this, assuming a constant motor speed. However, scaling similar obstacles and having similar performance over scaled terrains requires a change in torque. This torque is proportional to the robot's mass ($\propto L^3$) and the wheel radius ($\propto L$), resulting in the same torque scaling relationship found for the rotors ($\propto L^4$). Also similar is the scaling of shaft stress with L. Unlike the rotor drivetrain, however, the speed remains the same and thus the power requirements scale at the slightly higher factor of L^4. This would require that the ground motors scale disproportionately with the robot.

4.3 Alternate Rotor Configurations

The two designs discussed in this thesis use a coaxial dual-rotor configuration and a main-rotor-with-tail configuration. Other rotor configurations are possible; modeling them after existing rotor configurations from full-size helicopters to RC helicopters limits the selection to "n-rotor" or "2-n-rotor" designs, where n is an integer; n-rotor designs would be designs with n non-coaxial rotors, while 2-n rotors would be designs with n sets of coaxial rotors (infinite configurations could exist, such as an 8-rotor coaxial configuration. Such oddities are not considered practical for the following discussion). Such designs will have n or $2n$ rotors spaced on an n-gon, and in the interest of simplicity none but a “1-rotor” will have a tail rotor or other side-facing rotor, as that is unnecessary for full control.

For example, a simple ”coaxial” helicopter would be a 2-1-rotor design. A tandem-rotor helicopter (in which rotors are on different shafts spaced some distance apart) would be a 2-rotor design. The hobby market offers existing RC helicopter designs of both types with $n =$ 1,2,3,4.

For $n = 1$, either of the designs described herein could be used. For $n = 2$ (tandem-rotor), an entirely different design would have to be adopted, though a two-wheeled ground configuration may still be possible. It may involve, for instance, turning end portions of the robot up and extending rotor blades, while the main body remains in its ground orientation.

$n = 3$ is an awkward configuration, as most ground robots have a reflectively symmetrical design, making it difficult to handle the spacing required between the rotors when in the ground mode. An interesting option may be to use a robot with a triangular-shaped body with an omnidirectional wheel at each corner, like the PPRK [34]. To remain compact, the rotors could be placed on arms hinged near the corners of the triangle, which store the rotors near the body in the ground mode and extend them straight out from the triangle’s corners for flight (Figure 4.1). A common way to use three wheels is to use omnidirectional wheels oriented 120 degrees from one another. On drawback of this approach, however, is that such wheels typically do not have good terrain capabilities, making such a configuration counter to the ideal ground-focused robot.

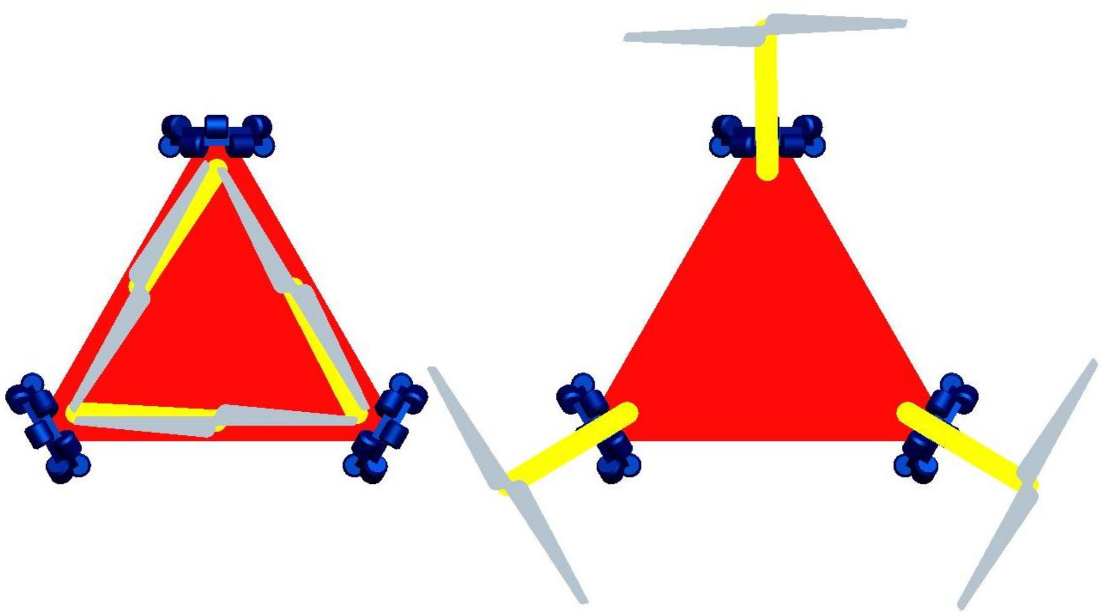


Figure 4.1: A three-rotor concept

$n = 4$ could utilize a similar design as the triangle-shaped robot in Figure 4.1. Such a robot could utilize a conventional four-wheeled ground mode with a roughly square chassis.

Clearly, numerous possibilities exist for each configuration. The concepts presented here only touch the surface, and are meant to illustrate the possibility of using alternate rotor configurations.

Chapter 5

Conclusion

Through the design and test of the hybrid-locomotion robots presented herein, much was learned about them and how to improve them in the future. Most notably, it was found that

- Adding a rotary-wing flight mode to a wheeled robot only adds significant value if the robot is very capable in its ground mode to begin with,
- As much as possible, weight-saving techniques should be used to minimize power requirements for the flight mode, particularly through incorporating multiple functions into single parts or mechanisms,
- Collapsibility is a key requirement for the flight hardware, without which a robot becomes cumbersome and excessively large,
- The drive systems used in the two modes are too disparate to be combined readily; it is more weight-efficient to use separate drive trains.

The Hybrid V1 design did not strictly adhere to these principles and it showed in the robot's performance. Its ground mode suffered due to a combined drivetrain, violating two of these principles. Collapsibility was not ideal, and subsequently the flight hardware was not well-protected. However, it did excel in the use of parts and mechanisms for multiple purposes.

The V2 design showed much improved ground performance, significantly improving the robot's utility in any possible scenario. It had a transformation process designed from the start to improve collapsibility and flight hardware protection, though fatal design errors discovered in the prototype meant that it was not fully functional. Relative to V1, it somewhat lacks in combination of functions, but the other improvements more than make up for this.

While the V2 design had its own set of problems, it nonetheless contributed significantly to the development of the design principles, and provides a good benchmark for future development.

References

[1] I. Burt, A. Drenner, C. Carlson, A.D. Kottas, and N. Papanikolopoulos. Impact orientation invariant robot design: an approach to projectile deployed robotic platforms. In *Proc. of the 2006 IEEE International Conference on Robotics and Automation (ICRA 2006)*, pages 2878–2883, May 2006.

[2] ARA Robotic Systems. Pointman [brochure], May 2010. http://www.ara.com/robotics/PDFs/Pointman-Brochure-051010.pdf.

[3] Sam D. Herbert, Andrew Drenner, and Nikolaos Papanikolopoulos. Loper: A quadruped-hybrid stair climbing robot. In *IEEE International Conference on Robotics and Automation (ICRA'2008)*, pages 799–804, 2008.

[4] Alex J Kossett. Design of a transforming robot capable of ground and air locomotion. Senior honors thesis, University of Minnesota, Minneapolis, Minnesota, December 2008.

[5] Alex Kossett, Jesse Purvey, and Nikolaos Papanikolopoulos. More than meets the eye: A hybrid-locomotion robot with rotary flight and wheel modes. In *Proc. of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009.

[6] A. Kossett, R. D'Sa, J. Purvey, and N. Papanikolopoulos. Design of an improved land/air miniature robot. In *Proc. of the 2010 IEEE International Conference on Robotics and Automation (ICRA 2010)*, pages 632–637, May. 2010.

[7] Roger D. Quinn, Gabriel M. Nelson, Richard J. Bachmann, Daniel A. Kingsley, John Offi, and Roy E. Ritzmann. Insect designs for improved robot mobility. In *Proceedings of 4 th Int. Conf. On Climbing and Walking Robots (CLAWAR), From Biology to Industrial Applications, edited by K. Berns and R. Dillmann, Professional Engineering Publishing*, pages 69–76, 2001.

[8] Alexander S. Boxerbaum, Julio Oro, and Roger D. Quinn. Introducing dagsi whegs: The latest generation of whegs robots, featuring a passive-compliant body joint. In *IEEE International Conference on Robotics and Automation (ICRA'2008)*, pages 1783–1784, 2008.

[9] Uluc Saranli, Martin Buehler, and Daniel E. Koditschek. Rhex: A simple and highly mobile hexapod robot. *International Journal of Robotics Research*, 20:616–631, 2001.

[10] A. I. Mourikis, N. Trawny, S. I. Roumeliotis, D. M. Helmick, and L. Matthies. Autonomous stair climbing for tracked vehicles. *International Journal of Robotics Research & International Journal of Computer Vision - Joint Special Issue on Vision and Robotics*, 26(7):737–758, July 2007.

[11] Mirko Kovac, Jean-Christophe Zufferey, and Dario Floreano. Towards the Self Deploying Microglider, a biomimetic jumping and gliding robot. In *4th International Symposium on Adaptive Motion of Animals and Machines*, pages 41–42, 2008.

[12] Mirko Kovac, Martin Fuchs, Andr Guignard, Jean-Christophe Zufferey, and Dario Floreano. A miniature 7g jumping robot. In *IEEE International Conference on Robotics and Automation (ICRA'2008)*, pages 373 – 378, 2008.

[13] Mirko Kovac, Manuel Schlegel, Jean-Christophe Zufferey, and Dario Floreano. A Miniature Jumping Robot with Self-Recovery Capabilities. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 583 – 588, 2009.

[14] Sascha A. Stoeter, Paul E. Rybski, Maria Gini, and Nikolaos Papanikolopoulos. Autonomous stair-hopping with scout robots. In *Proc. of the IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems*, 2002.

[15] Bram Lambrecht, Andrew D. Horchler, and Roger D. Quinn. A small, insect-inspired robot that runs and jumps. In *Proc. of the 2005 IEEE International Conference on Robotics and Automation (ICRA 2005)*, pages 1240–1245. IEEE, 2005.

[16] Hideyuki Tsukagoshi, Yotaro Mori, Masashi Sasaki, Takahiro Tanah, and At0 Kitagawa. Leg-in-rotor-ii: a jumping inspector with high traverse-ability on debris. In *In Proc. of the IEEE Int'l Conf. on Robotics and Automation*, 2004.

[17] Sandia News Releases. Sandia hopping robots to bolster troop capabilities, September 2009. https://share.sandia.gov/news/resources/news_releases/sandia-hopping-robots-to-bolster-troop-capabilities/.

[18] M. J. Spenko, G. C. Haynes, J. A. Saunders, M. R. Cutkosky, A. A. Rizzi, R. J. Full, and D. E. Koditschek. Biologically inspired climbing with a hexapedal robot. *J. Field Robot.*, 25(4-5):223–242, 2008.

[19] Sangbae Kim, Matthew Spenko, Salomon Trujillo, Barrett Heyneman, Virgilio Mattoli, and Mark R. Cutkosky. Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot. In *ICRA*, pages 1268–1273. IEEE, 2007.

[20] Daltorio K.A., Horchler A.D., Gorb S., Ritzmann R.E., and Quinn R.D. A small wall-walking robot with compliant, adhesive feet. In *Int. Conf. on Intelligent Robots and Systems (IROS)*, 2005.

[21] H. Yamada and S. Hirose. Development of practical 3-dimensional active cord mechanism acm-r4. *J. of Robotics and Mechatronics*, 18, 2006.

[22] Brett Hemes, Duc Fehr, and Nikolaos Papanikolopoulos. Motion primitives for a tumbling robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2008.

[23] Mark Yim, Babak Shirmohammadi, Jimmy Sastra, Mike Park, Mike Dugan, and C. J. Taylor. Towards robotic self-reassembly after explosion.

[24] F.J. Boria, R.J. Bachmann, P.G. Ifju, R.D. Quinn, R. Vaidyanathan, C. Perry, and J. Wagener. A sensor platform capable of aerial and terrestrial locomotion. In *Proc of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2005)*, 2005.

[25] K. Peterson and R.S. Fearing. Experimental dynamics of wing assisted running for a bipedal ornithopter. In *Proc. of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 5080–5086, 2011.

[26] K. Peterson, P. Birkmeyer, R. Dudley, and R.S. Fearing. A wing-assisted running robot and implications for avian flight evolution. *Bioinspiration and Biomimetics*.

[27] R C Michelson and S Reece. Update on flapping wing micro air vehicle research: Ongoing work to develop a flapping wing, crawling entomopter. In *In 13th Bristol International RP V Conference*, 1998.

[28] A. Kalantari and M. Spenko. Design and experimental validation of a hybrid aerial and terrestrial robot. In *Proc. of the IEEE International Conference on Robotics and Automation*, 2013.

[29] J. Seddon. *Basic Helicopter Aerodynamics*. BSP Professional Books, 1990.

[30] MicroMo. Micro drive systems, July 2011. http://www.micromo.com/.

[31] Maxon Motor. Maxon motor - driven by precision [online catalog], July 2011. http://www.maxonmotor.com/.

[32] Namiki Jewel Co. Ltd. Dc motors [online catalog], July 2011. http://www.namiki.net/product/dcmotor/index.html.

[33] J. Gordon Leishman. *Principles of Helicopter Aerodynamics*. Cambridge University Press, 2006.

[34] Carnegie Mellon University. Palm pilot robot kit, April 2010. http://www.cs.cmu.edu/ pprk/.

[35] E-Flite Inc. Blade cx2 rtf electric coaxial micro helicopter, November 2008. http://www.e-fliterc.com/Products/Default.aspx?ProdID=EFLH1250.

[36] Bernard Mettler, Jon Andersh, and Nikolaos Papanikolopoulos. A first investigation into the teleoperation of a miniature rotorcraft. In Oussama Khatib, Vijay Kumar, and George J. Pappas, editors, *ISER*, volume 54 of *Springer Tracts in Advanced Robotics*, pages 191–199. Springer, 2008.

Appendix A

Glossary

Care has been taken in this thesis to minimize the use of jargon, but this cannot always be achieved. This appendix defines jargon terms to help the reader.

A.1 Glossary

- **Angle of Attack** – The angle between an airfoil's chord line (line from leading to trailing edge) and the relative direction of the airspeed with respect to the aircraft.
- **Brushless DC Motor** – A motor which utilizes direct current electricity with electronic commutation. Electronic commutation is achieved by switching current in several windings as the rotor turns, such that the magnetic field is correctly aligned with the permanent magnets on the rotor to drive the rotor.
- **Collective Pitch** – The component of a rotor's pitch that is shared with all other rotors, which controls rotor thrust. For fixed-pitch helicopters like the V1 design described in the appendix, the collective pitch remains unchanged, and thrust is controlled by varying the rotor speed.
- **Cyclic Pitch** – The component of a rotor's pitch that changes cyclically. Changes to this component impart pitch or roll adjustments.
- **Flybar** – Also called a stabilizer bar, this is a rod that rotates with a helicopter's rotor, which increases the helicopter's stability. It does this by means of linkages that affect the pitch of the rotor blade. The inertia of the flybar (which has weights on its ends) causes a gyroscopic effect with helps to dampen the effect of stimulus on the rotor.
- **Rotor** – A helicopter's blades, which extend radially from the axis about which they spin. **Main rotors** produce lift. **Tail rotors** counteract the torque created by driving the main

rotor, allowing the helicopter's heading to be controlled. They control yaw by increasing or decreasing their thrust output.

- **Swashplate** – A pair of disks that rotate relative to each another that, in helicopters, translate control inputs from stationary motors to the spinning rotors.

Appendix B

The Hybrid V1 Design

As an initial test of the hybrid wheel/rotorcraft idea, a proof-of-concept prototype, the Hybrid V1, was designed and built. Soon after, a slightly modified version was made to address some issues with the design (V1.1). This appendix briefly describes the design of the robot and the lessons learned from it.

As it was the subject of the author's senior thesis and thus covered extensively therein, only essential aspects of this design are discussed here in order to provide background for the V2 design, and to provide additional evidence for the proposed design principles. For further information, see [4, 5, 6], which cover the design in much more detail than is appropriate here.

B.1 Objectives

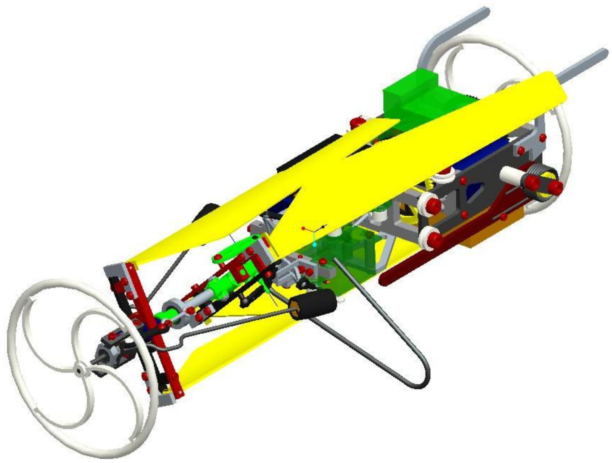
The primary objective of this design was simply to show that it is possible to integrate effective ground and air modes into one robot. Formally, the requirements were that it be capable of:

- Driving on smooth, flat ground (e.g. laminate flooring),
- Transforming into the flight mode, and
- Lifting off of the ground under powered flight.

The secondary objective was to serve as a learning tool for the development of future designs. While it can be verified theoretically that it is possible to create such a robot, such an analysis does not easily reveal at what cost, the actual performance of the robot, or the technical challenges involved in integrating the modes. Over the course of designing and troubleshooting V1 and V1.1, a great deal was learned about what makes an effective hybrid-locomotion robot. These lessons are covered in Chapter 3.

B.2 Design Overview

This section describes the approach to the V1 design, how the robot works, and the design of its main subsystems. CAD renderings of the robot in its ground and flight modes are shown in Figure B.1.



(a) Hybrid V1 in its ground mode.

(b) Hybrid V1 in its flight mode

Figure B.1: Hybrid V1 in its ground and flight modes.

B.2.1 Locomotion Configuration

As discussed in Section 1.2, a variety of possibilities exist for hybrid-locomotion robots. Wheels and rotary-wing flight appear to complement one another for achieving improved mobility, as wheels can have excellent mobility over relatively smooth terrain, and rotary-wing flight can be used to navigate particularly difficult terrain when it's encountered.

There are a number of feasible ways to implement the hybrid rotorcraft/wheeled vehicle concept. The simplest is to take a helicopter and add powered wheels to the landing gear. However, this design has disadvantages - it would be top-heavy in the ground mode, and the rotor blades may impact the environment (or mobility would be limited in an attempt to protect the blades). To alleviate these issues, and to provide a number of other benefits, a transforming system, in which the rotor blades fold down and the robot tips to its side in the ground mode, was selected. Additional configurations are explored in Section 4.3.

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 coplanar.

For the V1 design, a drivetrain configuration with coaxial rotors and wheels driven by the rotor shafts was selected for the following reasons:

- Dual, counter-rotating, coaxial rotors allow the full power output from the drive motors to contribute to lift, and provide more lift than single-rotor designs of the same rotor diameter. 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, 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, for V1 this trade off was considered acceptable. The ground mode is loosely based on the University of Minnesota's Scout robots.

B.2.2 Size

One overarching goal for these robots is to make them as small as possible while remaining useful to an end user for more than just entertainment. There is, however, a lower limit to how small they can be which comes from limitations of the flight mode. Primarily this is due to the difficulty that smaller rotorcraft have handling moderate breezes outdoors or even drafts indoors. Technological advances are likely to push this limit lower, but currently the designs presented in this thesis appear to be as small as they practically can be, given the selected rotor configurations.

The most basic requirement that a user may require is a live video feed; indeed, this was the primary sensor mode envisioned for this robot. Larger air vehicles can carry more capable sensors and are influenced less by air currents, which means a video feed from a larger vehicle would have fewer vibrations and other undesired movements. On the other hand, the robot should be able to operate indoors. This puts an absolute limit on rotor size; the width of a door frame is approximately 800 mm. A more realistic limit is much lower than that to provide a margin for error in the rotorcraft's movement.

Components available off-the-shelf also put limits on robot size if custom actuator and rotor designs are to be avoided. Standalone RC servos reach a minimum size around 8g in mass and about 6cm^3 in volume, hobby brushless motors bottom out at around 8g, and rotor diameters of 4-channel helicopters (one each for thrust, yaw, pitch, and roll, which is best for controllability) are typically in the 350mm range. With these limits in mind, this design was based on the Blade CX2 from E-Flite [35], which has a total mass of 227g and a rotor diameter of 345 mm.

Table B.1 shows the dimensions and mass of the both V1 and V1.1. Compared to the Blade CX2, the rotor diameter was increased to make room for the folding hinge. The mass increases considerably due to the added hardware; fortunately, the helicopter drivetrain had a thrust limit of roughly 450g.

Wheel diameter is dictated by the size of the chassis required to hold all of the parts; in this case, a 76mm wheel was capable of fully surrounding the structure. Wheel spacing is dictated by the rotor blade length and, for this coaxial design, the spacing between the two rotors.

B.2.3 Robot Operation

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

Metric	Hybrid V1	Hybrid V1.1
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	301 g	318 g

Table B.1: Hybrid V1 physical specifications folded in against the robot's body and disengaged from the motors. In order to transition to flight mode, it must undergo a transformation involving two mechanisms which turn the robot up on its side and engage the rotors with the motors. The rotors, which are hinged near the shaft, then passively unfold from the body of the robot as they start spinning.

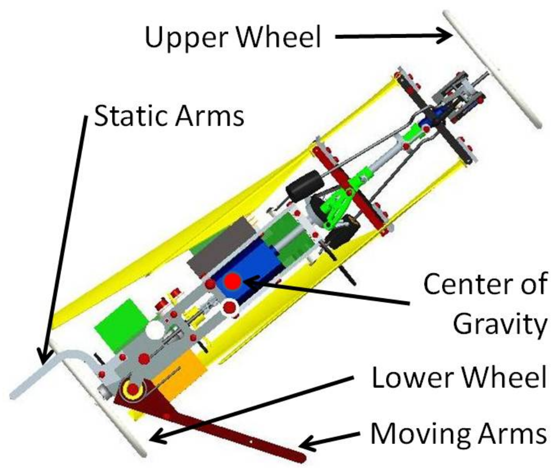


Figure B.2: Hybrid V1 in the middle of its uprighting action.

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 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). This torque is provided by friction between the landing gear and the ground.

In flight, the robot is controlled like most other coaxial-rotor 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 in turn controlled by two servo motors. A stabilizer bar linked to the upper rotor helps maintain stability and reject disturbances in pitch and roll.

To transition back to the ground mode, the process is reversed. The robot lands, spins down its rotor blades (lower rotor first), orients the rotors correctly, disengages the rotor drivetrain, and turns back to its ground orientation.

B.2.4 Orientation Adjustment Mechanism and Landing Gear

In the V1 design, the orientation adjustment mechanism consisted of a set of fixed arms and a set of arms that pivoted on the body (Figure B.2). The pivoting arms would contact the ground, effecting a torque on the robot body to tilt it up. This torque was provided by a torsion spring at the arm hinge (Figure B.3). The moving arms were on the bottom of the robot (in the ground mode), while the fixed arms were on the top of the robot and provided two more contact points when the robot was fully upright. An elastic band was suspended across the ends of the moving arms to hold the rotors against the body in the ground mode (see Figure B.7).

In the V1.1 design, operation was nearly identical, but another member was added that pivoted on the end of the moving arms and slid on the ends of the fixed arms (Figure B.4). Another member was fixed to the end of the moving arms, perpendicular to them (visible in Figure B.8). These member served to greatly increase the support polygon of the landing gear, improving stability (Figure B.5). The latter member replaced the elastic band for rotor containment purposes. Since it was rigid, it contained the rotors better than the band (more on this in Section B.2.6).

B.2.5 Rotor Transmission

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 described in this section.

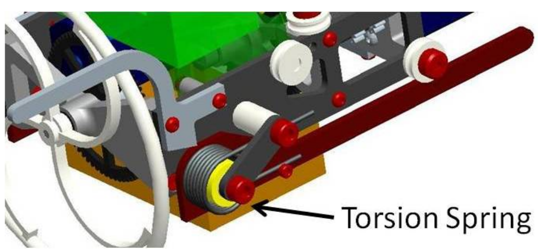


Figure B.3: A close-up view of one of the orientation adjustment arms in Hybrid V1 in their retracted position. Arm retraction cable not shown.

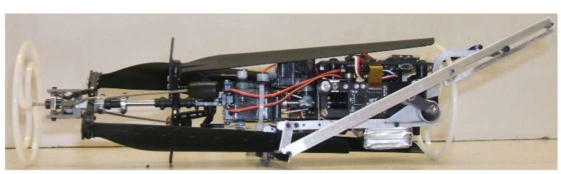


Figure B.4: Front view of Hybrid V1.1 in its ground mode, illustrating the new landing gear mechanism in its folded state.

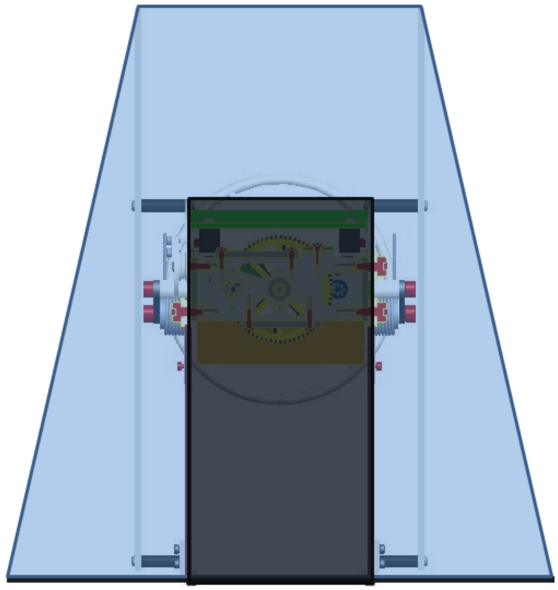
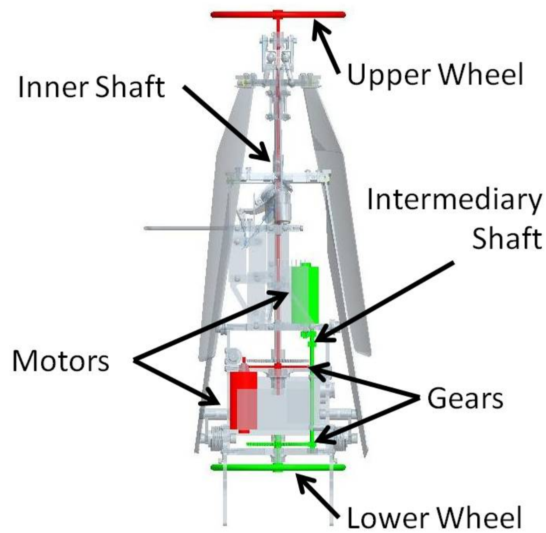


Figure B.5: The landing gear support polygon for Hybrid V1. The darker shading shows the original polygon (in V1), while the lighter shading shows the polygon with the expanded landing gear (in V1.1).

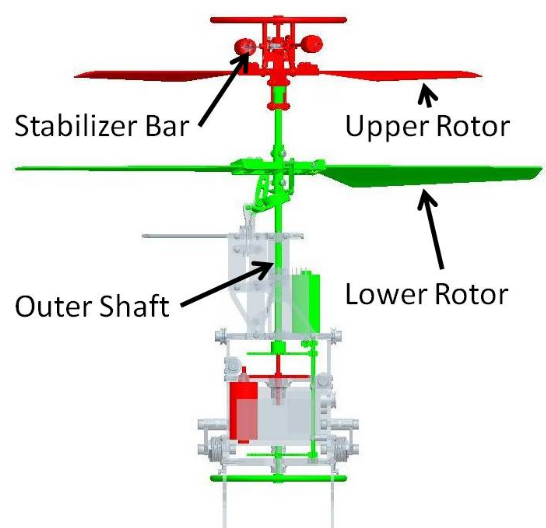
To drive the lower rotor, the motor drives an intermediary shaft, which in turn drives the lower wheel and the lower rotor's shaft (also called the outer shaft). The outer shaft is a hollow tube, through which runs the upper rotor's shaft (inner shaft). The outer shaft is supported by radial ball bearings, constrained axially only by a servo motor, which can shift the shaft axially as desired to engage or disengage the outer shaft's gear with its pinion. The transition can be seen in Figure B.6.

The upper rotor's motor is permanently coupled to the inner shaft via a gear pair. However, the upper rotor idles 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.



(a) Ground mode.



(b) Flight mode

Figure B.6: Views of Hybrid V1'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.

B.2.6 Rotor Containment

The V1 design, with only an elastic band suspended between the moving arms to catch rotors, suffered from a significant design fault: the rotors were not contained sufficiently in the ground mode, so they would typically drag on the ground (this lack of containment is shown in Figure B.7). This is in direct opposition to the design principle of protecting flight mode components described in Chapter 3. The moving arms did not extend far enough from the robot to "catch" the rotors in the transition from flight to ground mode.

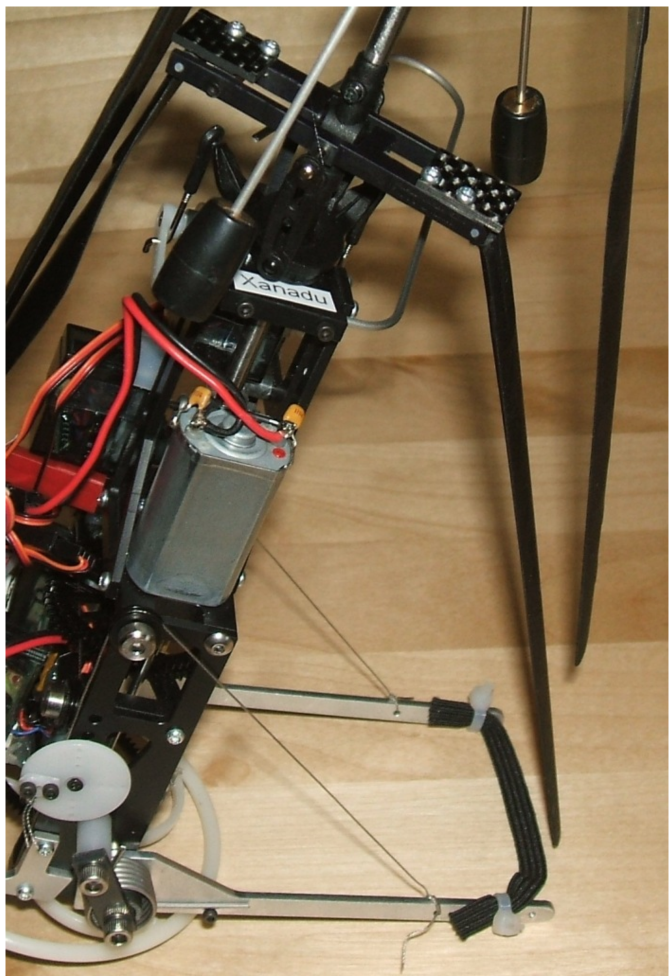


Figure B.7: Rotors escaping their containment mechanism during the air-to-ground transition in the V1 prototype.

This was corrected in the V1.1 design by preventing the rotors from rotating freely when transforming into the ground mode. When the robot is upright, a hook attached to the lower rotor catches the upper rotor when it is driven backwards. This holds the upper rotor close to the robot's body, which in turn keeps the lower rotor from unfolding (Figure B.8). These parts work in conjunction with a containment bar attached to the retractable arms. Once the robot has tilted over far enough, the rotors are within reach of the containment bar, which holds them closely against the body for the duration of the robot's time in its ground mode.

B.2.7 Avionics and Electronics

Off-the-shelf RC components designed for helicopters only drive brushless motors in one direction, and are therefore not suited to perform the air-to-ground transformation. To address this, and to provide improved control capabilities, 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 custom 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,

Figure B.8: A prototype of Hybrid V1.1 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.

motion controllers can be implemented.

The board was also designed to be used with a Gumstix Overo Fire computer-on-module, which could be used in place of the receiver in a more advanced setup, communicating with the microcontroller over an SPI bus. The Overo would enable wireless communication over WiFi or Bluetooth. A camera was wired to feed video to the Overo, which has enough processing power to perform simple vision processing and/or stream the video to a remote system. Eventually, the robot could be integrated into the system described in [36] for control augmentation and/or to be used as an experimental platform.

This system was never fully implemented due to technical difficulties, time constraints, and the fact that it contributed little to the goals of the project.

B.3 Design Evaluation

While this design met its objectives, it did not surpass them; the design suffered from a number issues that ultimately made it ineffective.

Chief among these issues was poor performance in the ground mode, where it had very poor controllability and easily got stuck on its environment. Indeed, as will be elaborated on in Chapter 3, the ground mode is of primary importance for this type of robot, and this design falls far short of where it should be.

In addition, the robot wasted a great deal of power in the ground mode (though it still lasted much longer than in the flight mode). This came from the design of the orientation adjustment mechanism, which required that a motor hold its position against the torsion spring. The power necessary to do this was 40% of the robot's power draw at the peak power state, and a significantly larger share when not moving or communicating.

Testing consisted of a brief set of tests: battery life in flight and ground modes, top forward speed on the ground, and the scalable step height. Results are shown in Table B.2. A further set of tests would better characterize the flight mode performance and other parameters, but this set was considered sufficient to show that the design met its objectives.

Table B.2: Hybrid V1 Performance

Metric	**Value**
Ground-mode battery life	52 minutes
Air-mode battery life	5 minutes
Ground-mode forward speed	1.58 m/s
Scalable step height (running start)	1.5 cm

As stated above, a further exploration of the design and performance of the V1 design can be found in [4, 5, 6].