Gamera IID: Expanding the Flight Envelope of Human Powered Helicopters

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ABSTRACT

The UMD *Gamera II* has significantly expanded the flight envelope of human powered helicopters. *Gamera IIXR*, a modified version of *Gamera II*, has performed separate flights reaching an altitude of over 2.75 meters and durations of over 60 seconds. These milestones have been achieved by systematic, incremental improvements in the aerodynamic, structural, and power transmission design of the helicopter. Improvements were developed in response to identified needs from flight test experience and were evaluated against both aerodynamic efficiency and vehicle weight. Flight testing of *Gamera IID*, an upgraded version of the craft with pilot controls, has demonstrated effective pitch and roll control as well as yaw stability.

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BACKGROUND

While human powered airplanes have flown since the 1960s, human powered helicopters have seen more limited success. To date, only six human powered helicopters have flown: *Da Vinci III, Yuri I, Gamera I, Gamera II, Upturn* and *Atlas* [2], with the last four vehicles having all been developed and flown since 2011. The longest human powered airplanes flights have lasted hours, while human powered helicopters fly for only seconds. The yardstick against which human powered helicopters are measured is the American Helicopter Society (AHS) Sikorsky Prize, which sets a goal of a 60 second flight during which the aircraft must reach 3 m (9.8 ft) altitude and remain within a 10 m (33 ft) box. No human powered helicopter has yet achieved this goal.

Prior to *Gamera IIXR*, some degree of success had been experienced with the endurance goal. After *Da Vinci III* became the first human powered helicopter to hover for any period of time in 1989, its 8 second flight record was broken when *Yuri I* hovered slightly above the ground for almost 20 seconds in 1994 [1]. This record stood for over 16 years. The *Gamera* project began at the University of Maryland in 2008. After three years of development and experimentation, *Gamera I* made its first flight in 2011.

Gamera I featured a quad rotor configuration and a string driven transmission in which string is spooled off from pulleys mounted on top of each rotor to a central pilot pulley. The quad rotor design allowed the rotors to be oriented very close to the ground for maximum ground effect and is much more stable than a single rotor configuration [2]. With a 110 lb female pilot, *Gamera I* completed a maximum flight of 11 seconds and a maximum altitude of just inches.

The successful flight of *Gamera I* led to the continuation of the project with a new aircraft, *Gamera II*. *Gamera II* was designed with the primary goal of completing a 60 second flight. Expanding upon many of the innovations used in *Gamera I* and using a similar configuration, the new vehicle was designed to be 15.4 kg (34 lb) lighter while accommodating heavier and more powerful pilots with weights up to 68 kg (150 lb). A new tapered blade design allowed the blade spars to be much more structurally efficient, reducing weight and increasing stiffness. In addition the structure was created entirely out of custom made micro trusses, which have a much higher strength to weight ratio than the carbon tubes used in *Gamera I*. For a complete description of the design of *Gamera II*, see Ref. [1].

TESTING SUMMARY

Gamera II was completed and ready for flight testing in the summer of 2012. Initial flight testing done in a 35 x 61 m

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Presented at the AHS 69th Annual Forum, Phoenix, Arizona, May 21–23, 2013.

Figure 1. Flight testing of *Gamera IIXR* in August 2012.

(115 x 200 ft) gymnasium in the Reckord Armory on the University of Maryland campus showed a dramatic increase in performance over *Gamera I*. A maximum flight time of 49.9 seconds was recorded and verified by the National Aeronautic Association (NAA) in the first round of flight testing. The record was FAI certified in class I-E experimental human powered aircraft. Altitude testing was performed separately, and a maximum height of about 1.2 m (4 ft) was reached. Despite the improvement over *Gamera I*, it was determined that the power required was still too high, and further modifications had to be made in order to achieve the 60 second goal.

After *Gamera II* testing, substantial modifications were made to improve performance and the resulting aircraft was renamed *Gamera IIXR*. The major changes included an increased rotor radius, modifications to the airframe, a new cockpit, and modified blade profile and planform. The changes made in *Gamera IIXR* are discussed in depth throughout this paper.

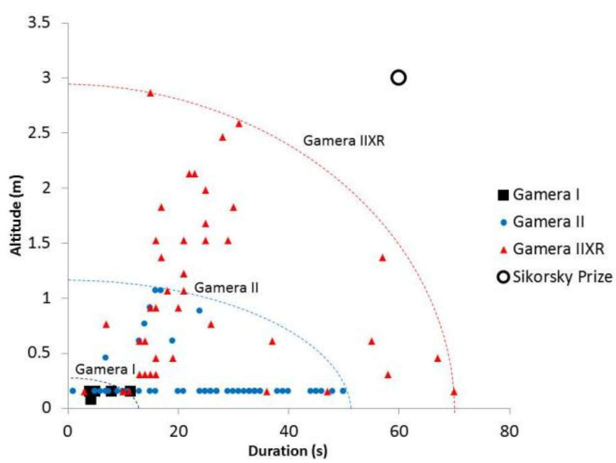

Figure 2. Expansion of the Flight envelope of *Gamera* Human Powered Helicopters.

Gamera IIXR was initially tested in August of 2012 in the University of Maryland Comcast Center. Substantial performance increases over *Gamera II* were recorded, including a 70 second tethered flight. Later that month, the vehicle was tested in the Prince George's Sports and Learning Complex in Landover, Maryland. The venue offered a much larger space of 72 x 99 m (235 x 324 ft), which reduced the risk of damage due to drift. The 60 second duration portion of the Sikorsky Prize was completed with a 65 second free flight. In addition, altitude testing resulted in a maximum height of 2.75 m, nearly reaching the 3 meter goal (Figure 1). Figure 2 outlines the expansion of the flight envelope for the different versions of *Gamera*.

The significant amounts of vehicle drift seen in the flight testing of *Gamera IIXR* demonstrated a need for a control system on the vehicle. There were further dynamic instabilities associated with blade imbalances. After several iterations, a more stable, controlled version of the vehicle has been developed, called *Gamera IID*. An RPM control system was implemented as well as a teetering hub with pitch-flap coupling.

Flight testing in early 2013 of *Gamera IID* resulted in several successful controlled flights including a 55 second flight while remaining in a 10 m (33 ft) box. A major dynamic stability issue associated with blade imbalance was solved through the implementation of a teetering hub. Currently the design is being improved to further reduce the power required by creating a more efficient transmission and control system.

AERODYNAMICS AND AIRFRAME

Blade Extensions

The extended blade radius introduced in *Gamera IIXR* was a primary reason for its substantial increase in performance compared with *Gamera II*. By increasing the rotor radius from 6.5 m (21.3 ft) to 7.2 m (23.6 ft), while adding only 2.3 kg (5 lb) of additional structural weight, the disc loading was decreased from 1.752 N/m^2 (0.0369 lb/ft^2)

to 1.467 N/m^2 (0.0309 lb/ft^2). Low disk loading is a key to an efficient human power helicopter due to limits of a human pilot. Basic helicopter momentum theory indicates that power loading (thrust per unit power) is directly proportional to the square root of disk loading, which is shown in the equation:

$$\frac{P}{T} = \sqrt{\frac{T}{2\rho A}}$$

where T/A is disk loading and P/T is power loading and ρ represents air density [3]. Based on this simple analysis, the 16% decrease in disk loading achieved by increasing the rotor area should result in a 5.8% reduction of power requirement.

In addition to deceasing disk loading, extending the radius of the blades further reduces the power required in hover by effectively putting the vehicle deeper in ground effect. Ground effect is the tendency of helicopters flying close to the ground to a have a reduction of induced power due to the wake interaction with the ground [3], and it is a key to achieve sustained flight in a human powered helicopter. Ground effect is quantified by the normalized rotor height z/R, where z is altitude and R is rotor radius. Every *Gamera* vehicle operates in deep ground effect, meaning that z/R is less than 0.5. Most conventional helicopters cannot experience deep ground effect because of the configuration of the rotor above the craft. *Gamera IIXR* however, is designed to place the rotors as close to the ground as possible. The extension of the radius for *Gamera IIXR* would decrease the normalized rotor height z/R from about 0.154 to 0.138 at a hovering altitude of 1 m (3.2 ft). The theory behind the exact power decrease that can be expected from this decrease in z/R is largely based on empirical data from experiments. Schmaus [4] provides a polynomial approximation of the power coefficient and ground effect scaling factor as:

$$C_P = k_G k\,\lambda C_T + C_{P0}$$

$$k_G = -.157\left(\frac{z}{R}\right)^4 + 0.932\left(\frac{z}{R}\right)^3 - 2.068\left(\frac{z}{R}\right)^2 + 2.090\left(\frac{z}{R}\right) + .146$$

where k_G and k are inflow scaling factors, λ is inflow, C_T is the thrust coefficient, and C_{P0} is the profile power coefficient. Using this formula indicates that a 5.5% reduction in power can be expected from the change in normalized rotor height at one meter for the blade extensions. A blade element momentum theory (BEMT) model described in Gilad [5] had been previously developed to estimate the power required by *Gamera* vehicles. The model includes the effects of flexible blades as well as spanwise variation in blade properties and references airfoil tables for lift and drag data. This model showed that the increase in rotor radius would result in a net 10% decrease in total power, accounting for the additional structural weight.

Aerodynamic testing was done using the Blade Balancing Rig (BBR), seen in Figure 3. The BBR is a hover stand originally designed to test the performance of *Gamera I* blades, and was modified to test *Gamera II* blades. The BBR is powered by a 370 W (0.5 hp) electric motor and uses four scales to determine rotor thrust and moment. A National Instruments DAQ box connected to a LabVIEW program collects and processes data from the BBR sensors. A hall effect sensor on the test stand is used to collect RPM data, while a torque cell on the shaft measures rotor torque. The pitch of each of the blades is controlled individually by a stepper motor, while an inclinometer senses the blade pitch. Data is collected at a rate of 1000 Hz in 30 second intervals for an individual test. The samples are averaged over the thirty second tests to get the thrust, moment, torque and RPM. Using the stepper motors, the rotor is trimmed to minimize the hub moments.

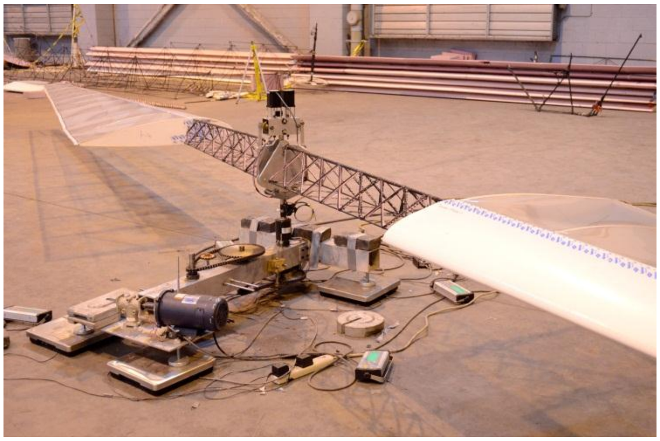

Figure 3. Blade balancing rig (BBR).

The initial blade extension tested had continuous taper and airfoil shape, to extend the radius to 7.2 m (23.6 ft.) Collective sweeps were performed at various RPMs to determine the ideal operating speed. At the operating thrust of 240 N (55 lb), it was determined that 20 RPM was optimal for hover as can be seen in Figure 4. The results showed an 11.5% decrease in power after accounting for the additional weight added by the rotor extensions and the necessary airframe changes.

A longer 8.2 m radius blade was tested in addition to the 7.2 m extended blade. BEMT results indicated a possible 5% power reduction. During testing it was found that tip deflections were very high under maximum load due to the increased bending loads throughout the blade. As a result, it was not possible to reach the predicted power which resulted in the decision to use the 7.2 m radius as opposed to the 8.2 m.

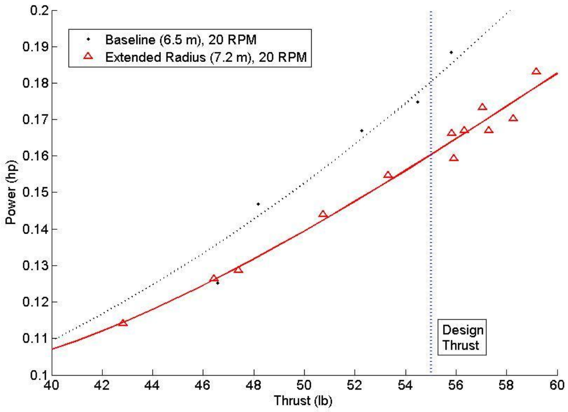

Figure 4. Blade extension testing.

Blade Tip Improvements

In addition to the radius increase, a more robust construction method was used for the outer portion of the blade. Initially, the construction of the blade was uniform from the root to the tip, using a foam leading edge and balsa reinforced foam ribs on the trailing edge. The entire blade was covered with a Mylar skin. During initial testing of *Gamera IIXR*, it was discovered that the skin of the outboard portion of the blade was expanding due to centrifugal pumping of air inside of the mostly hollow blade. This expansion had the effect of altering the shape of the airfoil (Figure 5). To maintain the airfoil shape at the outboard section, a new technique was developed, which used a solid foam section for the outer 1.2 m (4 ft) of the rotor, with a chordwise cutout in the trailing edge. The solid foam was reinforced with inlayed carbon tubes and demonstrated strength in bending comparable to that of the original construction. The new method eliminated issues of ballooning near the tip, which increased the efficiency of the blades as well as increasing the consistency from blade to blade.

Figure 5. Evidence of centrifugal pumping within spinning rotor blade.

Previous optimization studies had shown that adding variations such as bi-linear taper and varying airfoils could improve efficiency, but these more complex geometry blades were avoided to reduce the construction time. The switch to solid foam construction for the outboard section created an opportunity to easily modify the airfoil section and taper, since a CNC foam cutter could be used to create any linear variation in the blade section. As a result, the extension portion could be optimized for taper and airfoil shape. The properties of the outermost section of the blade were chosen using a genetic optimization algorithm and a BEMT code to maximize efficiency of the blade. The result was a SD7037 airfoil at the tip with a taper ratio of 3:1 from 90 % radius to the tip (Figure 6). This section was made to blend into the S8037 airfoil used for the primary portion of the blade. The BEMT code indicated a 2% reduction in power from this optimization study.

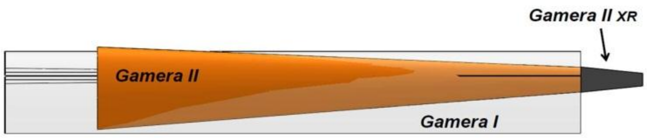

Figure 6: Gamera IIXR Blade Extension

One of the main reasons for the initial selection of the S8037 airfoil was its relatively large thickness ratio of 16%. Using a thick airfoil allowed for a taller and therefore more structurally efficient spar [1]. For the blade extension, the new construction technique eliminated the need to accommodate a large spar, so the 9% thick SD7037 airfoil became the preferred choice for the tip section because of the reduction in drag. Testing of the new tip section on the BBR verified the performance benefits of modifying the airfoil section of the tip. A 3.5% reduction in power was found compared to a baseline configuration, which used the same airfoil shape throughout.

Airframe

In order to prevent the extended blades from colliding with each other, it was necessary to modify the airframe of *Gamera II*. Although intermeshing the blades was considered, it was avoided due to the difficulty in syncing the blades and the later incorporation of the RPM control system. To prevent the paths of adjacent rotors from crossing, each truss arm would need to be extended 1 m for a 0.7 m blade extension.

The *Gamera II* airframe was constructed primarily of 3 cm (1 in.) tall micro-trusses, which have a much better strength to weight ratio than the commercially available carbon tubes used previously in *Gamera I* [1]. A truss code was written in MATLAB to predict the stresses in individual members of the airframe. The deflection predicted by the truss code at flight loads can be seen in Figure 7.

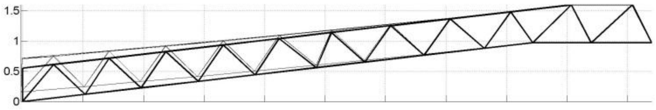

Figure 7. Deflection of *Gamera IID* airframe truss arm under operating thrust.

Gamera II had been designed for a pilot weighing up to 68 kg (150 lb.) With the extension of the trusses, the bending moment near the center of the aircraft was increased. This necessitated a reduction in the rated pilot weight from 68 kg (150 lb) to 63.5 kg (140 lb.) This reduction in load rating was deemed acceptable because many of the pilots were under the new weight limit. The total weight of the extension to the airframe was only 0.9 kg (2 lb). Successful flight tests were performed with *Gamera IIXR* using the de-rated airframe. Every time the aircraft was assembled for flight testing, the truss was proof loaded up to (68 kg) 150 lb to verify its integrity and ensure a safety factor.

For *Gamera IID*, a rebuild of the center section of the airframe resulted in an ability to accommodate pilots of up to 72.6 kg (160 lb). The additional strength came at a price of only 60 additional grams of structural weight due to the use of heavier micro-trusses. Although current plans are to fly with the same pilots, the additional strength in the structure is desired in order to maintain greater factor of safety in high altitude flight.

Weight to Power Conversion

Components of all *Gamera* aircraft were designed with the goal of minimizing total power required to fly. Many of the dynamic components in the transmission, as well as the control system added in *Gamera IID*, draw power directly, either through friction or from electrical power generated by the pilot. In order to optimize the design for these components, it became necessary to have a means of comparing weight and power.

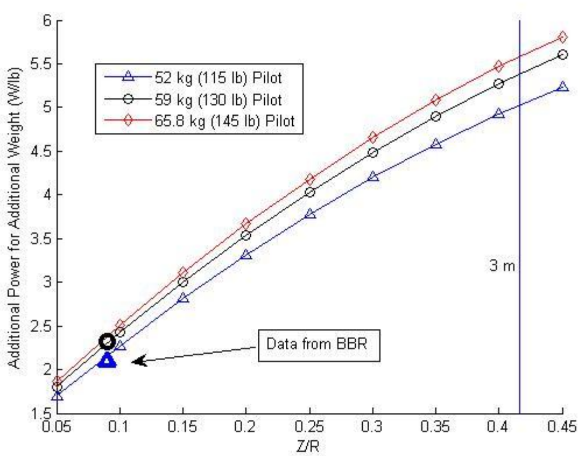

Figure 8. Weight to power conversion for 41 kg (90 lb) baseline vehicle.

In some cases, it became advantageous to use a heavier component which had less power draw. An example discussed in the following section is the flywheel. The weight to power conversion was essential in order to obtain a net effective power for the component.

The conversion was done using the same BEMT code described earlier. The conversion factor was affected by several factors, including pilot weight, total vehicle weight, and altitude. The conversion factor gave an estimated power increase for a given increase in total weight, which is equivalent to the slope of the power vs. thrust curve at a given flight condition. Results from BEMT and experimental data can be seen in Figure 8.

ROTOR HUB

Rigid Hub

Gamera II was originally designed with a fixed pitch, rigid hub. The hub was designed to be lightweight and allow for pitch adjustments between flights. A significant amount of the time during flight testing was spent making careful pitch adjustments to control blade tracking and vehicle trim. Due to the configuration of the blades under the airframe it is possible for a rotor blade to strike the truss arm if not properly tracked. In the *Gamera IIXR* configuration, a blade flap of greater than 5° would result in a collision with the airframe. At least two catastrophic failures of the airframe were a direct result of this type of collision.

In addition to the risk of blade strikes, an unbalanced rotor also results in a 1/rev variation in lift direction which can affect vehicle dynamics and fatigue the structure. The 1/rev change in the lift vector of each rotor also had the effect of coupling with the vehicle yaw motion to create a dynamic instability. For more information on the vehicle dynamics see and the yaw-flap instability in Ref. [6].

Using the rigid hub in *Gamera II* and *Gamera IIXR*, both blade tracking and rotor thrust were controlled by carefully adjusting the blade pitches between flights. Pre-coning of the blades could be adjusted by adjusting the connection point at the bottom of each spar. The BBR was used to adjust the tracking and thrust of the rotor before flight tests. By recording the rotating frame moments on the shaft, the blade imbalance could be quantified. For flights of *Gamera IIXR*, blades were balanced on the BBR at a close approximation to flight conditions, with the hub height at 1 m (42 in), and a rotational speed of 20 RPM.

It was found to be a difficult task to achieve good blade tracking by adjusting the root pitch. Differences in the torsional stiffness of the spars as well as slight variations in the manufacturing of the airfoil gave each blade a unique, nonlinear lift curve. A pair of blades could be balanced for one flight condition, but not necessarily for all flight conditions. Blade pairs with similar properties were chosen to increase the range over which they were well balanced. Figure 9 shows the balance of the blades against rotor thrust (fixed pitch, varying RPM). It can be seen that for three different pairings of blades, the moment of the blades vs.

thrust is highly variable, with some sets of blades pairing better than others. In Figure 9, the blades were balanced for a minimum moment at the design target, but become became unbalanced away from the design target. Some blades showed too much of a moment imbalance to be paired with any others and could not be used for flight testing.

Gamera IIXR used a stiffer rotor shaft to mitigate the issue of blade imbalance by reacting against the truss. The landing gear was also extended to allow for more negative precone, increasing the clearance between the blades and the airframe. Despite these changes, even after careful blade tracking, large imbalances in blades were sometimes observed during flight testing due to the yaw-flap coupling. As a result, blades could become more unbalanced throughout the flight. Activating the RPM control system, described later, exacerbated the instability, which led to failures as a result of blades striking the airframe.

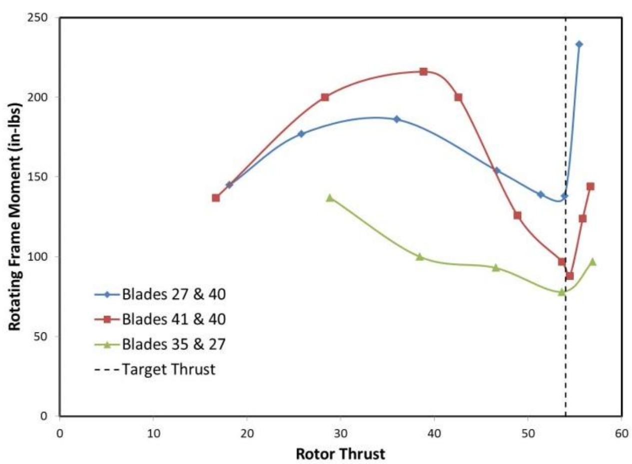

Figure 9. Rotating Frame blade balance moment.

Teetering Hub

A lightweight teetering hub with a large positive pitch-flap coupling hinge was implemented *Gamera IID*. By coupling flap up with pitch down, the lift on a blade which is flapped up is reduced, while the lift on the opposite blade is increased. The hinge effectively results in equal amounts of lift on each blade, while driving the blade tracking towards an equilibrium position. The hinge dramatically improves the process of blade balancing while eliminating the yaw instability.

The concept of pitch flap coupling is frequently used in helicopter main rotors and tail rotors to reduce flap excursions and modify the natural flap frequency [7]. There are several ways of introducing a pitch flap coupling. One of the most common ways is to skew the flap hinge. The amount of coupling is given by the arctangent of the hinge angle (δ_3).

In the development of the teetering hinge two different positive δ_3 angles were tested. Hinge angles of 45° and 56° were chosen for a 1:1 and 2:3 ratio of flap to feathering. Since cyclic control is not used, large angles were chosen to minimize flap excursions.

Initially a prototype hinge was developed to test on the BBR. The shaft was hinged halfway between the top and bottom of the spar. Hover stand testing of the hub revealed that the blades rapidly approached an equilibrium state when spinning up from rest and when perturbed by an external force. Both the 45° and 56° hinges showed good balancing characteristics. It was discovered that blade tracking could be adjusted independently from blade pitches, by simply adjusting the precone angle of each blade. In sharp contrast to the sensitivity of the blade tracking on the rigid hub, small changes in individual blade pitch had no visible effect on blade tracking. As a result, thrust of the entire rotor could be adjusted by modifying just one of the blade pitches without impacting blade tracking.

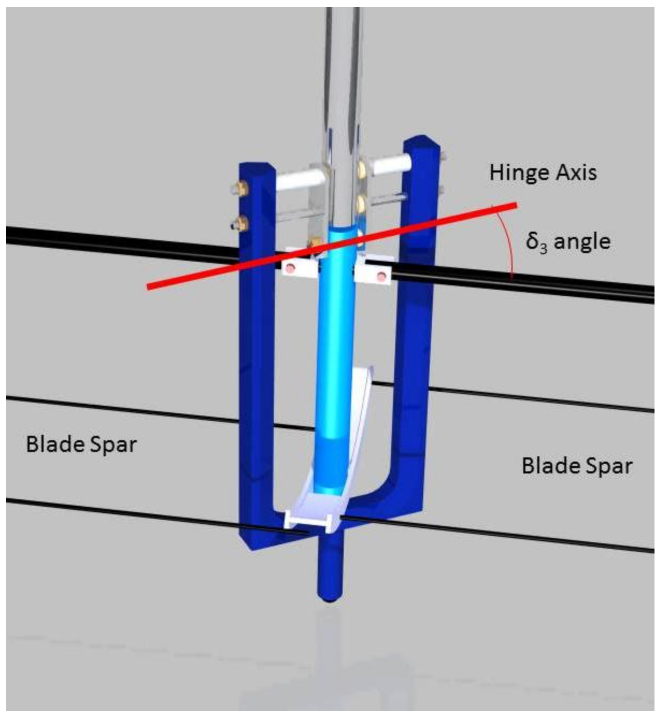

Figure 10. Teetering hub implementation on vehicle.

Testing also indicated that there was no loss of efficiency due to the teetering hub. While challenging to quantify, the elimination of vehicle yaw motion is predicted to result in an overall reduction of power required. By eliminating bending loads in the shaft from blade imbalance, a lighter weight shaft was able to be used.

The teetering hub was implemented using the 56° hinge angle. The hinge location was also moved vertically to just above the top of the spar. The vertical location of the hinge did not appear to have an effect on the stability of the blades in flight, and allowed the weight of the hinge to be reduced. The final flight configuration of the hinge and hub can be seen in Figure 10. The figure shows three tubes from each side of the hub representing the end condition of each of the blade spars. The structure that surrounds the shaft is the landing gear, which prevents the teetering shaft from touching the ground. A sleeve bearing was used with two plastic axial bearings to allow the shaft to teeter during flight.

COCKPIT AND TRANSMISSION

Tests performed for *Gamera I* design demonstrated that increased power is available from utilizing both pilot legs and arms [2]. Like *Gamera I*, the *Gamera II* cockpit featured pedals as well as hand cranks to utilize maximum pilot power. The *Gamera II* cockpit was designed with greater consideration for pilot ergonomics to allow optimal transfer of power to the vehicle.

Cockpit Ergonomics

After testing of *Gamera II*, a new cockpit was constructed based on pilot testimony of comfort and power transmission as well as the advice of a biomechanics expert. Consulting with a biometrics expert revealed the need to optimize various angles of the pilot's body at different points in the pedal stroke. The most critical of these angles were the angle between the pilot's back and the bottom member of the cockpit, the angle at maximum extension between the upper and lower leg, and the angle at maximum extension between the upper and lower arm. The leg angle (145°) and arm angle (150°) were incorporated into the cockpit design such that each of the pilots would be able to approximate these angles throughout the cycle.

Due to structural limitations of the helicopter, the ideal back angle of 120° was too large to be implemented. The primary reason that a larger angle is desirable for the back is to allow full lung capacity during aerobic exercise. Since the Sikorsky Prize flight profile requires predominantly anaerobic performance by the pilot, it was determined that a deviation from the ideal back angle would be acceptable, since it would not inhibit maximum power over short time periods. A 93° back angle is used in the *Gamera IIXR* cockpit, and is considered an acceptable compromise between structural considerations and pilot comfort.

Gaining full use of the arm muscles required that the hands be brought closer to the pilot's chest, as previous elbow angles had been observed to be close to 175°. In order to test the new configuration before constructing the cockpit, a pilot sizing jig was constructed that positioned the pilot's seat, foot pedals and hand cranks. Once these measurements were verified and checked for clearance during the pedaling motion, the design was finalized to be the average measurements between the different pilots. It was found that this average deviated only marginally from any one of the pilots' preferred configurations. Figure 11 shows the final configuration of the *Gamera IIXR* cockpit.

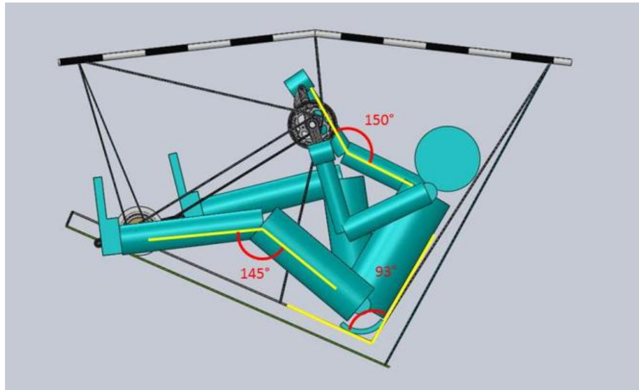

Figure 11. Pilot ergonomics in *Gamera IIXR* cockpit.

Flywheel

Due to the nature of the pedaling motion, it is not feasible for pilots to deliver the same amount of power throughout the entire stroke. Phasing the hand and foot power strokes 90° from each other helps with the power distribution, but still does not enable a completely smooth transmission of power. In *Gamera I* flight testing, it became clear that poor power transmission to the rotors was hurting the overall performance.

Gamera II utilized a flywheel to allow for smoother power transmission from the pilot to the vehicle. The flywheel was designed to store the energy equivalent to one third of a pilot pedal stroke. The original inertia of the flywheel was 0.020 kg·m^2, and it was designed to rotate at 800 RPM when in a low hover. Pilots reported that despite the substantial increase in smoothness over *Gamera I*, there were still some noticeable discontinuities in power transmission.

In *Gamera IIXR*, the weight of the flywheel rim was increased by 150 grams to increase the flywheel inertia to 0.028 kg·m^2. Combined with other changes in the transmission, such as the chain described in the following section, the result was a much smoother transmission of power.

The flywheel used in *Gamera IIXR* had been designed primarily for weight minimization. This resulted in a large radius and high rotational speed. Despite its light weight, direct testing of aerodynamic drag indicated in a large power loss due to the flywheel. For *Gamera IID*, a new flywheel was been designed to optimize the total power required by the pilot, using the weight to power conversion described earlier. The new flywheel requires a net total power expenditure of about 6 W accounting for weight, about half of what was previously being used at a low hover RPM.

Whereas the previous flywheel was over 2.5 cm (1 in.) in width, the new flywheel is constructed of 0.32 cm (0.13 in.) steel to reduce the rim thickness and therefore reduce the drag on the flywheel.

Drive Chain

In *Gamera II*, a three-sprocket chain system was used to connect the flywheel, hand cranks and foot pedals. Throughout most of the pedal stroke the power is transferred directly from the feet to the spool, with the flywheel taking additional power. At any “dead zones” in the stroke, power is transmitted from the flywheel to the spool. This results in cyclic loads on the chain.

Gamera II used a plastic-steel hybrid chain for the transmission, which was chosen as the lightest weight option with reasonable stiffness. In initial testing of *Gamera II* however, pilots reported a substantial discontinuity in power transmission. This was attributed primarily to deflections in the chain which came as a result of the changing load paths.

In *Gamera IIXR* the plastic-steel hybrid chain was replaced by an entirely steel chain. The stiffness of the steel chain was 10 times greater than the previous chain, and added only 80 additional grams of weight. To help offset the weight penalty as a result of the steel chain, the chain tensioning system was modified to reduce weight. The original aluminum parts were replaced with carbon fiber and balsa structures. Despite the slight increase in weight from the steel chain, the pilots reported a feeling of increased efficiency and authority over the system. The steel chain prevented losses due to strain energy in the chain, thereby increasing the ability of the pilots to deliver their maximum effort.

CONTROL SYSTEM

The Sikorsky Prize requires that in addition to the performance requirements, the drift of the aircraft must be limited such that a point on the aircraft remains within a 10 m (33 ft) square. Despite careful trimming of rotors, testing of *Gamera IIXR* indicated that it is extremely difficult to obtain this stability goal without an active control system. Typically, flights of previous non-controlled versions of *Gamera II* were cut short by vehicle drift, rather than pilot fatigue. Even long, relatively stable flights drifted up to 30 m (100 ft). Initial attempts at controlling the craft were made by having the pilot lean in the desired direction of motion during flight testing of *Gamera II*. This resulted in some anecdotal success but with limited repeatability.

CG Control System

The first attempt at an installed vehicle control system was made in later testing of *Gamera IIXR*. A system was implemented that moved small weights along the length of the truss arms of the vehicle with electric motors. It was hoped that some level of vehicle control could be achieved as a result of these masses changing the location of the center of gravity (CG) of the helicopter. Shifting the CG location on a quadrotor changes the moment arm at which each thrust vector from the rotors is being applied. If all thrusts remain the same as before the CG shift, this induces a control moment on the helicopter.

During flight testing, a team member on the ground controlled the system using a wireless remote control. While using a remote controlled system to actuate the controls of the helicopter violates the rules of the Sikorsky Prize, this method was valid for determining the overall effectiveness of the control system.

The CG shifting control system was tested using various control masses. While initial predictions had indicated that 100 g (0.22 lb) masses on each truss arm would provide adequate control authority, flight testing showed that the minimum mass per arm required to establish even marginal control authority was 400 g (0.88 lb). Combined with the electronics, motor and other hardware required, this resulted in a total control system weight of 2.3 kg (5.1 lb). It was determined that the mass required for sufficient control authority would be too large to make the CG shifting system a feasible option for Sikorsky Prize attempts.

RPM Control System

After the CG control system proved to be infeasible during flight testing, a rotor RPM control system was conceived. Changing the RPM of different rotors in a quadrotor configuration is a standard control method employed by small radio controlled (RC) quadrotors. By changing the thrusts of individual fixed pitch rotors, control moments of pitch and roll can be easily induced. This is a simple prospect for a RC quadrotor, which typically has each rotor mounted to its own motor [8]. However, for a vehicle like *Gamera IIXR* where each of the rotors is run by the same mechanical transmission, direct control over rotor RPM is less straightforward.

To implement this control method, a system was installed which involved changing the string path of each of the four drive strings to wrap around two additional pulleys. An example of the new string path can be seen in Figure 12. By moving one of the pulleys during the flight, the amount of string spooling from a rotor could be increased or reduced. The moving pulley is referred to as the floating pulley.

Coupling the floating pulleys of two opposing rotors with a string reduces the required force to move the pulley. Without coupling, the maximum control force would be on the order of two times the flight string tension for a total of 711 N (160 lb). With coupling, the maximum control force required was measured to be about 15 lbs. Linking opposing rotors also eliminates a yaw coupling with pitch and roll, by keeping a relatively constant overall rotor torque during actuation. The coupling string was moved through the use of an electric motor. As a result, a single motor could provide attitude control about one horizontal axis. Thus, only two motors are required to control both pitch and roll on *Gamera IID*.

The motors are powered by a generator connected to the transmission, thereby maintaining the fully human powered nature of the vehicle. Actuation of the controls is done by the pilot via switches inserted into the hand grips. The signals from these switches were fed to an onboard Arduino microcontroller, which is also powered by the generator. This Arduino controls the speed of the motors via speed controllers. The pilot is only able to control the vehicle in four directions (left, right, fore, aft) with a step input in each direction. The amount of control is a result of the amount of time of actuation.

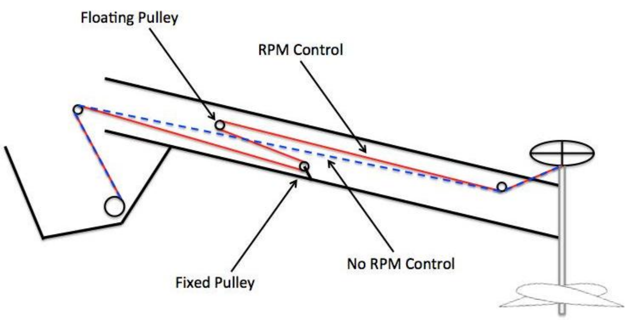

Figure 12. RPM control system string path.

Initial testing of the RPM control system was performed in ground testing. The vehicle was placed on scales, and control moments were measured as a result of weight shifting on the scales. Parts of the vehicle were weighed down to prevent it from lifting off of the scales. Changes in RPM were recorded from video of each of the rotors and can be seen in Figure 13. The vertical lines represent the times at which controls were actuated by the pilot. It can be seen that an RPM differential of over 0.5 RPM was possible with this configuration.

After successfully demonstrating sufficient control authority over the rotor RPM in ground testing, the system was implemented on the vehicle. The first round of flight testing resulted in limited success of the control system due to issues with vehicle yaw instability and blade imbalance. Despite these issues, the vehicle responded to controls and was able to change direction multiple times in response to controls.

Using the rigid hub, the RPM control system had the effect of worsening any blade imbalance to unacceptable levels. *Gamera IID* incorporated the teetering hub with the RPM control system to result in a stable and controllable design. During several flights the total drift was controlled to remain within the 10 m box requirement of the Sikorsky Prize.

The total power draw of the control system varies with pilot pedaling RPM and control activation. The sources of power draw include the frictional losses in the generator, electrical power required for the logic board and speed controllers, and the electrical power required for the motor activation. The efficiency of the generator was tested and found to be about 50%. The total net control system power is estimated to be about 16 W, with the weight to power conversion factor described earlier at a z/R of 0.05.

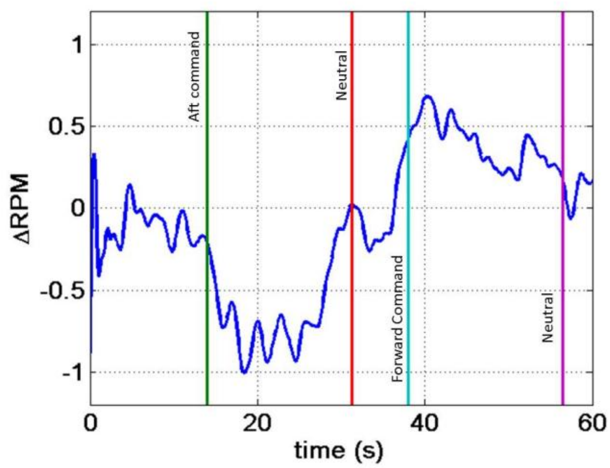

Figure 13. RPM differential between forward and aft rotor.

In future testing, plans have made to eliminate the need for the speed controllers and Arduino board through the use of a double pole double throw switch. By eliminating the power draw from the Arduino board and speed controllers, as well as the weight of the components, it is estimated that the power draw of the control system during a state of no control input can be reduced from 16 W to 4 W, accounting for weight.

CLIMB PROFILE

Following an optimized climb profile is essential to minimizing the power required to accomplish the Sikorsky Prize. To develop the optimal profile, as well as project the total pilot energy expenditure, a dynamic vehicle model was used [6]. The model uses 6-degree of freedom dynamics and a Pitt-Peters dynamic inflow model, as well as a ground effect factor for inflow calculation. For a given set of input parameters, the model trims the collective of the rotors at a baseline hover altitude.

Using the dynamic vehicle model, various climb profiles were modeled to determine total pilot energy required. First the altitude modeling was verified by comparing to data from a high altitude flight test. The RPM and altitude data were obtained from flight videos. The rotor RPM from the flight was then approximated in the model as the pilot input. As shown in Figure 14, very good agreement was found between predicted vehicle response that was seen during the flight test.

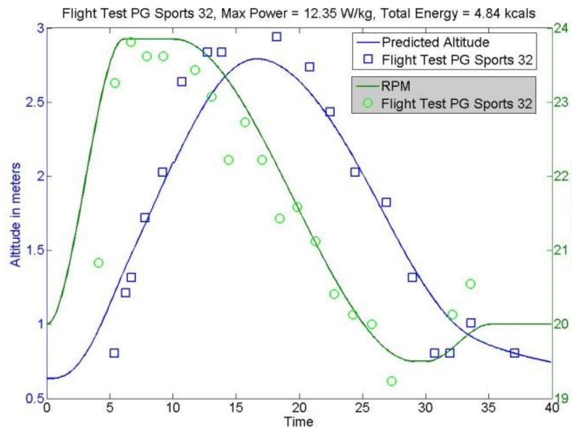

Figure 14. Vehicle projected climb and experimental data.

Once the dynamic model had been verified with the flight data, it was then used to find the optimal climb profile. Parameters to be minimized were total energy and peak power in two separate optimizations. Penalty functions were used to ensure that the maximum height was at least 3 m and that the minimum height was no less than the baseline hover height.

An RPM profile was created, with various parameters that could be changed during the optimization. The climb RPM (maximum RPM) and descent RPM (minimum RPM) could be varied within limits. Additionally, the time of climb, time of descent, and transition times could be modified. The prescribed RPM profile can be seen in Figure 15.

For a total energy minimization the flight profile was found to be as is shown in Figure 16. The total energy is minimized by remaining close to the ground for as long as possible. This means that the optimizer will choose the maximum possible climb rpm, and then descend as quickly as possible. In this climb profile, the maximum power is 14.42 W/kg and the total energy is 6.26 kcals.

For minimization of peak power, the optimum profile is a slow steady climb for the entire flight, as in Figure 17. The climb profile was constrained so that the maximum altitude of 3 meters was reached 50 seconds into the flight. This climb profile results in a much lower maximum power, at 11.37 W/kg, however this power must be maintained for almost the entire duration of the flight. The result is a much higher total energy expenditure of 8.74 kcals.

During high altitude testing, the total energy minimization profile was followed. Pilots were not able to sustain the high power required for the slow climb profile. Although the peak power is greater for a faster climb, the rest period that follows it allows the pilots to recover slightly before holding a low hover for the rest of the flight. In order to take full advantage of the rest on the descent phase, the climb is performed at the beginning of the flight.

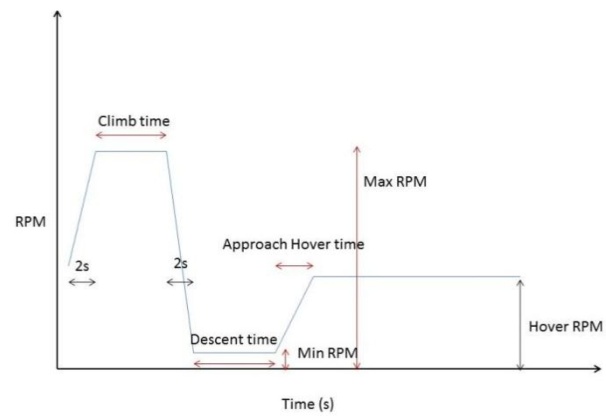

Figure 15: Sikorsky Prize prescibed rotor RPM profile

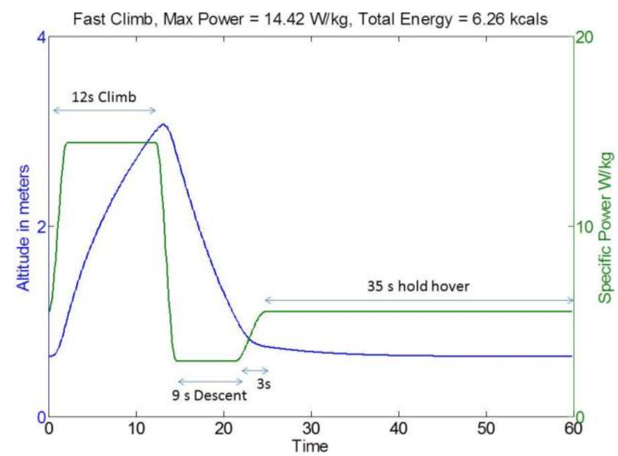

Figure 16. Rotor RPM profile to minimum total energy expenditure (fast climb profile).

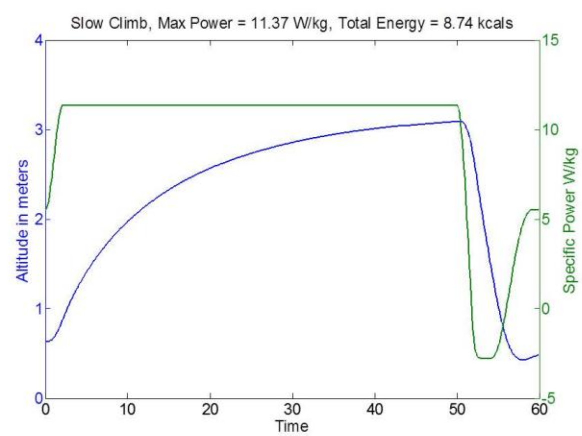

Figure 17. Rotor RPM profile to minimumize the maximum power output (slow climb profile).

PILOT POWER

The primary challenge of building a human powered helicopter comes from the limitations of the human body as an engine. It is important to have an understanding of the performance potential of the human body in order to take full advantage of it. A total of 6 pilots have flown *Gamera IIXR* and *Gamera IID*. Testing of these pilots on a machine similar in configuration to the cockpit has shown that pilots can deliver about 14 W/kg bodyweight for up to 10 seconds and about 8 W/kg for 60 seconds.

Throughout the *Gamera* project, pilot training and evaluation has evolved. Initially, the focus was on endurance only; pilots were evaluated in their ability to maintain a power above a set limit for as long as possible. After initial success with the duration aspect of the Sikorsky Prize, training was changed to more closely match the expected power requirements of climb profile required.

Flight testing and modeling of pilot power gave a more realistic estimate of what power the pilots would have to generate in order to achieve the Sikorsky Prize. This led to the development of a Sikorsky profile test that became an integral part of the pilots' training and evaluation.

The Sikorsky Profile test is a one minute long exercise in which the pilot begins with a high RPM ramp-up, holds this rate for a brief period of time, and then speed to 90 RPM, which is held for as long as possible. The pilot RPM profile, shown in Figure 18, corresponds to the high power climb and the lower power hover phase. The resting descent period (minimum RPM) is removed to push the pilots beyond the expected power, for training purposes.

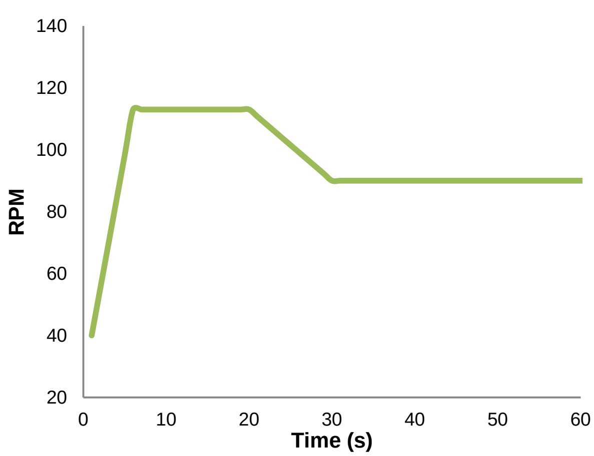

Figure 18. Sikorsky profile test, pilot pedaling RPM.

Figure 19 shows the pilot power available over different lengths of time. Pilots can generate a much greater amount of power over a short period of time and less over a long period of time. As demonstrated in the previous section, the ideal climb profile for the Sikorsky Prize requires an initial climb phase of about 12 seconds, followed by a 12 second descent phase and ending with a 30 second hover phase. Since step changes are not possible, there is also 6 seconds of time for transition between phases.

Based on the pilot power available and the power required it is clear that each part of the climb profile is possible individually. Figure 19 shows that the three main phases of the profile are within pilot power available. However, it is unclear what effect on the pilot combining these phases will have. It is hoped that the pilot will be able to recover sufficiently during the descent phase to perform the remainder of the 60-second flight.

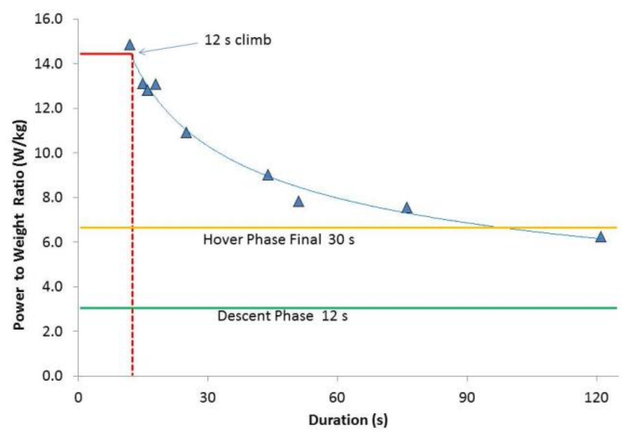

Figure 19. Average pilot power available vs. duration.

FLIGHT TESTING PROCEDURE

Flight testing of a human powered helicopter presents many challenges. The power plant is a human who can become fatigued throughout a day of testing, resulting in a reduction of power available. For maximum time efficiency during flight testing, it becomes necessary to use multiple pilots, rotating them throughout the day to allow time for recovery.

Vehicle Trim

Prior to flight testing, rotors are trimmed individually on the BBR, which can be modified to use the actual flight hub. The flight hub does not incorporate active pitch control, so the pitch of each blade is adjusted manually between rotor tests. Once the blade pitches are set for a rotor to achieve the correct thrust with minimal blade imbalance, the flight hub is removed and attached to the vehicle, leaving the pitch settings in the same position. For single rotor trim of the *Gamera IID*, the target thrust is 240 N (55 lb), determined as the vehicle empty weight plus the approximate weight of the pilot, divided by four.

After the rotors are trimmed individually on the BBR and attached to the vehicle, low RPM tests are performed with all four rotors spinning. This is done to validate the transmission and the attachment of the rotors. Once all four rotors have been validated at low speed, short 10 second flights are performed in which the pilot is instructed to maintain an altitude of about 0.3 m (1 ft).

After each test, the magnitude and direction of drift is noted and corrections are made by adjusting the blade pitch. Generally the adjustments to pitch are on the order of 0.25° - 0.5°. If the vehicle drifts forward, the drift can be mitigated by either increasing the pitch of the blades on the front rotor, or by decreasing the pitch of the blades on the back rotor. The decision or whether to increase or decrease a rotor collective was made based on yaw considerations. Although generally a secondary consideration, yaw can be reduced by decreasing the collective of a rotor which spins in the opposite direction as the vehicle yaw, or raising the collective of a rotor which spins in the same direction.

In *Gamera IIXR* testing, the blade balance and tracking was carefully adjusted through subtle pitch changes to individual blades. This resulted in a trim process in which adjusting the collective of a rotor as little as 1/8° could throw off the blade tracking. In *Gamera IID* testing, the blade tracking is adjusted by setting the precone of the blades.

Uncontrolled Flight

Without flight controls, the vehicle was trimmed to consistently drift within acceptable limits. Following trim tests, longer duration tests could be performed to validate the performance of the vehicle. Tests are performed with a pilot coach near the center of the craft to assist the pilot and give instructions. At each rotor, a team member holds the rotor until takeoff, to ensure tension on the drive strings. Any slack in the drive string could result in a string becoming misaligned from the rotor pulley.

Due to the lack of digital telemetry it is necessary to coordinate several people to record flight data using synced video cameras. This is done for test data and official verification for flight records. For each flight attempt, separate cameras are pointed at each landing gear to get an accurate time of liftoff and touchdown. For higher altitude testing, an additional camera is used to verify the maximum altitude against reference features on the opposite side of the vehicle.

A primary issue during endurance testing was drift of the craft during long flights. The large space available at the PG Sportsplex venue reduced the risk of a blade striking a wall. Despite the larger space, the longest flight (65 s) achieved by pilot Colin Gore was terminated due to excessive drift rather than pilot fatigue.

During endurance testing of the *Gamera IIXR*, pilots tended to hover at higher altitudes than with previous versions. According to pilots, an altitude of approximately 0.5 meters felt more comfortable than hovering just above the ground, despite the decreased ground effect. This had the added benefit of reducing the risk of one of the landing gear accidentally touching the ground during the flight test.

Pilots found with *Gamera IIXR* they could climb to higher altitudes, however, with increased altitude came decreased stability. Ascent to high altitudes was found to be very stable, but upon descent there was a tendency for the craft to pitch or roll, causing an acceleration of the drift. Out of 6 flights greater than 2 meters, two resulted in crashes that were caused by out of control drift upon descent.

Controlled Flight

In controlled flight testing of *Gamera IID* performed in early 2013, the vehicle was trimmed in a similar manner to uncontrolled *Gamera IIXR* testing. Although control was available, the vehicle was trimmed to minimize the required control inputs to reduce pilot workload and minimize control system power draw.

Once the vehicle is trimmed to remain within acceptable drift limits, controlled flights can be performed. To minimize pilot workload, two spotters are used to call out direction. One spotter watches the craft in the pitch axis and the other watches in the roll axis. The relay of information from spotter to pilot was improved with practice to result in a vehicle response time of about 1 second from command to movement. Control inputs are used conservatively, as pilot induced oscillations were encountered with too much control input.

After the vehicle had successfully performed controlled flights at low altitudes, higher altitude flights were attempted. A maximum altitude of about 1.8 m (6 ft) was reached using the control system. With further power reductions from flywheel optimization and control system efficiency improvements, it is hoped that the target altitude may be reachable in the future.

CONCLUDING REMARKS

Prior to the development of *Gamera II*, the longest flight of a human powered helicopter was about 20 seconds. Building upon previous designs and using new enabling technologies has allowed *Gamera IIXR* to set a new flight record that is over 3 times longer than the previous record. At the time of flight, the altitudes reached by *Gamera IIXR* were more than 3 times higher than any other recorded by a human powered helicopter. With the added stability and control capability of *Gamera IID*, the aircraft may be able to satisfy the drift requirements of the Sikorsky Prize. Although there are still advances to be made, *Gamera* is on the brink of accomplishing what was once thought to be nearly impossible.

Throughout the process of development and testing of *Gamera IID* the following conclusions have been made:

1. The flight envelope of human powered helicopters has been significantly expanded. Flights durations of 60 s and altitudes of 2.75 m (9 ft) are now possible.

2. Control is critical in longer duration flights, to avoid obstacles and satisfy the requirements of the AHS Sikorsky Prize.

3. Stable, controlled flight of a human powered helicopter has been achieved through the use of an RPM control system and a teetering hub with pitch-flap coupling.

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REFERENCES

[1]Berry, B., Bowen-Davies, G., Gluesenkamp, K., Kaler, Z., Schmaus, J., Staruk, W., Weiner, E., Woods, B., "Design Optimization of *Gamera II*: a Human Powered Helicopter," 68th Annual Forum of the American Helicopter Society, Fort Worth, TX, May 2012.

[2]Schmaus, J., Berry, B., Bowen-Davies, G., Bush, B., Friedman, C., Gilad, M., Sridharan, A., Staruk, W., Woods, B., "Design and Development of *Gamera*: A Human Powered Helicopter from the University of Maryland," American Helicopter Society Future Vertical Lift Aircraft Design Conference, San Francisco, CA, January 2012.

[3]Leishman, J. G., *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, NY, 2008.

[4]Schmaus, J., Berry, B., Gross, W., Koliais, P., "Experimental Study of Rotor Performance in Deep Ground Effect with Application to a Human-Powered Helicopter," 68th Annual Forum of the American Helicopter Society, Fort Worth, TX, May 2012.

[5]Gilad, M., "Evaluation of Flexible Rotor Hover Performance in Extreme Ground Effect," University of Maryland, College Park, MD, 2011.

[6]Staruk, W., Schmaus, J., Sridharan, A.,Karcher, C., "Control and Stability Characteristics of *Gamera II:* A Human Powered Helicopter, " 69th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 2013.

[7]Johnson, W., *Helciopter Theory*, Dover Publications Inc., New York, NY, 1980.

[8]Hoffman, G.M, and Tomlin, C. J., "Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment," AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head, SC, 2007