Control and Stability Characteristics of *Gamera II*: A Human Powered Helicopter

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ABSTRACT

In the pursuit of the AHS Sikorsky Prize, a team of students from the University of Maryland have built and flown the human powered helicopter *Gamera IIXR*. Having achieved flights of over 60 seconds and approaching 3 m in altitude, the team has been focusing on stability and control. Three primary stability issues have been identified: translational drift, coupled yaw-flap oscillations, and long period forward pitch behavior. Methods for alleviating these issues include: (1) an active control system that varies rotor RPM, and (2) a teetering rotor hub in conjunction with pitch-flap (δ_3) coupling. Both of these techniques have been successfully implemented on the latest vehicle, *Gamera IID*.

NOTATION

A	= disc area, m^2 (ft^2)
C_T	= thrust coefficient
D_{RP}	= diameter of rotor drive pulley, m (ft)
h	= vertical center of gravity position, m (ft)
$I_{xx,yy}$	= vehicle roll, pitch moment of inertia, kg·m^2 (lb·ft^2)
I_{zz}	= vehicle yaw moment of inertia, kg·m^2 (lb·ft^2)
l	= truss arm length, m (ft)
$\overline{M}_\beta$	= Non-dimensional aerodynamic flap moment
R	= rotor radius, m (ft)
r	= vehicle yaw rate, rad/s
T	= thrust, N (lb)
u	= in-plane translational velocity, m/s (ft/s)
V_A	= linear velocity of RPM control pulley, m/s (ft/s)
V_∞	= aircraft translational velocity, m/s (ft/s)
β	= flap angle, rad
δ_3	= pitch-flap coupling ratio angle, rad
γ	= Lock number
υ_β	= non-dimensional flap frequency, /rev
ρ	= air density, kg/m^3 (lb/ft^3)
σ	= solidity
θ_0	= blade root pitch, rad
ψ	= rotor azimuth, rad
Ω	= rotor speed, rad/s

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INTRODUCTION

The AHS Igor I. Sikorsky Human Powered Helicopter Competition was established in 1980 to foster the development of human powered rotorcraft. The prize, currently $250,000 sponsored by the Sikorsky Aircraft Corporation, requires a hover for 60 seconds and momentarily reaching an altitude of at least 3 m (9.8 ft) without leaving a 10 m (32.8 ft) square box using solely human power [1]. Team Gamera from the University of Maryland, composed of graduate and undergraduate student volunteers, has been working strenuously to accomplish this milestone since the fall of 2008. Two helicopters have been developed and flown, *Gamera I* and *Gamera II*, both quadrotor designs described in detail by Schmaus et al. [2] and Berry et al. [3].

In August of 2012 a modified version of the second helicopter, *Gamera IIXR*, hovered for 65 seconds at low altitude. In a separate flight, the vehicle reached a maximum altitude of over 2.75 m (9 ft). With improvements in structural, aerodynamic, and power transmission efficiency and regimented pilot training, it is believed that a combined flight of 60 seconds plus 3 m altitude might be possible. However, the third requirement of the prize, staying within a 10 m (32.8 ft) box, has proven to be extremely challenging. Neither *Gamera I* nor *Gamera II* was designed with a control system, and in dozens of flight tests significant drifting of the vehicle was observed. Careful trimming of the helicopter by adjusting the thrust from the four rotors has been demonstrated to mitigate drift, but not eliminate it entirely.

Prior analysis of the stability characteristics of human powered helicopters has been performed by Totah and Patterson [4], Bruce et al. [5], Hawkins [6], and Brown [7].

Three stability issues have been observed during flight testing of the *Gamera* human powered helicopters. First is a translational instability, leading to large amounts of drift in response to a perturbation. Second is a yaw-flap oscillation; imbalance in the rotor blades can cause the entire vehicle to experience unstable yawing oscillations which have been observed to lead to structural failures and blades striking the airframe. Third is a long period pitch forward behavior (Figure 1), a tendency for the helicopter to pitch, and therefore drift, forward throughout a flight, in spite vehicle trim.

This paper explores each of these instabilities and discusses the techniques considered to overcome them. For this purpose, an active control system and a new rotor hub design were developed and implemented on the latest aircraft, *Gamera IID*.

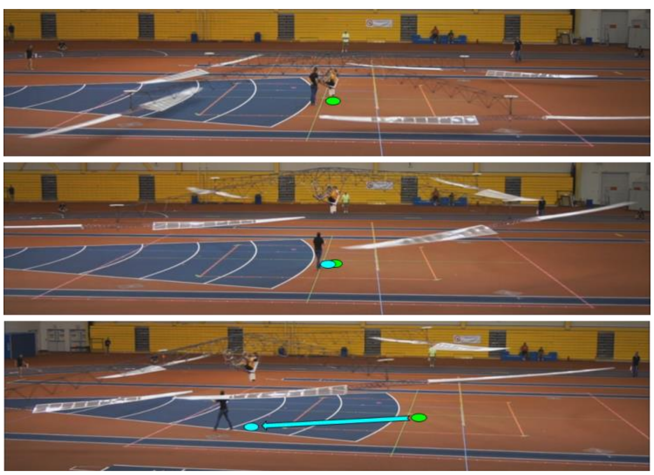


Figure 1. Images of a high altitude flight attempt at 1, 9, and 17 seconds of flight, with markers for starting and current position, show almost 10 m (0.75 rotor diameters) of forward drift.

VEHICLE CHARACTERISTICS

Gamera I and *Gamera II* are both quadrotor helicopters, with two blades on each 13 m (40.6 ft) diameter rotor. After testing in the summer of 2012, the rotors of *Gamera II* were extended in radius to 7.2 m (23.6 ft) and the modified vehicle was named *Gamera IIXR* (Figure 2). With the addition of a modified hub and an active control system, the current iteration of the helicopter is named *Gamera IID*. Table 1 presents relevant vehicle parameters for the various helicopter versions. To maximize ground effect, and thereby improve aerodynamic efficiency, the rotors are placed close to the ground, below the level of the cockpit. Since the pilot weighs in at about 150 % of the empty weight of *Gamera IIXR*, the center of gravity (CG) of the helicopter is above the rotor hubs.

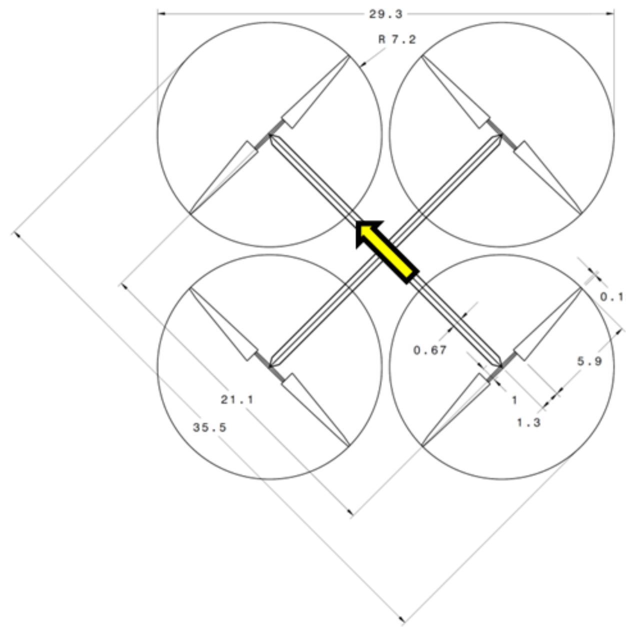


Figure 2. Schematic of *Gamera IIXR*, dimensions in meters. Superimposed arrow shows pilot facing forward.

Table 1. Properties of the *Gamera* HPHs.

	Gamera I	*Gamera II*	*Gamera IIXR*	*Gamera IID*
Mass (kg) [Empty]	48.7	32.3	38.6	42
Mass (kg) [With Pilot]	97.2	95.9	93.6	97
R (m)	6.5	6.5	7.2	7.2
A (m^2)	531	531	651	651
σ	0.098	0.036	0.037	0.037
γ	270	240	360	360
$I_{xx,yy}$ (kg·m^2)	1800	1300	1500	1500
I_{zz} (kg·m^2)	3500	2600	3000	3000
ν_β	3.2	2.9	2.4	8.3

Quadrotor dynamics is primarily affected by fuselage roll, pitch, and yaw attitudes. Pitch and roll moments are generated by imbalances in thrust among the four rotors. The effects of tip path plane tilt with respect to the rotor hubs have a small effect on the vehicle attitude, in contrast to single main rotor helicopters where the effect of blade flapping is significant. Since the blades are relatively rigid in flap and lag, the rotor thrust vectors are aligned approximately with the vehicle vertical axis. As the vehicle pitches and rolls, the components of thrust parallel to the ground plane induce accelerations, building up velocities over time [8]. Efforts to minimize drift for the *Gamera* quadrotors are therefore best served by controlling vehicle attitude.

TRANSLATIONAL DRIFT

During multiple flight tests of *Gamera I*, *Gamera II*, and *Gamera IIXR*, a slow but consistent translational drift motion was observed. A linearized time-invariant model was obtained from a flight dynamics simulation to predict drift and understand vehicle stability characteristics. A small perturbation (due to wind gusts or rotor imbalance) induces vehicle pitch, roll, or yaw, thus tilting the thrust vectors away from a vertical orientation, causing drift to build up.

The vehicles were tested indoors to minimize the influence of external disturbances. Despite this, asymmetries due to variation in rotor blade construction, shaft alignments, truss weight and stiffness, rotor drive pulley ratios, and pilot seating are sufficient to induce enough pitch or roll for significant lateral or longitudinal drift to occur (10 – 15 m over 60 seconds].

HPH Dynamics Modeling

Further analytical investigations were carried out to determine which physical parameters could be modified to mitigate drift during flight and hence avoid the weight, as well as the complexity, associated with an active control system. To this end, an HPH quadrotor flight dynamics analysis was developed.

The vehicle, with a rotor mounted at the end of each of its four truss arms and the cockpit at the center, is modeled as a rigid body with 6 degrees of freedom (3 translations and 3 rotations). The rotor blades are considered rigid since the blades are stiff in flap in order to maximize ground effect. The lag and torsion stiffness values were experimentally determined to be large enough to be treated as rigid as well. Given the relatively small deflections observed, the effect of blade motion relative to the hub on the vehicle flight dynamics is small and therefore neglected. A Pitt-Peters dynamic inflow model is used for each rotor, and coupled to an in-house experiment-based ground effect model [9].

Based on the flight profile of *Gamera II*, the simulation proceeds in three phases: trim, linearization, and time integration.

Trim: The governing ordinary differential equations (ODEs) for the vehicle rigid-body motion and dynamic inflow are converted into algebraic equations, which are solved iteratively using a non-linear equation solver. For a given hover altitude and rotor speed, collective pitch settings and vehicle pitch and roll attitudes are obtained by enforcing force and moment balance for the vehicle and the inflow ratios corresponding to the steady-state solution of the dynamic inflow equations with a ground-effect correction.

Linearization: A linearized dynamical model is obtained for the vehicle, which is valid for small excursions from the trim state. For this linearized model, marginally stable (and unstable) modes are identified. This serves as a good "early warning" for the onset of instabilities, and additionally as a method to obtain roots loci with different vehicle parameters (e.g. CG position, shaft tilt angles).

Time integration: This section of the program simulates a general unsteady flight condition, required for drift predictions during climb and descent. The governing equations of motion are numerically integrated with an ODE solver from an initial condition (in this case, the trim state).

The speed of the rotors is assumed to change according to a set profile based on observations made during flight tests. The initial rotor speed, 20 RPM, is chosen as the trim value near the ground, then is increased over a short time to 24 RPM, which is maintained for a fixed amount of time during which the helicopter climbs vertically. Finally, the rotor spins down to 20 RPM over 10-15 seconds, settling back to a low height. As the RPM changes for fixed collective pitch, the positions and orientations of the vehicle are tracked through the system states.

Center of Gravity Placement

One option to limit drift was to modify the placement of the center of gravity of the vehicle. The HPH dynamics analysis revealed that drifting behavior was sensitive to longitudinal and lateral offsets of vehicle CG. Due to the high concentration of mass in the pilot, slight misalignment of the cockpit could cause the center of gravity to shift a noticeable amount. Having several different pilots with varying weights and heights exacerbated the problem, as the CG position would change from flight to flight depending on who was flying. Measurements taken by putting scales under each of the four rotors showed that the center of gravity was frequently aft of the vehicle's geometric center by as much as 5 cm (2 in.). Attempts were made to use small trimming masses to adjust the CG back to the center of the vehicle. Although the masses were small, they were placed at the end of the 10.55 m (34.6 ft) structural arms of the airframe, giving sufficient moment arm for the CG to be adjusted by over 5 cm. While adjusting the CG helped reduce drift, it did not eliminate the phenomenon entirely.

Analysis indicated that the primary source of drift instability was the high position of the center of gravity of the vehicle relative to the rotor hubs. A lateral perturbation results in drag on the low rotors, generating a pitching moment on the vehicle in the direction of motion. Lowering the CG of the vehicle would therefore improve stability, but would require positioning the pilot below the rotor plane. This would entail making the vehicle taller and hanging the cockpit lower to the ground. The increase in rotor height would present an increase in power required due to the loss of ground effect, so much so that the possibility was eliminated from consideration.

Tetrahedral

Similar to dihedral on an airplane, the idea of tetrahedral is to cant the rotor shafts towards the center of the helicopter, which introduces passive stabilization for a quadrotor configuration. A simple interpretation of the scheme is presented in Figure 3. As the vehicle begins to drift in a particular direction, the rotor leading the vehicle experiences an up-wash and the opposing rotor a down-wash. The resulting force differential creates a restoring moment, thus decreasing total drift when compared to a baseline vehicle with zero shaft tilt.

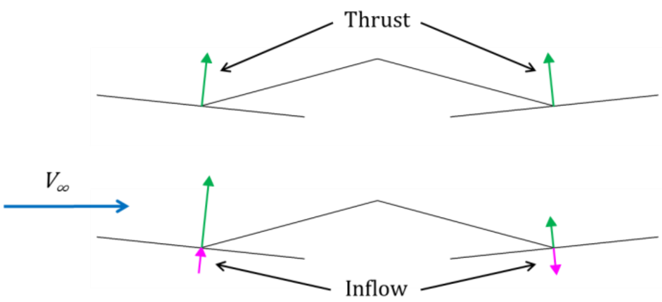


Figure 3. Schematic showing tetrahedral operating principle.

During flight, the thrust of the rotors causes the structural arms of the airframe to deflect upward, resulting in approximately 1° of natural tetrahedral. A root locus for varying shaft tilt (Figure 4) indicates that modifying the structure to provide additional shaft tilt inward (positive tetrahedral angle) is beneficial, but yields diminishing returns beyond the first one degree of inward tilt.

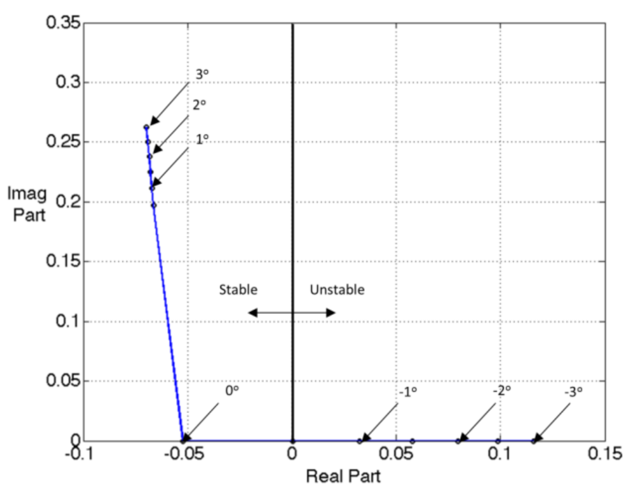


Figure 4. Root locus plot showing improved stability with increasing tetrahedral.

The primary disadvantage of canting the shafts away from the vertical is an effective power increase. Although the penalties of tilting the thrust vector by 2° are small, having the same effect as adding 60 g (0.13 lb) of mass to the vehicle and adding an extra 8.4 N (1.9 lb) of compression along each of the truss arms, significant aerodynamic penalties are incurred due to a reduction in ground effect. The rotor blades of the *Gamera* helicopters are mounted on the shafts with a negative precone angle, placing the tips deeper in ground effect, and thus increasing the rotor efficiency. Canting the rotor shafts reduces the available pre-cone range by a corresponding amount, resulting in a performance penalty. Analysis carried out using blade element momentum theory (BEMT) [3] with a ground-effect correction based on experimental data [9] indicates that the additional power draw for 2° of shaft tilt is equivalent to carrying an extra 4.75 kg (10.5 lb). Furthermore, while tetrahedral has potential to attenuate drift, it would not eliminate it completely. For these reasons, tetrahedral was considered not to be worth the effort and weight of the structural modifications required to implement it.

YAW-FLAP OSCILLATIONS

Testing of *Gamera II* revealed yaw oscillations on many flights. It was found that rotor flapping was coupling with yaw to create a divergent instability. Pairs of blades could be carefully balanced prior to flight testing using a specifically built hover stand known as the Blade Balancing Rig [10], with the goal of achieving blade tracking in a plane. On the vehicle, however, it was challenging get the tips of both blades in a rotor to track due to high sensitivity to blade pitch.

Blade flapping imbalance could also be divergent in ground testing or during medium length flights. It even resulted in catastrophic mishaps on two occasions; in one case a diverging blade hit the airframe and in another case the increased bending loads from a flap imbalance caused the airframe truss structure to buckle. Traditional pitch divergence [11] was suspected, but careful measurements and analysis of videos taken from cameras placed in the rotating frame did not show any evidence of excessive blade torsion. It was observed that vehicle yaw oscillations were occurring at the rotational speed of the rotor, and that the behavior seen was caused by a coupled yaw-flap instability.

Analysis

The high root stiffness of the rotors and the relatively soft truss and rotor shafts on *Gamera II* mean that the two blades together behave like a teetering rotor with a large root spring. Steady imbalanced flap deflection of this teetering arrangement causes the direction of the thrust vector to sinusoidally vary in the vehicle fixed frame. The long truss arms and the small magnitude of the yaw oscillations allow the behavior of an isolated rotor to be considered as a teetering rotor with a one degree of freedom flap oscillation as shown in Figure 5. First, a small yaw perturbation causes the rotor to enter forward flight with a velocity equal to the vehicle yaw rate times the length of the arm on which the rotor is mounted. The rotor flaps in response to this translational velocity, causing the thrust vector to tilt away from the direction of motion. The tilted thrust vector stops the translation and then causes it to build up again in the opposite direction. Detrimental to rotor stability, the result of this behavior is that one blade will always be advancing and the opposite always retreating.

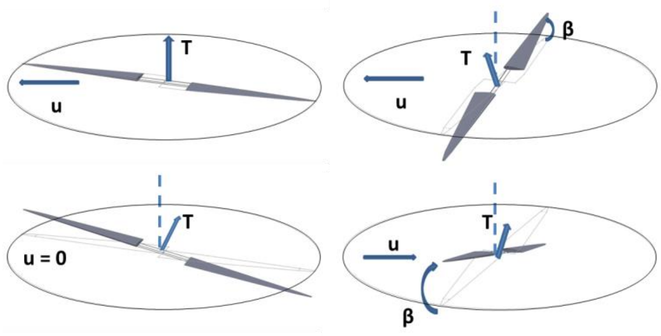


Figure 5. Schematic of yaw-flap oscillations.

This instability occurs at a much higher frequency than other elements of the observed vehicle dynamics, allowing the time scale to be separated and a simple two degree of freedom model to be used to help identify solutions to this problem.

The yaw dynamics is modeled simply; yaw acceleration is driven by the relevant component of rotor thrust ($T \sin \psi$) rotated by the flap angle (β) operating at a moment arm l,

$$I_{zz}\dot{r} = Tl\beta \sin(\psi), \quad [1]$$

and flap is modeled using classical flap dynamics,

$$\ddot{\beta} + \nu_\beta^2 \beta = \gamma \overline{M}_\beta. \quad [2]$$

Using perturbation forms of these equations (with zero flap and zero motion as the trim state) the equations expand to:

$$\dot{r} = \gamma\left(\frac{\theta_o}{3} - \frac{\lambda}{2}\right)\frac{I_b}{I_{zz}}\frac{l}{R}\beta\cos(\psi), \text{ and} \quad [3]$$

$$\ddot{\beta} + \frac{\gamma}{8}\dot{\beta} + \nu_\beta^2\beta = \gamma\left(\frac{\theta_o}{3} - \frac{\lambda}{2}\right)\frac{l}{R} r \sin(\psi). \quad [4]$$

These equations were modeled time accurately in MATLAB using a numerical ordinary differential equation solver to predict response to flap and yaw perturbations. Parametric studies suggest that Lock number, flap frequency, and vehicle yaw inertia are the critical variables in the stability of this system. High flap frequency and high yaw inertia help stabilize the system while a high Lock number is destabilizing. *Gamera IIXR* has a high flap frequency, 2.4/rev, but the Lock number is very large at 360 because of the low rotational speed and lightweight manufacturing techniques. Table 1 lists these and other vehicle parameters. Numerical analysis shows this configuration with low flap frequency to be unstable, as seen in Figure 6 in which the time scale is presented in terms of rotor azimuth. Note how the amplitude of the yaw rate oscillation increases as the flap deflection grows.

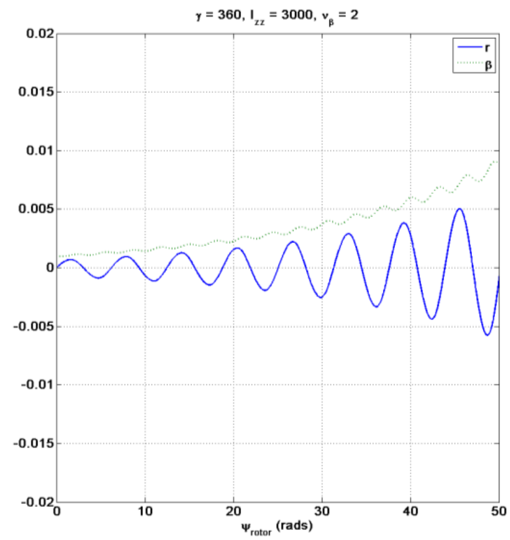


Figure 6. Pitch rate and flap angle response for a rotor undergoing unstable yaw-flap oscillations.

Modifying either the Lock number or yaw inertia is challenging on the completed vehicle, so the effect of rotor flap frequency was examined in detail. It was found that increasing the flap frequency could stabilize the vehicle, as shown in Figure 7, where the flap frequency is 8/rev. In this case the yaw velocity slowly damps out without oscillating.

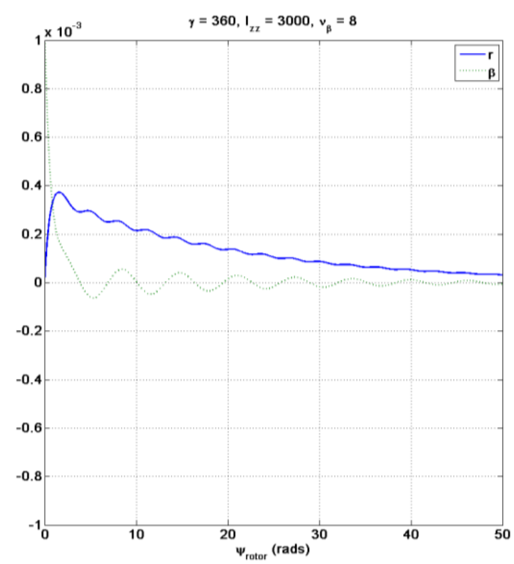


Figure 7. Predicted yaw-flap oscillation damps out for a rotor with high flap frequency.

Kinematic Pitch-Flap Coupling (δ_3)

Both *Gamera I* and *Gamera II* had rigid rotor hubs. Imbalances in blade thrust were manifested as a bending moment. This moment was resolved by the rotor shaft and the airframe truss arm supporting it but not without elastic deflection, tilting the thrust vector and causing the yawing motion. One attempt made to correct this instability was an increase in the stiffness of the rotor shaft, thereby reducing the amount of flap deflection, and the associated risk of a blade strike, and limiting the coupled yaw-flap motion via the increased flap frequency. Although this helped, it was not sufficient to eliminate flapping as the airframe had limited stiffness, allowing the rotor to flap by twisting the truss arm at the end of which it was mounted. Stiffening the truss arms would have been structurally difficult and required adding a significant amount of weight to the airframe. Instead, the solution found was to eliminate the imbalanced flapping behavior through the use of a teetering hub designed to induce a positive δ_3 kinematic pitch-flap coupling.

Skewing the flap hinge on a rotor hub at an angle, as shown in Figure 8, will cause the blade to pitch as it flaps, proportional to the tangent of the angle δ_3 as described by the equation

$$\Delta\theta = -\tan(\delta_3)\,\beta, \qquad [5]$$

in which $\Delta\theta$ is the change in blade pitch and β is the flap angle [11]. Using positive δ_3 causes a blade which is generating more lift and therefore flapping up to pitch nose-down, alleviating the lift and thereby reducing the flapping, with the effect of increased flap frequency. This technique is used on the tail rotors of many helicopters to reduce flapping response [12].

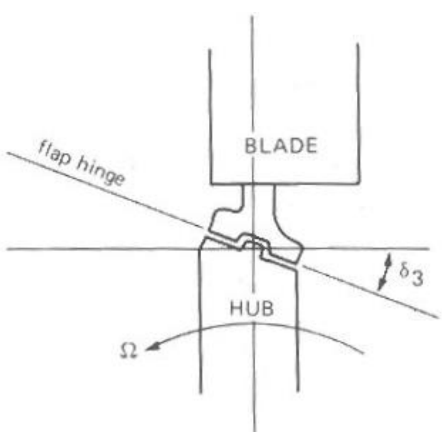


Figure 8. Illustration of δ_3 coupling on a helicopter blade [11].

Gamera IID (a modified version of *Gamera IIXR*) was equipped with a new teetering hub featuring a skewed flap hinge (Figure 9). Use of a teetering hub allows the kinematic pitch-flap coupling to be achieved with minimal added weight. A hub with a δ_3 of 56° induces 3° of pitch for every 2° of flap, and showed a marked improvement in blade balance, making tracking the blades much easier. Further, the rotors showed good stability in response to pitch perturbations as well as artificial gusts. The kinematic pitch-flap coupling raised the rotor flap frequency from 2.4/rev to 8.3/rev, greater than that shown to be stable in Figure 7.

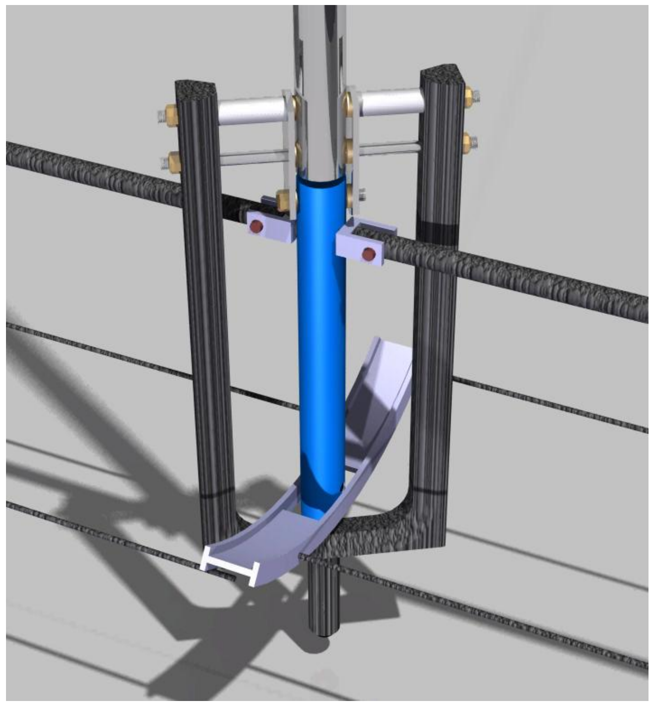


Figure 9. Rendering of teetering hinge with kinematic pitch-flap coupling installed on *Gamera IID*.

Flight testing revealed drastic improvements when pitch-flap coupling was introduced. Flapping imbalance was immediately reduced, and the blades could be easily tracked. Without the flapping imbalance the observed yaw oscillations vanished, as expected. Additionally, the elimination of moments about the hinges allowed the shafts supporting the rotors to be made lighter. The flight testing procedure was also accelerated, as tracking the blades became much simpler.

LONG PERIOD FORWARD PITCH

Consistently during testing of *Gamera II*, a forward drifting behavior has been observed. It is a long period phenomenon, with pitch building up during longer duration flights, causing the vehicle to accelerate forward. Even when trimmed to initially drift backward, the vehicle would slow down and reverse direction. This behavior, which has been the limiting factor for many long endurance flight attempts, has not been captured by the newly formulated HPH dynamic analysis or other analysis methods. The behavior is especially pronounced when descending from higher altitude, and is hypothesized to arise from mechanical asymmetry about the lateral plane.

Several potential sources for this behavior have been identified. One possible cause may be the motion of the pilot during the flight. It was hypothesized that during longer flights, the pilot's posture would deteriorate as fatigue set in and the pilot would lean forward, therefore shifting the center of gravity of the vehicle forward. After flight tests of *Gamera II* were performed with the pilot taped to the back of the cockpit, maintaining upright posture, this hypothesis was dropped when forward drift was still observed.

Another possible source considered was deflection of the truss arms of the vehicle. The original transmission string path for the forward rotor of *Gamera II* ran to the bottom of the truss arm, before being redirected down to the front of the cockpit (Figure 10), whereas the other three rotor strings ran to the center of the helicopter first. With the string under high tension, it was postulated that the force of redirection was enough to bend the forward truss arm down, misaligning its thrust vector. However, changing the string path by running it to the center of the vehicle before redirecting it to the cockpit, did not affect the behavior. It is also possible that structural asymmetry in the vehicle could cause redirection of the thrust vectors of one or more of the four rotors, leading to the increasing forward pitch. In an effort to limit this, key structural components near the center of *Gamera IID* are being rebuilt.

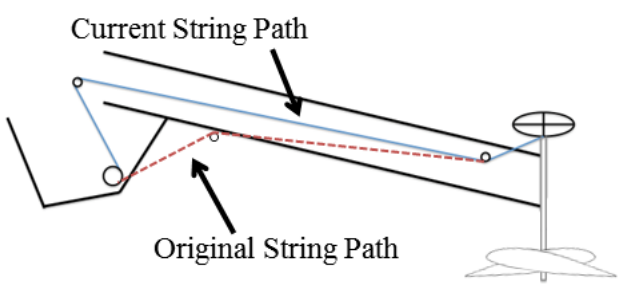


Figure 10. Original string path for forward rotor of *Gamera II*.

It is also possible that dissimilarities in rotor RPM may be the cause of this issue. Although all four rotors are driven by a single pilot-side pulley, differences in the rotor pulleys or in the spooling for the four strings on the pilot-side pulley could cause the rotors to turn at slightly different rates. To ensure equal operating speed, four new rotor pulleys were built for *Gamera IID*, with focus being placed on matching diameters exactly. The spooling within the cockpit was also examined more closely, with pains being taken to adjust string paths within the cockpit to ensure even wraps. Though this evened out spooling on the pilot pulley, these measures failed to resolve the forward drifting problem. It may be possible that the four pulleys were not being wrapped with identical tension before flights, resulting in variation in rotor RPM. A new wrapping technique is being developed to mitigate this risk.

The final possible source of pitch instability is the flywheel used in the transmission. A flywheel is needed to smooth out the pedaling stroke of the pilot and deliver power evenly to the rotors. This flywheel is mounted parallel to the longitudinal plane of the vehicle. Conservation of momentum suggests that accelerating or decelerating the flywheel will affect the pitch of the vehicle. It is possible that as the pilot increases RPM to climb, the vehicle takes on a pitch attitude. Torque generated by aerodynamic drag on the spinning flywheel also may contribute a pitching moment to the aircraft. The possibility of adding a second, counter-rotating flywheel is being considered to eliminate these concerns.

To overcome the forward pitching behavior as well as any translational instability, an active control system was developed for *Gamera IID*.

ACTIVE CONTROL

When considering active control options a few factors were considered. The first concern was how to achieve control with minimal power drawn from the pilot. A mechanism was required that could exert adequate control authority with minimum added weight and power draw. Second, it was important to determine how the device would be actuated to correct for drift and maintain position. Finally, the control system had to fit within the rules of the competition.

The regulations for the AHS Sikorsky Competition [13] stipulate that no energy storage devices are permitted. A clarification of the rule stated that batteries could be used, so long as none of the stored energy entered the drive system. This clarification was later struck from the regulations, though its use was permitted until August 31, 2013 to grandfather in groups who began the competition when the rule clarification was in effect. The more stringent reading of the rules suggests no batteries or other energy storage devices may be used to power a control system.

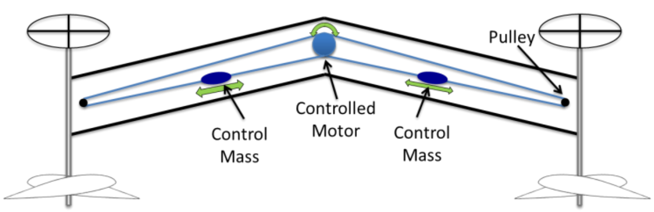
Several different control concepts were considered for use in *Gamera II*. Two were prototyped, implemented, and flight tested. The first was a center of gravity shifting system by means of sliding masses. The second, which was ultimately implemented, was a system which can alter the speed of opposing rotors, varying their RPM and thereby inducing control moments.

CG Shifting

The idea of CG shifting is to implement a mechanism that can move the center of the gravity of the vehicle. This would alter the length of the moment arms for the four rotors and thereby exert a control moment on the vehicle.

It was determined using the HPH dynamic analysis that the dynamics of the helicopter were sensitive to the position of the CG of the vehicle. A position feedback control system model was applied which would shift the center of gravity in an attempt to return the helicopter to its initial position. The dynamics analysis was run with a perturbation in rotor thrust and, although initially unstable, it was shown that using a control mass of 100 g on each arm allowed the system to keep the vehicle centered in space.

A prototype CG shifting mechanism was implemented in *Gamera IIXR* in November of 2012. The mechanism consisted of traveling masses placed in each of the four structural arms of the helicopter. By moving pairs of masses on opposing sides up and down the arms, the center of gravity of the helicopter could be shifted left and right, forward and backward. The masses were mounted on strings looped around an idler pulley at the rotor end of the arm and a pulley driven by a control motor in the center of the structure, similar to a conveyor belt, as shown in Figure 11. Opposing pairs of masses were linked to a single motor, such that actuating one transverse motor could create a roll moment, and a second longitudinal control motor could similarly move the CG forward and aft to control pitch.



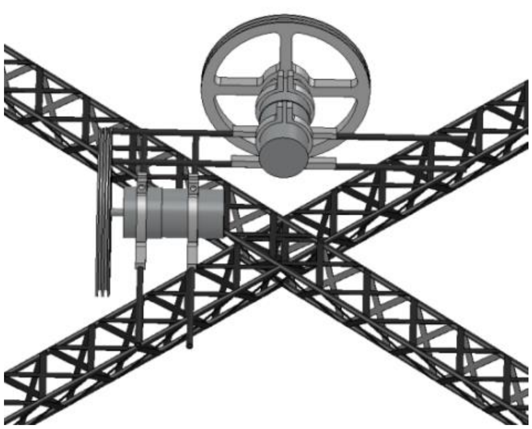


Figure 11. Schematic of CG shifting active control system and rendering of control motors as mounted on *Gamera IIXR*.

One of the challenges in implementing this system proved to be the actuation of the motors. In order to comply with the rules of the Sikorsky Prize, the helicopter must be "controlled by the crew during the entire flight." [13] As such, the first design iteration of this system included an Arduino microcontroller that receives inputs from an inertial measurement unit (IMU) that could be controlled by the pilot, allowing the vehicle to be controlled using body gestures. However, due to time constraints, this idea was abandoned in favor of a radio controlled (RC) system using a standard hobby RC transmitter and receiver pair. While this would not comply with the rules of the Sikorsky Prize, it would provide data and observations as to the effectiveness of the control system.

In implementing this system, each of the two DC motors was connected to a speed controller, which received control commands directly from the RC receiver. The speed controllers were connected to a single battery to save weight. Table 2 provides a mass breakdown of the system by component. Note that although batteries were used, no stored energy would enter the drive system, so this control scheme would be legal under the AHS Sikorsky Competition rule clarifications discussed above.

Table 2. Mass breakdown of CG shifting system components.

Component	Mass	
Control mass	100 g (0.22 lb)	(x4)
Motor	87 g (0.19 lb)	(x2)
Motor battery	192 g (0.42 lb)	
Speed controller	23 g (0.05 lb)	(x2)
Control pulley	15 g (0.03 lb)	(x2)
Redirection pulley	14 g (0.03 lb)	(x4)
RC Receiver	26 g (0.06 lb)	
Controller battery	31 g (0.07 lb)	
String	30 g (0.07 lb)	
Mounting equipment	150 g (0.33 lb)	
TOTAL	1135 g (2.50 lb)	

For flight testing, control inputs were made by a team member located at a vantage point from which the motion of the helicopter could be easily observed. The control masses were marked in brightly colored tape to allow observation of control inputs (Figure 12).

Figure 12. CG shifting control system in flight testing before (top) and after (bottom) giving "right" command, with left and right control masses called out by arrows. Note the 10 m (32.8 ft) square marked on the floor.

Initial tests of the control system used 100 g (0.22 lb) weights for each of the control masses. The commands were received as intended and the motors were capable of moving the masses the entire length of the structural arms in about 2 seconds. Despite this, the change in CG position did not appear enough to exert adequate control moments on the vehicle. The control masses were increased to 200 g (0.44 lb) but still did not effect sufficient control moments. The size of each of the control masses was increased to 400 g (0.88 lb), capable of exerting a roll or pitch moment of up to 41 Nm (30.5 lb·ft). Visible control was achieved at this level, but it required the addition of a significant weight penalty; 1200 g more mass was needed than expected, for a total system mass of 2.3 kg (5.1 lb). This weight penalty was deemed unacceptable for the limited control authority demonstrated.

RPM Control

The concept for RPM control of a quadrotor helicopter is simple in principle and frequently used by small, unmanned quadrotors [8]. The thrust generated by a rotor is proportional to the square of its angular velocity (RPM) by the equation

$$T = \rho A(\Omega R)^2 C_T. \qquad [6]$$

[14]. Since each of a quadrotor's four rotors are offset from the center, increasing the RPM of one and decreasing the RPM of the opposite will cause an increase in thrust on one side and a decrease in thrust on the other, thereby generating a roll or pitch moment.

Each rotor arm of *Gamera IIXR* is 10.55 m (34.6 ft) long (Figure 2). Each of the rotors spins at approximately 20 RPM in hover at low altitude and generates about 240 N (54 lb) of thrust. Increasing the speed of one rotor by 0.5 RPM and decreasing the speed of the opposite by the same amount will result in a roll moment of 255 Nm (188 lb·ft), 600 % greater than that generated with full actuation of the CG shifting system, which is enough to change the direction of motion of the helicopter.

All human powered helicopters to date feature a winching, string driven transmission system. Lighter than chains, belts, or shafts, the winching system on the *Gamera* helicopters consists of a pulley between the pilot's feet and another pulley above each of the rotors (Figure 13). A single string is wrapped around each of the four rotor pulleys, which are fixed to the rotor shafts. The four strings run from their rotor pulleys, up their respective truss arms, and into the cockpit, where they are each attached to the pilot pulley. As the pilot pedals, this string is reeled off of the rotor pulleys and into the cockpit, thereby delivering torque to the rotors to power the flight.

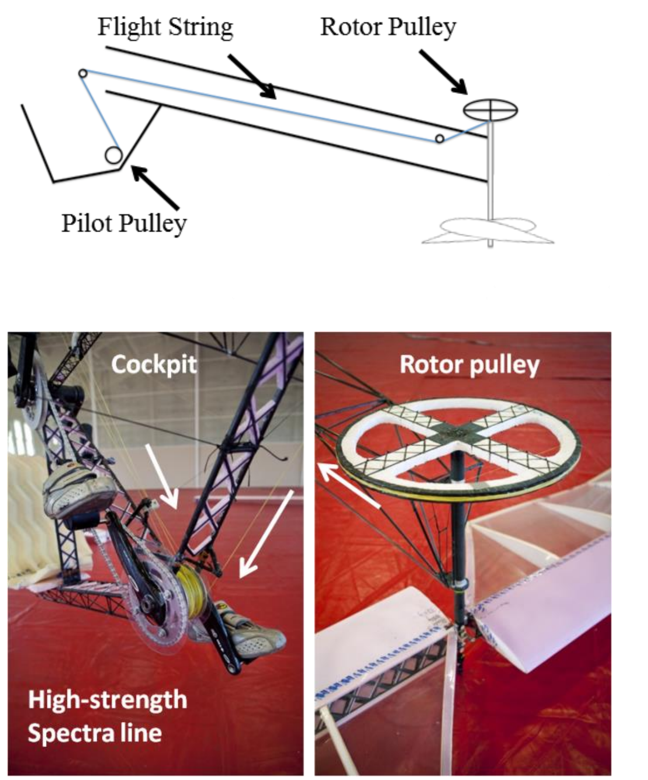


Figure 13. Schematic of winch drive transmission system (top) and *Gamera I* cockpit and rotor pulley showing path of the transmission string (bottom) [3].

Since the string is taken up at a constant rate which is the same for all four rotors, the path the string takes must be modified to induce a change in rotor RPM. This is made possible by adding two pulleys on each arm (labeled A1, A2, B1, and B2 in Figure 14), causing the string to twice double-back on itself and thus creating a Z-shaped path. Two of the pulleys (B1 and B2) are fixed to the structure and the other two (A1 and A2) are left floating as control pulleys.

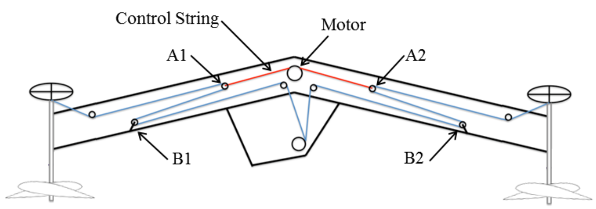


Figure 14. Schematic of *Gamera IID* transmission with RPM control system installed.

Moving pulley A1 along its truss arm toward the cockpit increases the length of the string path. The rate at which the length of string increases is approximately equal to twice the velocity of pulley A1. This induces a change in RPM ($\Delta\Omega$) according to the equation

$$\Delta\Omega = \frac{2V_A}{\pi D_{RP}}, \qquad [7]$$

where V_A is the linear velocity of the control pulley and D_{RP} is the diameter of the rotor pulley. The rotor pulleys have a diameter of 53.3 cm (21 in.), therefore a 0.5 RPM change in rotor speed requires the control pulley to have a velocity of only 0.7 cm/s (0.27 in/s). With required flight durations of only 60 seconds, this allows the control system to be activated for an entire test with only 0.42 m (1.4 ft) of travel required from the control pulley. Opposing pairs of control pulleys (A1 and A2) are linked together by the control system to ensure one rotor increases thrust and power while the other decreases thrust and power to avoid coupling of pitch and roll with yaw due to a torque imbalance.

Linking the opposing control pulleys to the same central control point also allows the tension coming from the two rotors to be reacted against one another, limiting the static load. Actuating the control system therefore requires pulling one control pulley in toward the center of the cockpit, while the other pulley will passively have its newly relieved slack taken in by the pilot pulley. The force required to pull the control pulley inward is related to the difference in torque taken by the two rotors exerting the moment, and is about 45 N (10 lb).

Unlike the earlier CG shifting system, RPM control does contribute power to the rotor system when it pulls the control pulleys in towards the cockpit. The system therefore must be powered solely by the pilot without energy storage. Mechanical systems for transmitting power from the pilot's hand cranks to a pair of pulleys above the cockpit, one for roll control and another for pitch, were considered. The need for two directions of travel and the ability to keep the system power-off most of the time would likely require many components, including clutches, which the pilot would need to actuate.

The complexity and weight of early designs led to a mechanical solution being abandoned in favor of a relatively simple electrical system, for which many of the required components had already been implemented in the CG shifting system. Electric controls are acceptable under Sikorsky Prize regulations so long as the pilot generates all of the power and no energy is stored. To maintain compliance, a generator is attached to the helicopter which can only run the system when the pilot is pedaling.

Two control motors are mounted above the cockpit with pulleys fixed to them, one for roll and another for pitch. Each motor is connected to a speed controller and powered by an off the shelf bicycle generator. This generator produces an AC output which is passed through a rectifier, outputting 15 V DC to the motors when the pilot is pedaling at full RPM. This voltage is also tapped through a voltage regulator to power an Arduino microcontroller, which is used to process pilot inputs. Bench top testing of the Arduino, speed controllers, and motors with no load revealed that they consume 3.3 W of power. With a generator efficiency measured to be 50 %, the power consumed is 6.6 W. Adding the power loss of the generator due to friction (1.2 W), the total power draw of the system on the pilot is calculated to be 7.8 W. Based on thrust versus power curves generated for *Gamera IIXR* [10], this power loss is equivalent to adding an extra weight of 1288 g (2.84 lb) to the helicopter. A mass breakdown of all components is provided below in Table 3.

Table 3. Mass breakdown of RPM control system components.

Component	Mass	
Motor	240 g (0.53 lb)	(x2)
Motor Pulley	57 g (0.13 lb)	(x2)
Generator and Gears	279 g (0.61 lb)	
Control Pulleys	20 g (0.04 lb)	(x8)
String	50 g (0.11 lb)	
Switches	28 g (0.06 lb)	(x2)
Arduino	28 g (0.06 lb)	
Breadboard	13 g (0.03 lb)	
Speed Controllers	26 g (0.06 lb)	(x2)
Rectifier Circuit	22 g (0.05 lb)	
Pilot Control Wires	48 g (0.11 lb)	
Other Electronics	41 g (0.09 lb)	
TOTAL	1343 g (2.96 lb)	

Unlike the off-board scheme used with the CG shifting system, the pilot has full control of RPM variation by means of two switches mounted in the grips of the hand cranks. Both are single-pole double-throw switches with a center off position. When the switch is depressed in a particular direction, it connects one of the digital pins of the Arduino to a 5V 'high' voltage. By changing the combination of inputs, the logic loaded onto the Arduino will write the outputs to the speed controllers in a manner that corresponds to the selected input. In order to give a command to the control system, the pilot must simultaneously actuate both the left and right hand switches. This is done to make control more intuitive, and to reduce the likelihood of an accidental command. The switch pairings were selected by the pilots during free association tests while holding handgrips with dummy switches. Table 4 shows the switch positions used to control the helicopter. It does, however, mean that only one direction can be actuated at one time. Thus, a drift along an axis that is not parallel to a truss arm must be corrected by short commands in two directions.

Table 4. Pilot control switch positions.

Command	Left Switch	Right Switch
"Forward" Pitch	Up	Up
"Backward" Pitch	Down	Down
"Right" Roll	Down	Up
"Left" Roll	Up	Down
"Neutral" (No input)	Either switch center	

A prototype of the control system, capable of inducing only pitching moments, was installed on the helicopter and ground tested using only the forward and aft rotors. Results from the tests validated that the differences in RPM and resulting control moments were comparable to those predicted, and the final control system was installed on the helicopter.

The control system was tested during two rounds of flight testing in February of 2013. To minimize pilot workload and because it is difficult to determine vehicle attitude from the cockpit, two spotters were placed outside of the vehicle to call pitch and roll commands. A pilot coach, who stands at the center of the vehicle for every flight, relayed the commands to the pilot. Since the controls only have an effect when the system was in operation, the spotters gave one command to start control in a given direction, and another to stop.

During flight testing it was discovered that the RPM control system was capable of arresting motion and controlling the vehicle at low altitude. Commands given were typically short, on the order of one second in a given direction before commanding the pilot to switch to neutral (no control), adjusting the attitude of the helicopter slightly each time. Four flights of 40 seconds or better were kept within the 10 m (32.8 ft) box using the control system, as well as several shorter test flights. Typically between 5 and 10 commands would be given during a flight, not counting returns to neutral. Based on video analysis of these flight tests, the average time for the helicopter to begin responding to a command (a direction or neutral) was about 1.1 seconds. Figure 15 shows the response of the rotor RPM during a typical controlled flight.

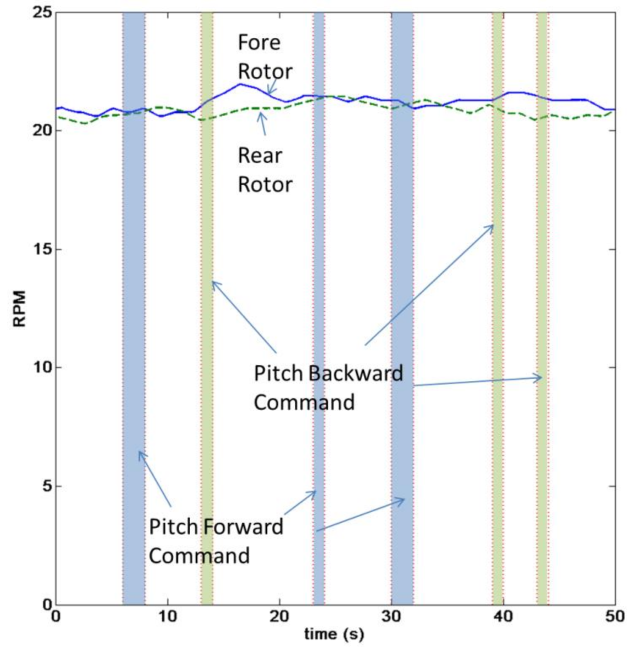


Figure 15. Rotor RPM variation in response to commands during a controlled test flight of *Gamera IID*.

There was an appreciable learning curve for the spotters. With practice, however, the spotters learned to give appropriate commands, and were able to keep longer flights centered. Although the mechanism proved effective at a low hover, further testing is needed to determine its efficacy at higher altitude.

CONCLUSIONS

Flight testing of the *Gamera* human powered helicopters revealed three major stability issues: a lateral and longitudinal instability, which would cause accelerating drift with a perturbation; a coupled yaw-flap instability caused by rotor imbalance, which would lead to potentially destructive yaw oscillations; and a long-period forward drifting mode, the source of which was difficult to ascertain.

It was found that positioning the center of gravity of the vehicle at its geometric center could reduce drift but would not eliminate the instability. Vertical CG position was found to have an effect on stability, but issues created by changing it were deemed prohibitive. Tilting the rotor planes toward the cockpit, known as tetrahedral, would improve stability as well, but its effect was too small to justify structural modifications.

A control system capable of shifting the center of gravity of the vehicle during flight was prototyped and tested. Although it could exert some control over the vehicle, the system was prohibitively heavy.

A rotor RPM varying control system was ultimately selected and proved able to control the vehicle for flight durations up to one minute. Further testing of the RPM control system at altitude is needed. Furthermore, efforts need to be made to reduce the power drawn by the control system.

The yaw-flap oscillation was eliminated by the use of a teetering hinge with kinematic pitch-flap (δ_3) coupling.

Several possible sources for the long period pitch forward behavior have been considered, but the behavior is yet to be eliminated. The control system, though, is capable of overcoming this drift. It is believed that if vehicle weight can be decreased and control system and transmission efficiency increased that *Gamera IID* will be capable of winning the AHS Sikorsky Prize.

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