Design Optimization of *Gamera II*: a Human Powered Helicopter

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ABSTRACT

In pursuit of the Sikorsky Prize, two human powered helicopters have been designed by a team of students from the University of Maryland. Significant experience was gained from the construction and flight testing of the first helicopter, *Gamera I*. This experience led into design optimization and refinement of the second-generation vehicle, *Gamera II*, presented in this paper. Human performance over short periods of time was studied to characterize the power available, and the transmission was designed to deliver as much of this power as possible to the rotors. The addition of a hand-cranking mechanism was shown to increase pilot power output by 20% for the intended 60 second duration. The quad-rotor configuration was continued in *Gamera II* because it was shown to provide passive stability in ground effect. Innovative lightweight structural concepts were developed, which helped reduce vehicle empty weight by 33% to 32.3 kg (71 lb). The rotors were designed using a comprehensive optimization process that coupled aerodynamics, blade spar stiffness, and airframe weight models to yield the lowest possible vehicle power required. Power required to hover is predicted to have been reduced by 35% compared to *Gamera I*, enabling the 60 second flight endurance required as part of the Sikorsky prize. Flight testing of *Gamera II* is scheduled for summer 2012.

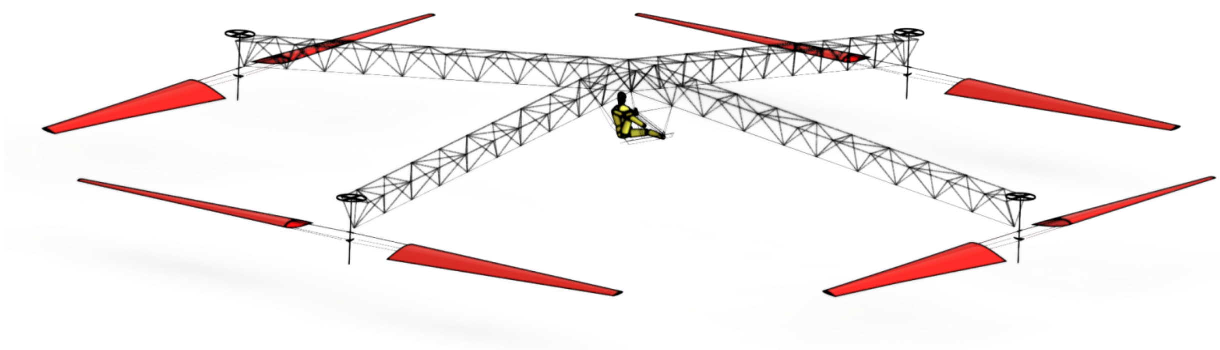

Figure 1: *Gamera II* vehicle concept.

INTRODUCTION

The Igor I. Sikorsky Human Powered Helicopter Competition was established in 1980 by the American Helicopter Society. The flight requires a 60 second hovering time and momentary achievement of 3 meters (10 ft) altitude under human power, among other regulations. As of 2011 there have only been three officially recognized flights of human powered helicopters, of which the longest was 19.4 seconds at around 0.6 m altitude (*Yuri I* designed by Dr. Akira Naito, affiliated with Nihon University, Tokyo, flown in 1994).

Team *Gamera* was formed in late 2008 at the University of Maryland to begin efforts to design a human powered helicopter. *Gamera* was named for a Godzilla-like gigantic fire-breathing flying turtle from Japanese monster movies. The team name is therefore in reference to the terrapin turtle mascot of the University

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of Maryland, as well as a nod to the flights of the Japanese human powered helicopter 17 years prior. The team, an ever-changing mix of part-time volunteer graduate and undergraduate students, spent 2½ years designing and testing components of what would become *Gamera I.* An enormous amount of enthusiasm and effort was put into all aspects of the program, including aerodynamics, ground effect, structures, human power, transmission, and logistics [1].

By April 2011, the team had constructed *Gamera I* and by July 2011 had conducted two flight tests, culminating with a hover time of 11.4 seconds, certified by the National Aeronautic Association and the Fédération Aéronautique Internationale (Figure 2). *Gamera I* was a huge success, being the team's very first vehicle iteration, and also the first human powered helicopter to lift-off in over 17 years.

Figure 2: *Gamera I* in flight during world record attempt, July 2011.

Through observations of the vehicle dynamics and levels of pilot fatigue before and after the successful flights, it was decided that *Gamera I* was capable of longer flight durations on the order of 20 seconds, but not the Sikorsky Prize. For this reason *Gamera I* was retired, and a new vehicle design was pursued which used the many lessons learned in the construction and testing of *Gamera I*. *Gamera II* takes advantage of both a broad knowledge base to accurately predict performance and a skilled workforce now familiar with lightweight construction techniques. The goal of *Gamera II* is to increase hover endurance to 60 seconds, as a step towards meeting the Sikorsky Prize requirements.

OVERVIEW OF *GAMERA II* DESIGN

Gamera II (Figure 1) retains the same overall quad-rotor layout of *Gamera I*, due to familiarity with the design and the non-trivial stability benefits it offers. Despite net performance benefits to increasing disk area, the four rotor diameters were kept at 13 m (42.6 ft) due to the space limitations of available indoor testing locations. Therefore, in layout and overall dimensions, *Gamera II* closely resembles *Gamera I*. However, for the same total size, vehicle weight has been reduced by 33% (16 kg, 34 lb) due to structural innovations that had been introduced initially in *Gamera I*, and further developed for use in *Gamera II*. Rotor weight has been reduced by 39% (10 kg, 23 lb) and the airframe truss weight has been cut by 39% (5.7 kg, 13 lb), an especially difficult accomplishment given the low weight of *Gamera I*. The appropriate sections of this paper will cover how the empty weight was reduced so significantly.

The rotor blades have a 3:1 taper ratio and the airfoil was changed from the 9% thick Eppler E387 to the 16% thick Selig S8037. Both of these changes allow for a much stiffer spar with no weight penalty. The reduced bending deflections of the cantilevered blades increase ground effect, and reduce the danger of striking the airframe structure overhead. The increased airfoil thickness also allows reduced blade chord/solidity, resulting in an overall smaller and lighter blade. Finally, targeted material changes have been made to save even more weight.

The airframe truss arms of *Gamera II* extensively incorporate specially developed micro-truss members, creating a truss composed of smaller trusses. Research efforts showed these micro-trusses were 620% more structurally efficient (*EI*/mass) than carbon tubes for buckling resistance, which was the primary constraint of the truss members (see airframe design section). These micro-trusses were first used in *Gamera I*, but in limited quantities. For *Gamera II*, an even lighter micro-truss design was developed and used for 90% of the truss members, cutting airframe weight by 39%.

Pilot testing and recruiting was expanded, and new data was gathered on short-duration human power output using legs only and then arms with legs. The results validated the design choice for powering *Gamera I*; hand and foot cranks were again utilized in *Gamera II* to increase power output by about 20% over legs alone. To smooth the power delivery, a flywheel has been designed into the drive-train of *Gamera II*. Structural improvements were also designed into the cockpit to better maintain alignment between the hand and foot crank sprockets, preventing chain-jumping and further increasing power transfer.

SECTION 1: RESEARCH, DEVELOPMENT, AND DESIGN OF *GAMERA II*

HUMAN POWER RESEARCH

Mechanism Design

A distinguishing feature of *Gamera* is the use of hand cranks in addition to the more conventional foot cranks. The 60 second target flight duration of *Gamera II* puts the human pilot in a very different regime, in a physiological sense, than other, longer duration human powered vehicles. Exercise physiologists have estimated that for short-duration exercises, between 20 and 60 seconds, energy production is fueled almost entirely by anaerobic glycolysis [2]. This process relies on the glycogen stores within the active muscles. The implication is that engaging more muscle mass should release more stored energy (glycogen). This is in contrast to prolonged-duration activities (several minutes to hours) where the energy production is primarily aerobic and therefore limited by oxygen supplied by the pulmonary system rather than muscle mass.

There were relatively few controlled experiments found in the literature comparing short-duration power output of exercises with and without the additions of the upper body. Ursinus' experiments from 1936 are commonly cited in human power publications. Experiments were performed on one subject involving several mechanisms, but notably compared leg cranking with leg and hand-cranking [3,4]. Wilkie [5] re-drew Ursinus's data in 1960, showing that the addition of hand-cranking yielded about 30% more power output than cycling alone for a 60 second effort, with increasing gains at shorter durations. Evans [6] compared the results from Ursinus as well as experiments by Bergh [7] and concluded that for human powered aircraft "useful improvements in power-to-weight ratio may be obtained by the addition of arm work," estimating 50% more power for durations of 90 seconds. Harrison [8] conducted experiments comparing rowing (legs and arms) and cycling (legs only), also concluded that for maximum power output of activities under 5 minutes the participant should make use of as much muscle mass as possible.

Despite this evidence pointing towards improvements in power with the addition of the upper body, it gave the team some concern that no other successful human powered aircraft had employed hand cranks. The reasons for this absence on fixed-wing aircraft was fairly clear. For one, human powered fixed-wing aircraft flight durations were measured from minutes (*Gossamer Condor*) to hours (*Gossamer Albatross*, *Daedalus*). These were well within the aerobic regime where engaging additional muscle mass has limited benefits. More importantly, these pilots were pilots in the true sense; they required their hands free to operate control levers in the cockpit. The previous two successful human-powered helicopters, the *Da-Vinci III* and the *Yuri I*, both utilized leg cranks only. There were no publications found to indicate whether those designers had considered adding hand cranks.

Initial studies were done on hand cranking during the design of *Gamera I*, but an expanded testing effort was undertaken for *Gamera II*. Two of the test pilots, Colin Gore and Kyle Gluesenkamp, were systematically tested for power output on a commercial exercise machine that had both hand and foot cranks (Figure 3). For each test point, the pilot maintained a fixed RPM at a fixed resistance setting until exhaustion. Results are shown in a power vs. duration plot (Figure 4). Note that the horizontal axis is duration at a constant power, not elapsed time. The results confirmed that the addition of hand cranks increases power output for the durations of interest. For the target flight time of 60 seconds, the addition of hand cranks can boost power output by about 20% to about 8.1 W/kg, or 500 W (0.67 hp) for a 61 kg (135 lb) pilot. The trends also indicate hand cranks offer a decreasing benefit as duration increases, which was expected from the physiology literature.

Figure 3: Test pilot Kyle Gluesenkamp on the SCIFIT Pro2 Total Body Recumbent Bike machine.

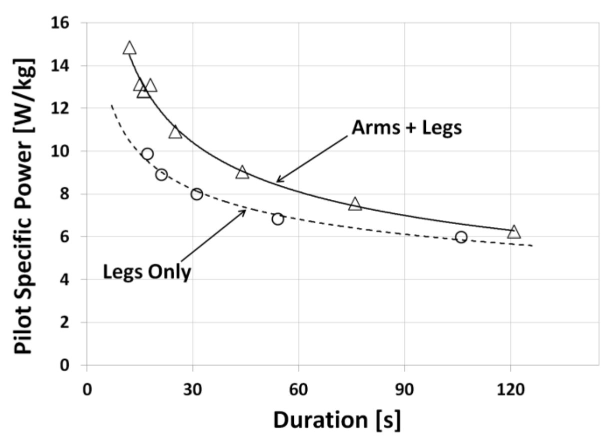

Figure 4: Pilot power output vs. duration comparing legs only to arms and legs for a *Gamera II* test pilot at 100 RPM. Note the x-axis is duration at a constant power, not elapsed time.

To understand the capabilities of the test pilots in the anaerobic regime, extensive testing was performed for durations less than 2 minutes. These data fit very neatly to a power law curve fit (Figure 4). For longer durations (aerobic regime), the power law fit becomes completely unsuitable and modifications are required. As illustration of this, one test point was conducted at a lower power of 4.8 W/kg. Although this is only 22% lower specific power output than a point with 2 minute duration, the duration was increased to 16 minutes (Figure 5). This exponential increase in human duration for lower power requirements highlights the critical need to reduce vehicle weight to meet the 60 second target.

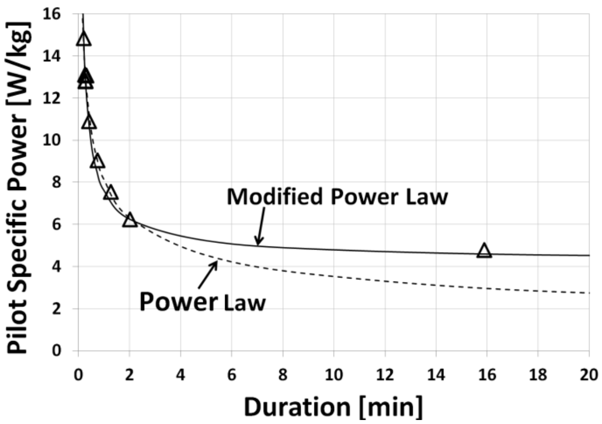

Figure 5: Human duration exponentially increases as the pilot enters the lower aerobic levels of power output.

Pilot Selection

With the design of *Gamera II*, the issue of pilot selection was revisited. The metric used to compare pilots was specific power measured in W/kg of body mass. Rotor momentum theory was used to get a first-order estimate of what the ratio of pilot weight to vehicle weight should be for minimum pilot specific power required. These results in the following formula,

$$\frac{P}{W_p} = \frac{1}{W_p}\frac{W^{3/2}}{\sqrt{2\rho A}} = \frac{1}{W_p}\frac{\left(W_p + W_v\right)^{3/2}}{\sqrt{2\rho A}}$$

$$= \left(\frac{\boldsymbol{W_p}}{\boldsymbol{W_v}} + 1\right)^{3/2}\left(\frac{\boldsymbol{W_p}}{\boldsymbol{W_v}}\right)^{-1}\sqrt{\frac{W_v}{2\rho A}}$$

$$\frac{d\left(P/W_p\right)}{d\left(W_p/W_v\right)} = 0 \longrightarrow \frac{\boldsymbol{W_p}}{\boldsymbol{W_v}} = \boldsymbol{2}$$

where P is the power required, W_p is the weight of the pilot, W is the gross weight, W_v is the vehicle empty weight, ρ is the air density, and A is the total rotor disk area, indicated that for minimum specific power required, pilot weight should be twice the vehicle empty weight. The projected empty weight of *Gamera II* is around 70 lb, therefore a 140 lb pilot would be optimal, all other factors held constant. However, the percent deviation from optimum is less than 1% for pilot weights in the range of 110 to 180 lb (Figure 6). Therefore pilots within this range were considered and judged on their specific power output performance.

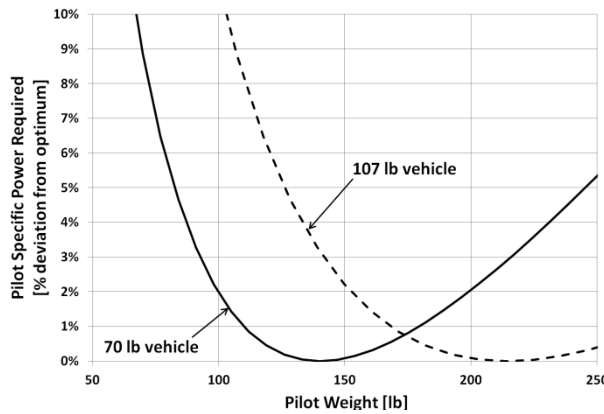

Figure 6: Optimal pilot weight for minimum specific power required based on vehicle empty weight.

A recruitment effort for pilots was carried out on campus and in the Washington, D.C. area. Using pilots who were not based locally was ruled out for the logistical challenges and the team's desire to have frequent face-to-face contact for design decisions and team cohesion. General advertisements were posted around the University campus, with a focus on athletic facilities, encouraging students to apply for the opportunity. Targeted messages were also sent to various University athletic teams as well as local cycling clubs.

A wide variety of applicants were evaluated. In general, those with competitive cycling experience outperformed athletes trained in other sports who did not have such experience. At the writing of this paper the team had identified four pilot options, all male students within 135-140 lb body weight range. Similar body weight is especially ideal for flight testing, since pilots can be alternated as they fatigue without needing to reset the rotor collective pitch. Figure 7 shows the results of all the potential pilots that were tested.

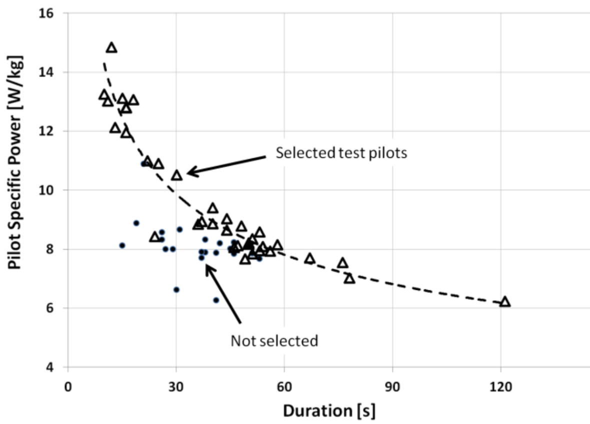

Figure 7: Comparison of the selected *Gamera II* pilots with all other applicants tested

Pilot RPM Studies

For *Gamera I*, the cadence was selected as 120 RPM based on in-house data for very short durations (less than 15 seconds). During the first test flight of *Gamera I*, pilot feedback indicated the pedaling speed was too high. For the second flight, the pedaling cadence was dropped to 110 RPM with better qualitative results reported by the pilot.

For *Gamera II*, the topic was revisited since the target flight duration was increased to 60 seconds. At the time of this paper, limited RPM sweeps had been conducted for test pilot Colin Gore. The preliminary results indicate that at a lower cadence of around 90 RPM Colin produced the most power for a 60 second effort (Figure 8). These studies are continuing to validate these findings.

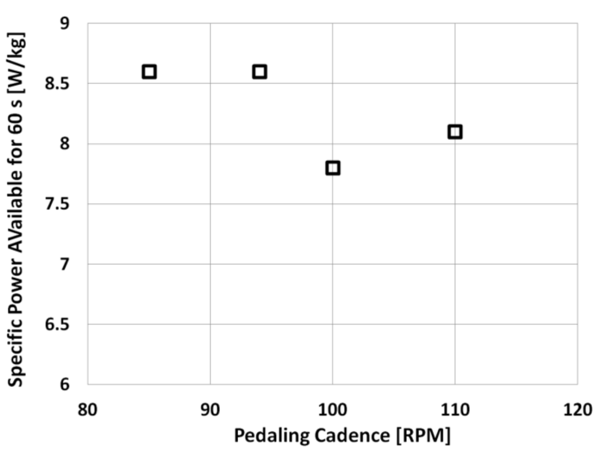

Figure 8: Preliminary results of trade study to determine optimal pilot pedaling cadence for 60 second duration.

GROUND EFFECT RESEARCH

Ground effect is a well-known phenomenon in which rotorcraft or airplanes experience an increase in performance when operating near the ground. For rotors, the practical result is an increase in thrust for the same power, or conversely, a decrease in power requirements for the same thrust. The primary characterizing parameter is the height of the rotor above ground (z) normalized by rotor radius (R). When operating more than 2 rotor radii above the ground ($z/R > 2$) ground effect becomes much less significant and the rotor can be considered out of ground effect (OGE). For full-scale helicopters, the lowest possible rotor height for flight test measurements of ground effect is constrained by the fuselage and landing gear heights, and thus no flight test data exists for heights lower than z/R of about 0.5. Laboratory tests have no such restriction on height, yet there are still very few data below z/R of 0.25. *Gamera* was planned to hover around z/R = 0.1, so it was necessary to conduct new experiments to quantify the benefits that could be expected from ground effect in order to properly size the vehicle.

Sub-scale Rotor Testing in Ground Effect

To explore this regime of "deep ground effect," the team constructed a variable-height, sub-scale rotor test stand known as the ground effect test rig (Figure 9). The stand was instrumented for thrust, torque, and RPM measurements and the rotor has adjustable pitch. Full details of this experiment can be found in Reference 9. For *Gamera I*, the test stand collected data on rectangular, untwisted rotor blades to match the full-scale design. The *Gamera II* research effort expanded data collection to three additional rotor geometries: negative pre-twist, positive pre-twist, and taper. All four blades had the same span, airfoil (NACA 0012), rotor RPM (Reynolds number), and thrust-weighted solidity to accurately compare geometry effects.

The results of the experiments, shown in Figure 10, showed that blade pre-twist, either negative or positive, had about the same performance in deep ground effect as the untwisted blade. Only the tapered blade showed an improvement in performance over the baseline blades at all heights. These results, as well as the increased manufacturing difficulty, eliminated blade twist from the optimization design space of *Gamera II*.

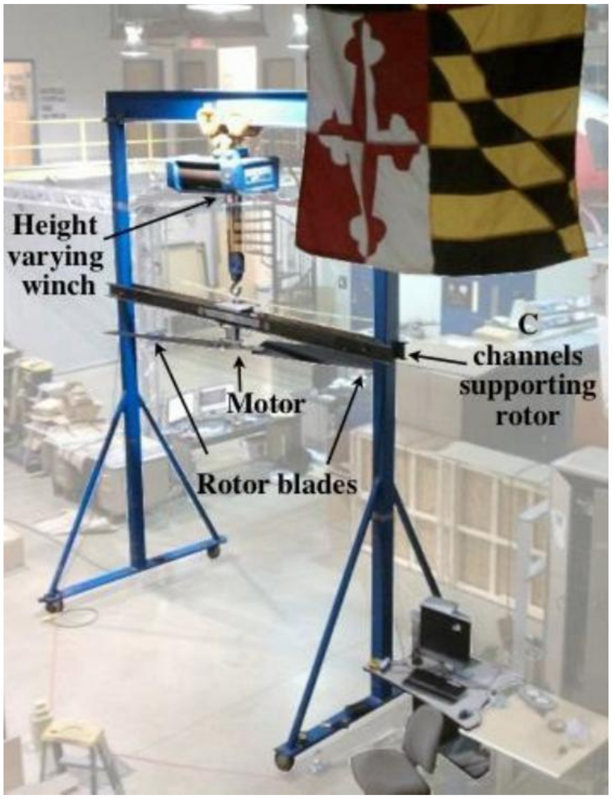

Figure 9: Sub-scale variable-height ground effect test rig.

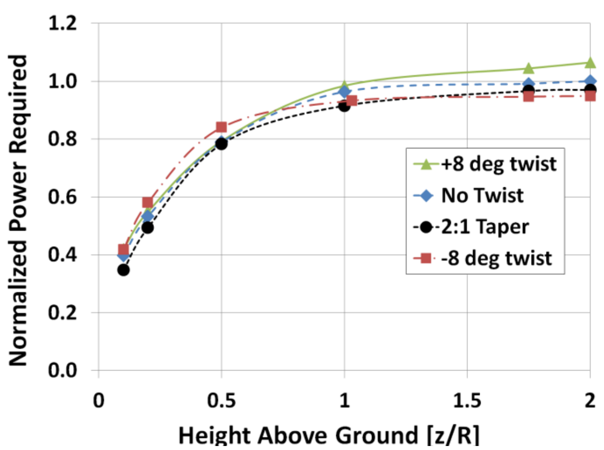

Figure 10: Experimental ground effect variation with blade twist and taper.

Flexible Blades in Deep Ground Effect

The full-scale rotor blades of *Gamera I* were relatively flexible in flapwise bending, and the low rotational speed and low weight resulted in negligible centrifugal stiffening. Flapwise tip deflection at full thrust was on the order of 15% of radius, as observed on the full-scale rotor test stand (Figure 11). At the intended hovering height of z/R = 0.1 (65 cm, about 2 ft), this meant the blade tips would be at a local height of z/R = 0.25. In deep ground effect rotor performance is highly sensitive to changes in height and, as shown in Figure 10, a change of 0.15 z/R results in a 35% increase in power. It was theorized that a loss in ground effect could be expected due to the large rotor coning, and that this needed to be taken into account in the modeling effort.

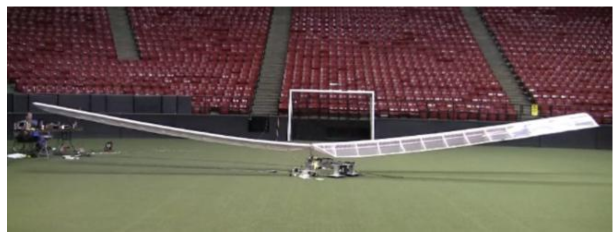

Figure 11: *Gamera I* rotor blades at full 60 lb thrust on the full scale rotor test stand.

A modeling tool based on blade element and momentum theory (BEMT) for rotors was modified to predict elastic structural deflections (FEM routine) and implement ground effect based on the local height of each blade element instead of simply using the hub height [10,11]. This novel ground effect implementation was shown to greatly improve correlation with the full-scale flexible blade data (Figure 12). This modeling methodology formed the core of the design optimization process for the *Gamera II* rotor system, which is described in the rotor aero-structural optimization section.

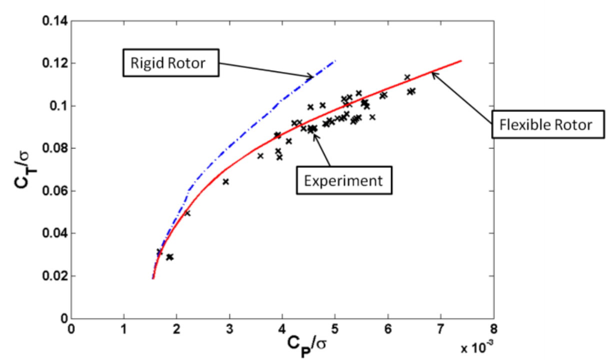

Figure 12: Improved correlation of full-scale rotor hover data with prediction model that includes elastic effects.

ROTOR BLADE STRUCTURE RESEARCH

The majority (55%) of the empty vehicle weight on *Gamera I* came from the rotor blades (Figure 13). As "low-hanging fruit," the blades were aggressively targeted by weight reduction efforts. The main load-carrying member, the blade spar, contributed about half of the blade mass, with the leading edge and trailing edge structures splitting the remainder. This section will briefly go over the design of the *Gamera I* blade structure (overview in Figure 14), and then describe the development and testing of lighter structures used on *Gamera II*.

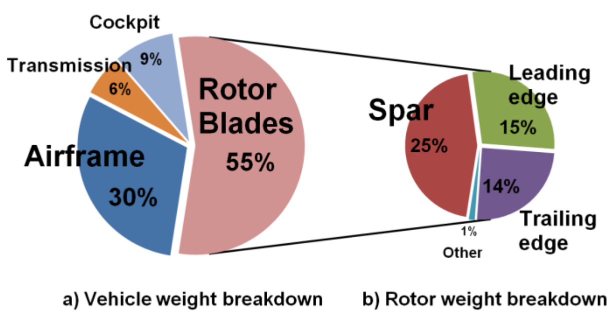

Figure 13: Weight breakdown of *Gamera I*.

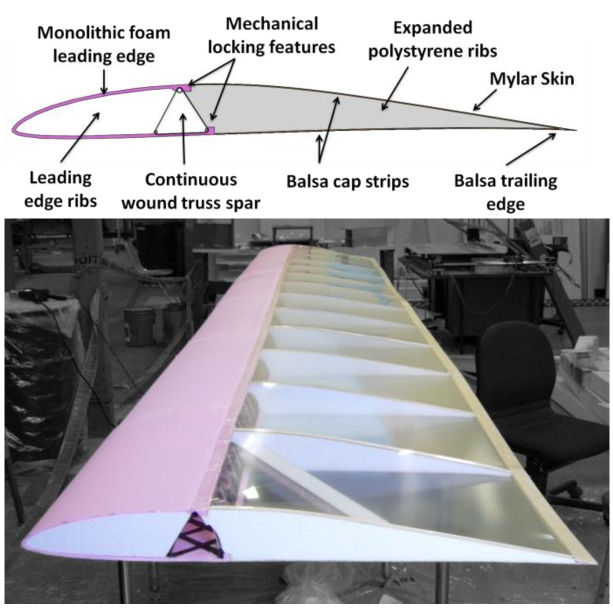

Figure 14: Schematic and photograph showing *Gamera I* blade construction.

Spar Truss Structure

The core of the *Gamera I* blade structure was the spar. The blade spar was a triangular truss structure instead of the traditional tube, D-spar, or I-beam. Each vertex of the triangle featured commercial off-the-shelf pultruded carbon fiber tubes that acted as spar caps (Figure 15). The connecting shear web was filament-wound to achieve optimal orientation of carbon fiber with minimal labor intensity. Foam strips (Figure 15, top) were strategically placed in the web members that experienced compressive loads, creating high stiffness sandwich structures to resist local buckling. These strips added very little weight but significantly increased overall spar strength.

The spar weight reduction research effort focused on developing a lighter prototype spar that would meet the same stiffness and strength as the *Gamera I* spar, while adhering to the same airfoil thickness constraint. The spar of *Gamera I* was a uniform beam, with constant spar cap mass along the span. The prototype spar design instead had the spar cap mass (and hence *EI*) distributed along the span by decreasing the diameter of the carbon tubes used from the root to the tip (Figure 15, middle). This reduced spar cap mass by 19% while maintaining the same level of tip deflection.

The shear web weighed more than the spar caps, contributing 58% to spar weight. The shear web on *Gamera I* used two layers of a 50K (50,000 fibers per bundle) carbon fiber filament tow wrap. For the prototype spar, 24K size carbon tow (Figure 15 bottom) was used, reducing shear web mass by 45%. Finite element analysis indicated this reduced shear web mass had negligible impact on tip deflection and, with the application of foam reinforcement strips, would not experience local buckling under design loading. With these two relative simple design changes, weight for a matched-performance *Gamera I* spar was reduced by over 30%. The prototype spar was constructed to prove the projected weight savings and was statically loaded to demonstrate that tip deflection and overall strength requirements were met.

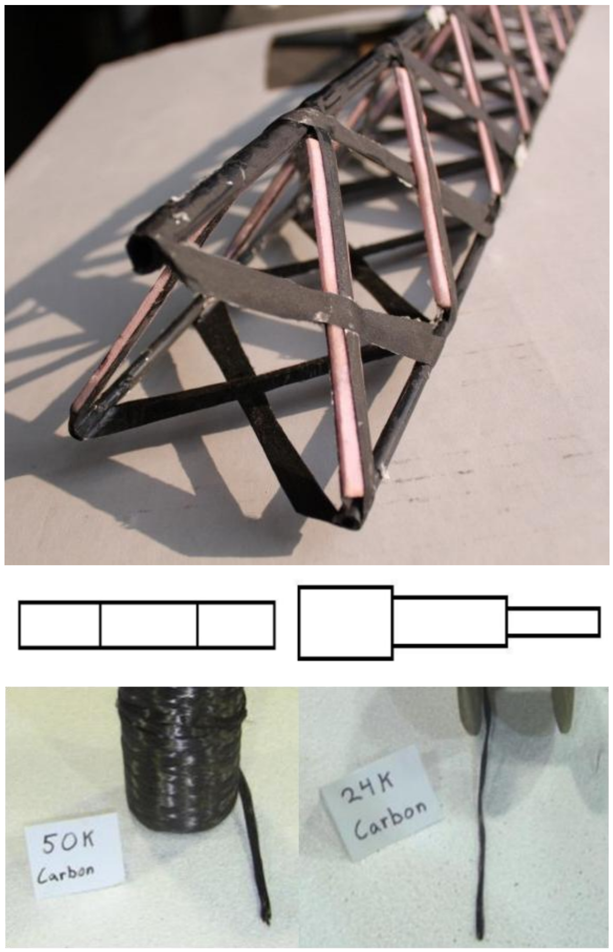

Figure 15: *Gamera I* Blade spar truss design (top) with uniform spar caps (left middle) and 50K carbon tow shear wrap (left bottom). Prototype spar used distributed cap mass through stepped tube diameters (right middle) and 24K shear wrap (right bottom).

Leading Edge Structure

The leading edges of the *Gamera I* blades were cut from large blocks of extruded polystyrene (XPS) pink foam using a hot wire, creating a single monolithic shell structure. This approach minimized the number of joints, reduced construction time and weight due to adhesives, and increased fidelity of the airfoil section. However, the total weight of these leading edge structures was significant (Figure 13). Expanded polystyrene (EPS) white foam offered an attractive weight alternative with a density 40% less than that of XPS. Additionally, the hot wire cutting technique was refined to allow thinner shell walls to be consistently manufactured. The thinner shell wall and the lower density foam reduced leading edge weight by an estimated 53%. There were, however, concerns about the implications of the reduced stiffness and the relatively rough surface—compared to the XPS foam—on aerodynamic performance. These concerns were addressed in the proof-of-concept blade testing detailed in the next section.

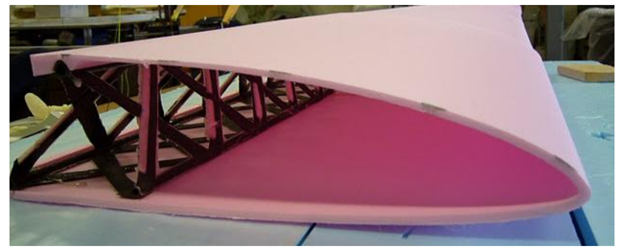

Figure 16: *Gamera I* rotor blade leading edge constructed of an extruded polystyrene (XPS) foam shell.

Trailing Edge Structure

The trailing edge of the *Gamera I* rotors was built up from lightweight foam ribs, a balsa trailing edge wedge, and a thin Mylar skin. Alternatives to these components were explored, such as replacing the trailing edge with a thin foam shell, similar to the leading edge. At the end of the trade studies it was found the current design was the lightest option and was continued with minor changes.

Blade Structure Technology Demonstrator

A prototype full-scale rotor blade (Figure 17) was constructed out of the new spar and leading edge technologies as a proof of concept. For a fair comparison with the original *Gamera I* blades, it was built to the same geometry (radius, chord, airfoil, etc) and was designed to match tip deflection under design loading. The goal was to validate projected weight savings, and also quantify any changes to aerodynamic performance.

Figure 17: Prototype rotor blade matching *Gamera I* blade geometry but constructed using *Gamera II* materials and techniques as proof-of-concept of weight-reduction technology.

The prototype blade was tested in hover on the full scale rotor test stand at design conditions. Several important lessons were learned from this testing. Initially the power requirements were much higher than the original blades. This was theorized to be caused by porosity and surface roughness in the thin EPS foam leading edge shell. To seal and smooth the surface, a single layer of Mylar—similar to what was used as the trailing edge skin—was wrapped over the leading edge. Subsequent tests showed a reduction in power to levels equivalent with the original *Gamera I* rotor blades (Figure 18). Even with the extra Mylar weight, the change to an EPS leading edge still offered a significant weight reduction. The total blade weight savings of the prototype blade was about 30% compared to *Gamera I* blades, with no change in aerodynamic performance.

During hover testing torsional oscillations were observed and were traced to local buckling of the thinner shear web in the prototype spar. This was noted and addressed in *Gamera II* by placement of the spar for minimum pitching moment as well as expanding the use of the carbon-foam sandwich structures to all shear web members.

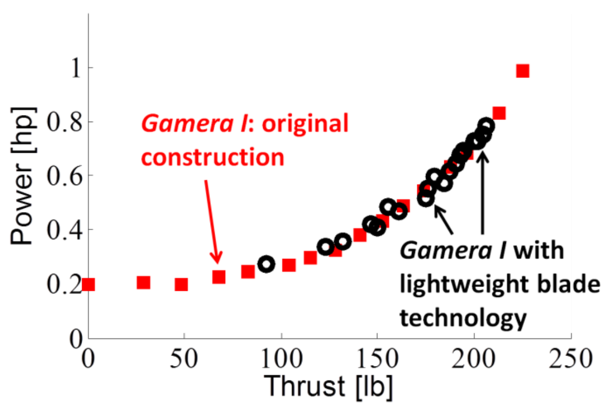

Figure 18: Full-scale hover stand results (scaled for all 4 rotors) at 51cm height, 18 RPM, demonstrating the lightweight blade technology did not negatively impact aerodynamic performance.

AIRFRAME STRUCTURE DESIGN

The airframe truss arms of *Gamera I* (see Figure 2) were built using commercially-available pultruded unidirectional carbon fiber tubes. The advantages of these tubes were high specific axial stiffness and a ready availability of supply. The major limitation of these tubes was the discrete set of sectional properties available. An optimization routine based on a genetic algorithm was specially developed to design the 3D truss—in both layout and tube size distribution—based on given degrees of freedom and constraints (Figure 19). Further details of this optimization process can be found in Reference 1.

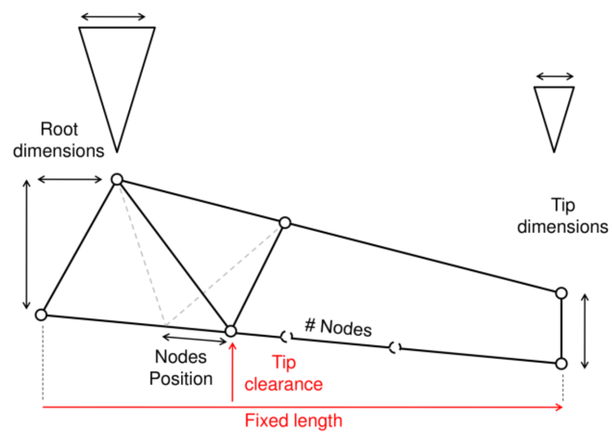

Figure 19: Truss optimization degrees of freedom.

During *Gamera I* airframe development, the discrete set of tube diameters available off-the-shelf was problematic to address the high compressive loads near the truss root. The design limitation in these members was buckling stability, which is addressed by increasing bending stiffness (*EI*). Due to relatively small tube diameters and high wall thicknesses available, the tubes which could resist the highest compressive loads had *EI*/mass efficiencies lower than the team preferred. To address the deficiencies of the commercial tubes, the team developed micro-truss structures as replacements.

Micro-Truss Technology

Mitigating the weight penalty imposed by the heavy compression root truss members required further innovations from the team. Adapting lessons from the blade spar design, a continuously wound micro-truss construction method was developed (Figure 20). These innovative structures allowed specialized truss members to be designed with a high buckling resistance (*EI*) but at low weight.

Figure 20: Detail of micro-truss structure (top) and micro-truss under compression testing (bottom).

The first micro-truss design was not fully matured until the *Gamera I* truss arms had already begun construction. Thus, there was limited use of the micro-truss technology on *Gamera I*; it was only applied to the members experiencing the highest compressive loads. *Gamera II* was able to take advantage of these micro-truss structures from inception. Additionally, a new lighter variant of the micro-truss was developed to be able to replace even the lightest carbon tube options. This new “light” micro-truss and the “heavy” (relatively speaking) micro-truss from *Gamera I* were included as alternatives to commercial carbon fiber tubes in the genetic optimization algorithm. Figure 21 shows the two sizes and efficiencies of micro-trusses in comparison with the commercial carbon tubes. A 620% increase in buckling efficiency was achieved while the linear density was comparable to the smallest commercial tubes considered in the design.

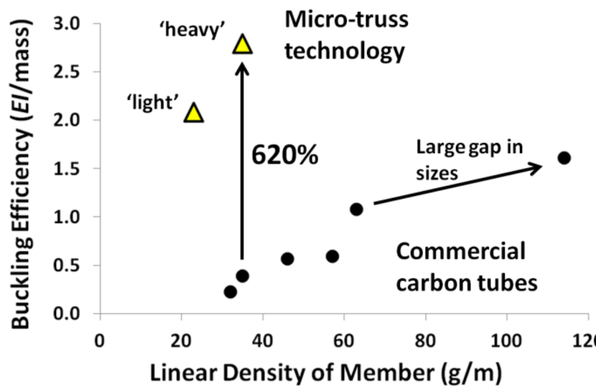

Figure 21: Comparison of buckling efficiency between commercially available carbon fiber tubes and micro-truss technology.

One arm of the final airframe structure of *Gamera II* is shown in Figure 22, which illustrates the extensive use of the micro-trusses. Heavy micro-trusses were selected on the upper root sections for highest buckling resistance, while the light micro-trusses were selected near the tip and for all diagonal and lateral members. The tension members on the lower side of the truss remained as carbon tubes since they only required axial stiffness.

The significant impact of micro-truss technology on the design weight of the airframe is shown in Figure 23. The airframe of *Gamera II* is 39% (5.7 kg, 12.5 lb) lighter than *Gamera I* and 44% lighter than the pre-*Gamera I* airframe, which did not utilize any micro-trusses.

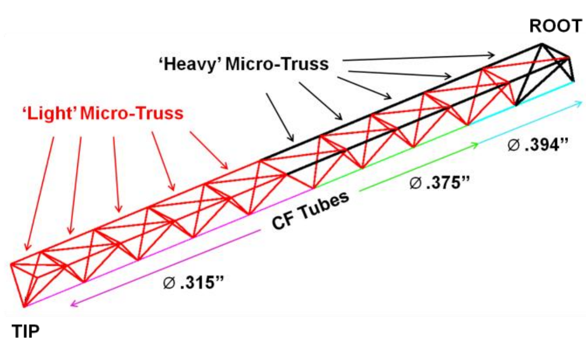

Figure 22: Member selection and truss layout for optimized *Gamera II* airframe.

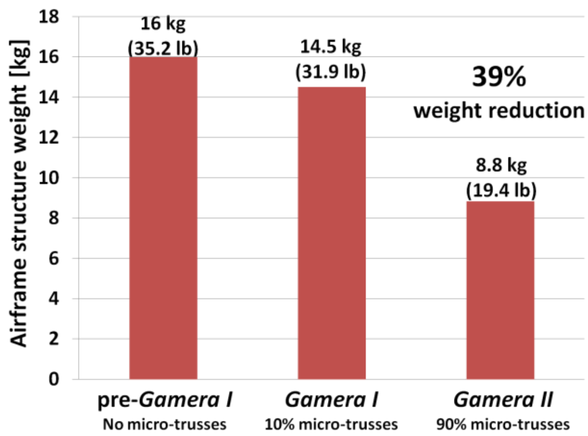

Figure 23: Weight reduction achieved in design of *Gamera II* airframe through prolific use of micro-trusses.

ROTOR AERO-STRUCTURAL OPTIMIZATION

From experience on *Gamera I,* it was learned that blade elasticity can significantly impact performance when operating in deep ground effect. Steady flapwise bending (coning) deflections cause a loss of ground effect in the outboard region of the blades. Because of this phenomenon, the structure of the blade has a major impact on aerodynamic performance, and cannot be considered independent in the design process. Therefore, an optimization process was developed that simultaneously sized the spar structure (spar cap tube sizes) and the blade aerodynamic design (airfoil, planform, radius) to give minimum power required to hover.

Structural Weight Models

Vehicle gross weight was updated with each iteration of the optimizer based on the design variable values and weight models that were developed from experience on *Gamera I* and through the *Gamera II* research and development efforts detailed earlier in this paper.

The spar cap tubes provided resistance to bending by maximizing the second moment of area (I) within the airfoil shape. Thus the choice of tube sizes (cross-section area) and spar height fully define the flapwise bending stiffness (EI) of the blade. The spar height was limited by the airfoil choice, chord length, and finite blade skin thickness (Figure 24). Spar weight consisted of the spar cap tube sizes and the shear web wrap, which had known mass distributions from prior builds.

The blade leading and trailing edge structures were assumed to scale linearly with local blade chord length and were benchmarked from the measured weights of similar components on the *Gamera I* blades and the prototype lightweight blade mentioned earlier.

An airframe truss weight model was developed that was a function of rotor radius and required tip load (itself a function of gross weight). This model was a regression of a parametric sweep of truss length and tip load run by the airframe optimizer. Cockpit and transmission component weights were assumed fixed.

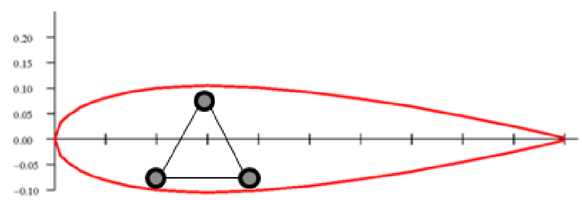

Figure 24: Schematic showing spar placement and height constraints within a notional airfoil.

Optimization Methodology

The optimization process was set up to find the minimum power required to hover for a given pilot weight and target altitude. There were global design variables (radius, tip speed, root cutout length) and design variables that were defined for each blade element (airfoil choice, chord, spar tube diameter). Blade pre-twist was not included in the design space after showing small or no gains in deep ground effect over untwisted blades in sub-scale testing (see prior section on ground effect). The optimizer had a selection of 13 airfoils (Figure 25), all with airfoil tables that covered the Reynolds number range of interest (10^5 to 10^6). The carbon tube choices for the spar caps were from the same discrete selection as for the airframe truss arms (Figure 21).

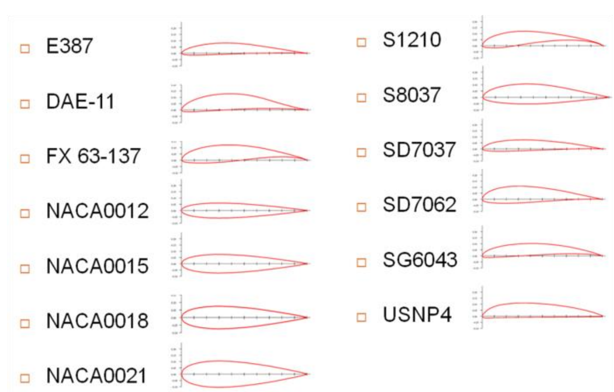

Figure 25: The list of airfoil options included in the rotor optimizer, including the E387 (*Gamera I*) and the S8037 (*Gamera II*).

A genetic algorithm was selected as the rotor optimization routine for the ability to handle discrete variables (airfoil, tube size). Importantly, it has a random search ability that is more likely to find global optimums. The potential for local optimums is very high with the rotor optimization, since each airfoil choice could have a very different optimum chord distribution, tip speed, etc.

Rotor Trade Studies

Multiple trade studies were performed during the design process, the results of which are summarized in Figure 26. Aero-structural optimization was first performed using *Gamera I* structural weight models for a sweep of rotor radius. This sweep included the option for five different airfoil choices along the span, as well as bi-linear planform taper. The optimized blade designs typically featured thick airfoil choices at the root, for maximum flap bending stiffness, and thinner airfoils at the tip for lower profile drag. This sweep highlighted the enormous benefits of performing combined aero-structural optimization, with a 25% decrease in power over the *Gamera I* rotor for the same structures technology and same radius (Figure 26).

Once the *Gamera II* research efforts were complete, these new weight models—including significantly lighter blade and airframe structures—were included. These structures technology improvements and the combined optimization showed a remarkable 44% decrease in power required over *Gamera I* (Figure 26). The pilot power-duration data from Figure 4 was added to the secondary axis of Figure 26, indicating these new technologies allow greater than the target 60 second hover duration, a significant breakthrough. Note the non-linear increase in duration for decreases in power, an artifact of human physiology in the region between anaerobic and aerobic exertion (reference Figure 5 and the discussion in the human power research section).

It is also clear that the new structures allow for a larger rotor radius due to the smaller growth in vehicle weight. Using *Gamera I* structures the optimal radius is 8.5 m, and with *Gamera II* structures the optimal radius is closer to 9.0 m. Increased radius has the typical benefit of lower disk-loadings, but also enhances ground effect for the same dimensional hovering height.

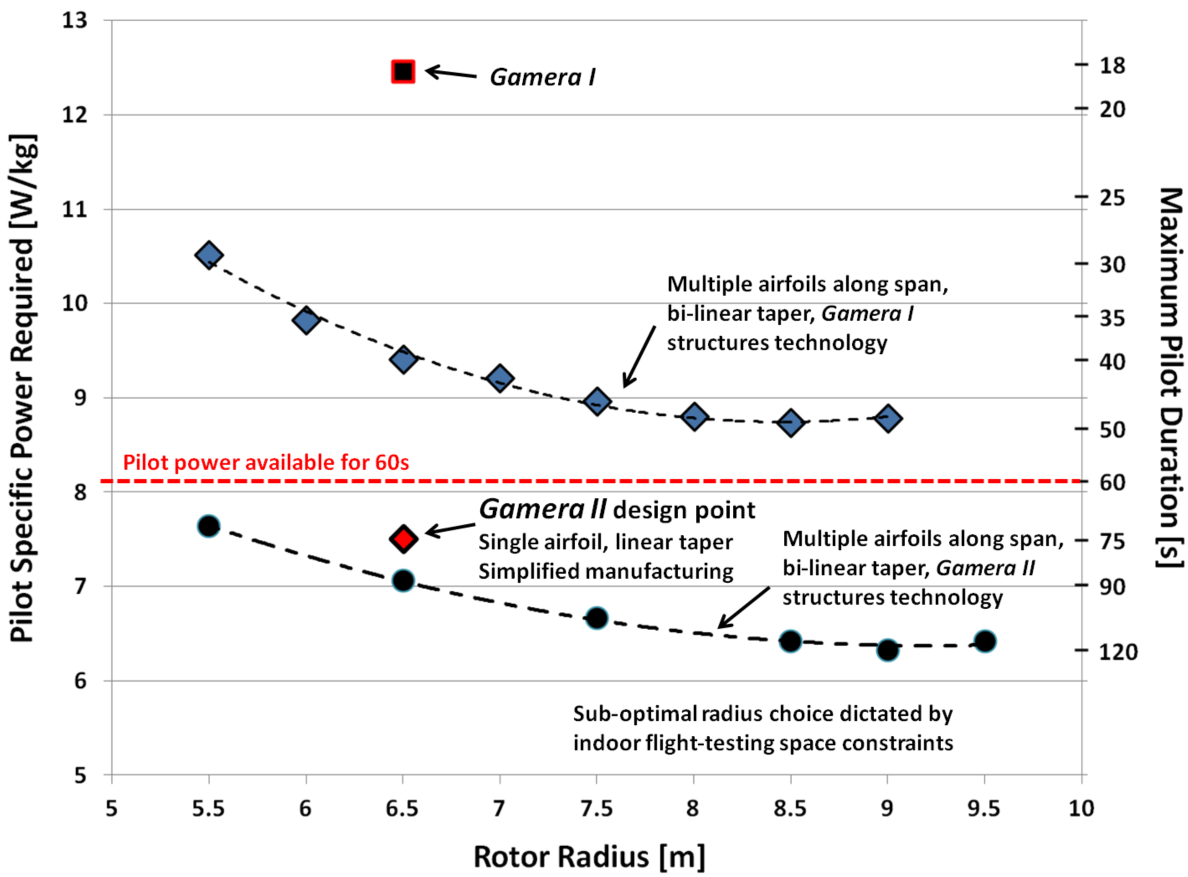

Figure 26: Rotor design trade space for radius, structural technologies, and manufacturing complexity. *Gamera I* and *Gamera II* design points highlighted. Power required is shown for rotor height of 60 cm above the ground plane.

However, logistical constraints had to be accounted for in the design process. The very low operating tip-speeds of the rotors demands that flight-testing be performed in a quiescent flow environment (indoors). *Gamera I* was tested in a large indoor gymnasium and even this space appeared smaller than would be desired for wall clearance and drift allowances (there is no active control system). Therefore, for *Gamera II*, it was decided to limit the maximum rotor radius to that of *Gamera I* (6.5 m). This incurred a net power penalty of almost 10%, but was unavoidable.

The second logistical concern was the complexity involved with manufacturing a rotor blade with bi-linear taper and changing airfoil shape along the span. It was certainly feasible, but would incur a project schedule delay. A trade study was conducted to quantify the performance penalty of a rotor restricted to simpler geometries. Optimization was limited to 6.5 m radius, single linear taper ratio, and single airfoil choice for the entire span. This 'simplified manufacturing' option increased power by about 6%. This was deemed acceptable since it still met the 60 second duration target and it offered non-trivial construction benefits. This design point (Figure 26) was selected for implementation on *Gamera II*.

Gamera II Rotor Characteristics

The important aerodynamic distinctions between the rotor of *Gamera I* and *Gamera II* are listed in Table 1, and visual differences can be seen in Figure 27. The 16% thick S8037 airfoil and the tapering blade/spar create a much stiffer spar structure near the root. The higher thickness also allowed reduced blade chord—while still maintaining adequate stiffness—which significantly reduced blade skin structure weight. Root cutout additionally reduced blade weight while increasing root stiffness.

Table 1: Comparison of *Gamera I* and *Gamera II* rotor parameters.

	Gamera I	***Gamera II***
Radius	6.5m	6.5m
Airfoil	E387	S8037
Taper ratio	1:1	3:1
Twist rate	0	0
Solidity, σ_e	0.098	0.049
Operating C_T/σ_e	0.106	0.155
Tip speed	12.3 m/s	13.5 m/s
Tip Reynolds #	$8.4\text{x}10^5$	$2.8\text{x}10^5$
Root cutout	0%	20%
Root stiffness	1x	6x
Blade mass	3.3 kg	2.0 kg

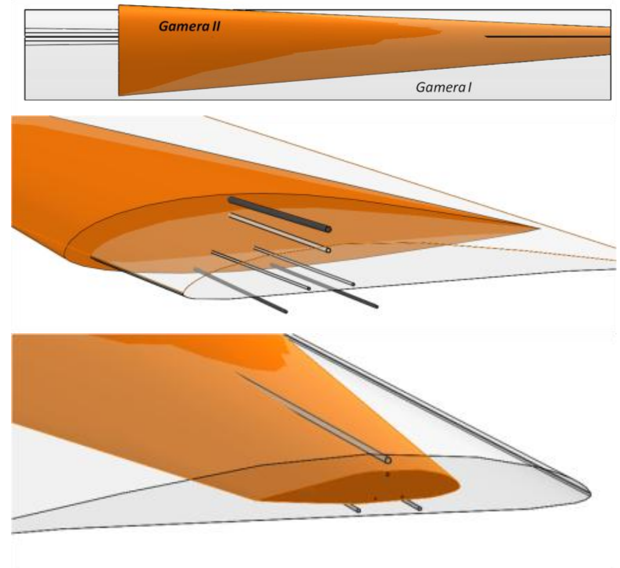

Figure 27: Computer models of the optimized *Gamera II* rotor blade (orange) contrasted to that of *Gamera I* (transparent).

TRANSMISSION SYSTEM

The winch drive transmission concept that was adopted for *Gamera I* will be used again in *Gamera II*. This system transmits power from the cockpit to the rotors by the spooling of four high strength Spectra cords. Figure 28 illustrates a schematic of the system and shows its use on *Gamera I*. A single cord is wrapped around each of the four rotor-side pulleys which are mounted to the rotor shafts. Enough string is used to allow the desired flight time, amounting to over 150 m (500 ft) for a full 60 seconds. When the pilot pedals and turns the hand cranks—which deliver power to the feet by means of a synchronous chain—the pilot-side pulley spools in all four cords. Torque is transferred to the four rotors as the cords are spooled in by the pilot (Figure 28). The cords are directed into the cockpit from the main airframe structure by a series of lightweight redirecting pulleys.

The gear ratio of the pilot-side pulley diameter to that of the rotor pulley is set by the desired rotor speed (for best aerodynamics) and the pilot's optimum pedaling RPM (for best power output). On *Gamera I*, pedaling RPM was set at 120 to maximize power output over a short duration to achieve lift-off. For *Gamera II*, a target pilot cadence of 90 RPM will be used, better suited to longer duration flights as shown previously in Figure 8.

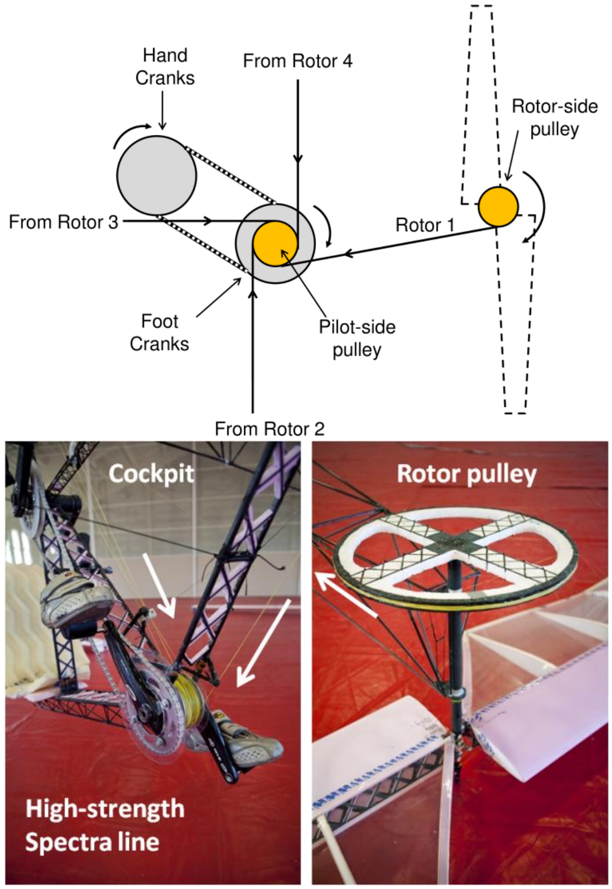

Figure 28: Schematic of winch drive transmission system (top) and *Gamera I* cockpit and rotor pulley showing path of transmission line (bottom).

The advantages of the spooling system are a simplification of the transmission mechanism and a significant reduction in weight. The weight of the cord used during the flight testing of *Gamera I* was 65 g for 60 seconds of allowable flight time. Alternatives to the winch drive included chain- and belt-driven systems. These options would provide continuous operation and decrease set up time between flights, however they would add weight and mechanical complexity. A synchronous chain drive would weigh about 130 g/m, totaling 10 kg for all four rotors. Even though a belt drive would be half as heavy as a chain at approximately 5 kg, it is still considerably heavier than the string required. The additional sprockets and tensioning needed for these alternatives would add further weight which is avoided by use of the winching drive.

A flywheel is being added to the transmission system in *Gamera II*. A drawback of the one-way drive system is that the rotor inertia does not assist the pilot in maintaining a constant RPM. The pedaling motion is highly impulsive with cyclic variations in pilot torque. It was believed that utilizing hands with their power stroke synced 90° out of phase from that of the feet would be adequate to alleviate this problem, eliminating the need for a flywheel used in other human-powered aircraft. This was found qualitatively to be insufficient. The transmission cord elasticity and elastic deflections in the cockpit structure were believed to be exacerbating impulsive pilot pedaling motion and causing alignment issues between the hand and feet chain sprockets, all of which waste energy. The flywheel was sized with enough inertia to smooth the pilot motion at full power output.

Although it should improve efficiency, increasing the amount of power delivered to the rotor, the addition of the flywheel comes with a weight penalty of 500 g; not only from the wheel itself, but also the additional structure, sprockets, and chain weight. Initial flight testing of *Gamera II* will evaluate whether the smoother pilot motion is worth the weight. A modular design is being employed which will allow the system to be removed in the event that it does not provide a net benefit, leaving only a negligible amount of residual weight.

COCKPIT DESIGN

The *Gamera II* cockpit, which houses the human pilot, must be both comfortable and stiff to ensure maximum power generation. The cockpit was designed to suit the pilot candidates, with a custom sizing rig used to tune the cockpit dimensions. Adapting the filament-wound truss concept to the load carrying members of the cockpit has allowed the stiffness to be maximized while maintaining low weight and without impacting the motion of the pilot. Elastic deformation in the region of the cockpit connecting the hand and foot cranks caused repeated transmission failures in *Gamera I* as deflections caused the hand and foot chain sprockets to become misaligned.

To increase the stiffness in this critical area, the *Gamera II* cockpit is built around a 3D box truss that creates a rigid link between the bearings of the pilot hand and foot cranks (Figure 29). From this core structure, several 3D truss members form the rest of the cockpit, connecting the transmission to the pilot seat and the main airframe (not shown). The connection to the airframe consists of three clevis fasteners, allowing the cockpit to be removed for transportation. The cockpit features several attachment points for guy lines which extend outboard and connect to the airframe structure. These wires add support against lateral deflection, reducing the energy wasted on undesired motion.

The hand grips, shown in Figure 30, were made using a novel multistate mandrel system, which allowed for complex and captive geometries to be quickly made with very low tooling cost. This mandrel was perfectly molded to the hand of its specific pilot for an ideal fit. In addition to being strong and comfortable, the custom carbon fiber grips only weigh 16 g each. The same technology was successfully proven on *Gamera I*.

Figure 29: Box-truss cockpit core concept with hand and foot cranks mounted.

Figure 30: Ergonomic custom-made pilot hand grips.

SECTION 2: *GAMERA II* CONSTRUCTION AND COMPONENT TESTING

Full-scale construction of *Gamera II* began in November 2011 and is currently in progress. Estimated date of completion and flight testing is during the summer of 2012. The following sections will summarize progress to date on the construction of major components, as well as compare design estimates with actual component weights/performance where available.

Airframe Construction

Construction of the each of the four airframe truss arms begins with the production of 100 m (320 ft) of micro-truss structures. These micro-trusses are manually filament-wound using a patent-pending manufacturing method developed by members of the team. Innovations in winding techniques and a relentless focus on efficiency increased production output capacity of micro-truss structures by an order of magnitude compared with *Gamera I*.

Assembly of the micro-trusses and carbon tubes into the full-length truss arm was facilitated by a custom-built construction jig (Figure 31). This jig ensured correct and repeatable geometry for all four truss arms and was another significant logistical improvement over *Gamera I* techniques. To date, two full truss arms have been completed (Figure 32), each weighing slightly under the 2.2 kg design estimate. Cantilevered static proof loading of the truss arms is planned before final vehicle assembly.

Figure 31: Assembly jig for one airframe truss arm.

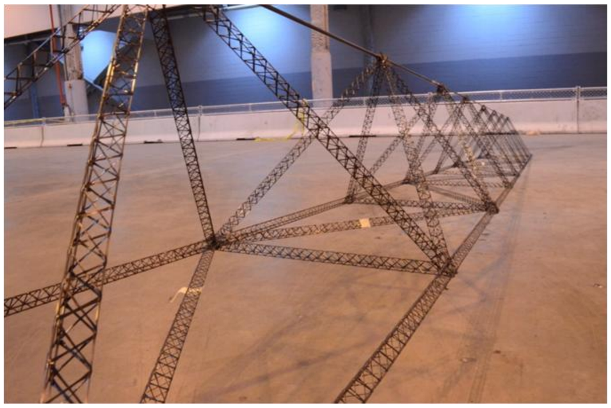

Figure 32: Completed airframe truss arm composed of micro-truss structures.

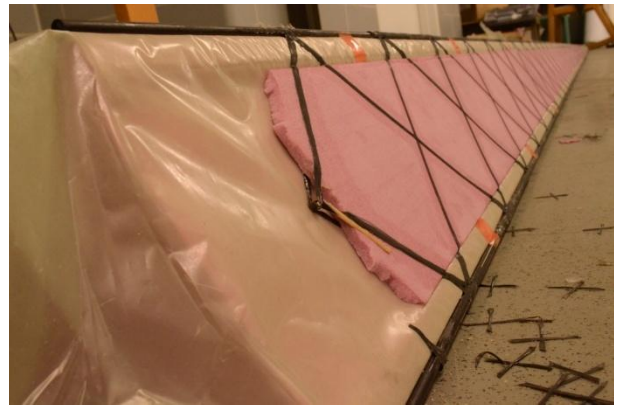

Figure 33: *Gamera II* spar with foam plates after filament-winding, vacuum bagging, and room-temperature curing process.

Spar Construction and Testing

The spar construction process was relatively unchanged from *Gamera I*; however, the introduction of tapering spar thickness required some adjustment. One of the main differences was the thinner shear web wrap, which necessitated creating carbon-foam sandwiches for every member to prevent buckling. To create these sandwich structures, foam plates were inserted between the carbon filament layers during wrapping (Figure 33), and the excess foam was removed after cure by a razor blade (Figure 34).

Each spar was static tested to prove strength and validate design tip deflection. A series of discrete masses were hung from the spar, their weights chosen to mimic the thrust expected along the blade (Figure 35). Torsional loads were predicted to be small due to low airfoil pitching moments and proper chordwise placement of the spar. Tip deflection at full simulated thrust was measured as 30 cm (1 ft), fully acceptable compared to design estimates of 25 cm, and significantly reduced from the approximately 100 cm tip deflections of *Gamera I*. Spar weight estimates were also quite good; four completed spars weighed an average of 1074 g compared with design estimate of 1050 g.

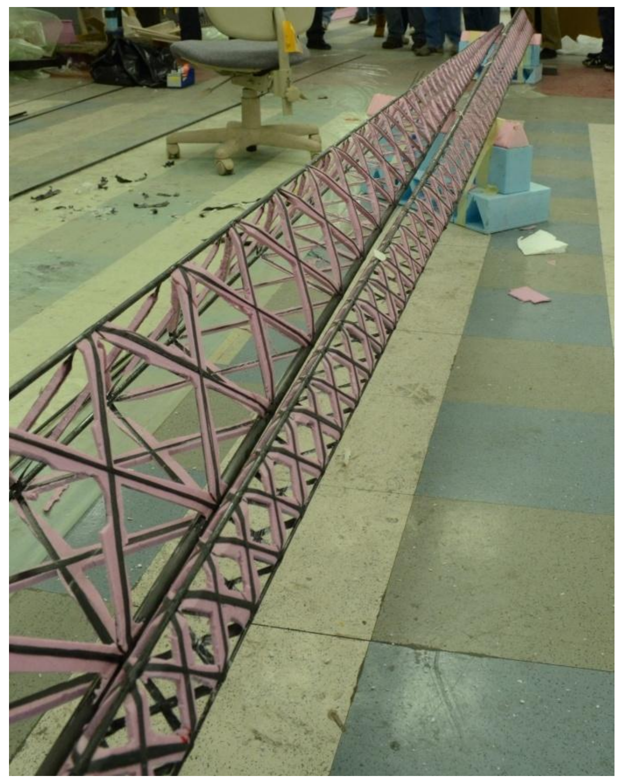

Figure 34: Finished *Gamera II* spars.

Figure 35: Image of a *Gamera II* spar under distributed static load simulating full thrust.

Rotor Performance Testing

Two spars were built into full rotor blades and the full-scale rotor test stand was used to evaluate their performance (Figure 36). Rotor blade weight was an average of 1880 g compared to 1750 g design estimates. Testing sweeps were performed over a range of thrust and rotor speeds (Figure 37). As expected, higher RPM values required more power at low thrust (higher profile power), but showed performance improvements at higher thrusts (lower induced power, higher stall margins). A rotor speed of 19-20 RPM was found to require the lowest power at the target thrust (206 lb), comparing favorably with the design estimate of 20 RPM.

However, power required at design thrust was higher than design predictions. The near-constant power offset at all thrusts implied the manufactured blades suffered from higher-than-expected profile drag. It was suspected that the airfoil shape was not being well-maintained near the tip, which has the most impact on profile power.

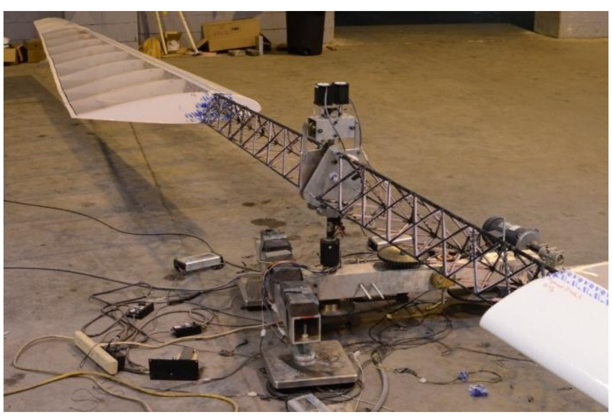

Figure 36: Full-scale hover test stand with *Gamera II* rotor blades.

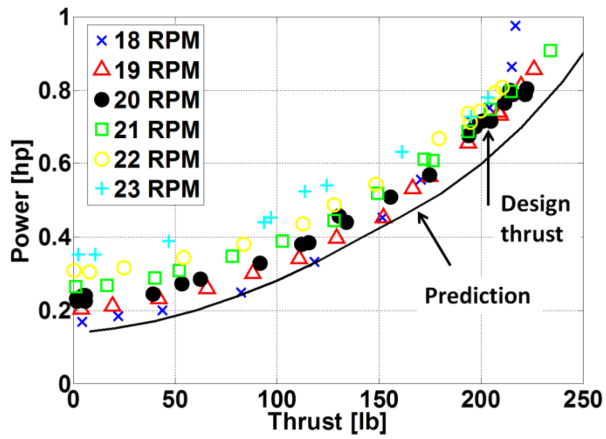

Figure 37: *Gamera II* RPM sweeps to identify best operating point (single rotor data multiplied by four to express total vehicle thrust and power).

To alleviate this, the tips of the blades were replaced with a thin EPS foam shell that covered the entire chord (Figure 38). Because the chord near the tip is relatively small, the weight penalty was only 90 g on top of an 1880 g blade. Performance improvements were observed, although power requirements were still about 9% above predicted. All future blades will include this foam shell tip.

A second trade study investigated the impact of rotor pre-coning on performance. As shown in the ground effect research section of this paper, the location of the blade tips relative to the hub were significant for the ground effect benefits seen by the rotor. When a 3° negative pre-cone was applied to the blade (Figure 39), the tip was initially positioned a full 30 cm (1 ft) closer to the ground, which resulted in a near-horizontal blade after coning deflections under design thrust. The benefit from pre-cone was significant: a further 10% reduction in power required was achieved (Figure 40).

Notice that Figure 40 has pilot weight instead of thrust on the x-axis. The known empty weight of the vehicle for each configuration was subtracted from the total thrust, converting thrust into pilot weight. This created a clear difference between the two vehicles; *Gamera I* requires between 12 and 13 W/kg from the pilots while *Gamera II* requires only 7.5 W/kg for the pre-coned blades. This corresponds to a savings in power density of over 35%.

With negative rotor pre-cone, *Gamera II* is meeting the original design estimate power of 7.5 W/kg. The power available from the 135 lb test pilots has been measured at 8.1 W/kg for 60 seconds (potentially higher for optimal cadence, Figure 8). Human performance is non-linear with power required, and this 7% power margin corresponds to a duration margin of 25%, or 15 seconds. Therefore it is estimated that *Gamera II* should be capable of hover durations up to 75 seconds.

Figure 38: *Gamera II* blade with full-chord foam shell at the tip.

Figure 39: Testing the effect of negative pre-cone (top: baseline, bottom: -3°) on hover performance.

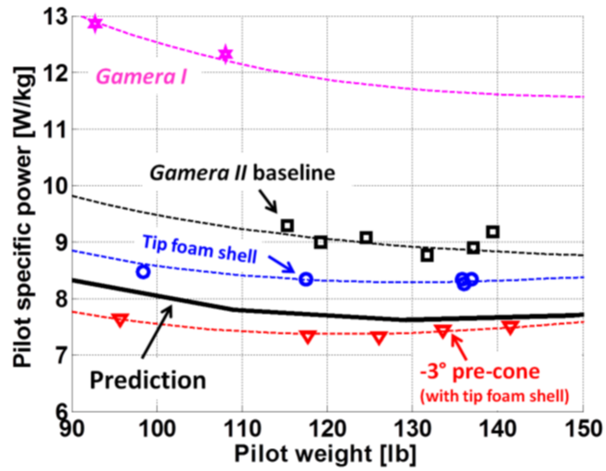

Figure 40: Rotor performance improvements through full-scale hover testing trade studies. Pilot power available for the 135 lb pilot is 8.1 W/kg for 60 seconds.

CONCLUSIONS

A team of students from the University of Maryland—building upon successes and lessons learned from the *Gamera I* human-powered helicopter—have designed and begun construction on *Gamera II*, a significantly improved vehicle. The goal of *Gamera II* is to achieve 60 second hover duration under human power, as progress towards meeting the requirements of the Sikorsky Prize.

Novel weight-saving technologies have been implemented, including prolific use of specially-developed micro-trusses in the airframe, more efficient structural design of the blade spars, and lighter blade skin materials. The new helicopter weighs 33% less than its predecessor, as summarized in Table 2.

Table 2: Summary of *Gamera II* weight savings.

	Gamera I	*Gamera II*
Rotors (Total)	26.3 kg	16.0 kg
Blade spar	11.9 kg	8.8 kg
Leading edge	7.5 kg	2.6 kg
Trailing edge	6.6 kg	4.2 kg
Hub mounts	0.3 kg	0.4 kg
Airframe	14.5 kg	8.8kg
Cockpit	4.3 kg	4.0 kg
Transmission	2.9 kg	3.5 kg
Total	**47.9 kg**	**32.3 kg**
Total Savings	-	**15.6 kg**
(% of total)	-	**33 %**

A combined aero-structural optimization was performed to simultaneously design the blade structure and aerodynamics, resulting in a 44% decrease in required power over *Gamera I*, and a projected quadrupling of possible hover endurance. Stiffer blades and a negative pre-cone allow ground effect to be exploited to a greater extent, and a tapered planform offers increased efficiency.

With improved measurements of the power available from a human engine, it is currently estimated that *Gamera II* will be capable of up to 75 seconds flight endurance at a 60 cm (2 ft) height, achieving the target goal of a 60 second hover. Construction is underway at the time of writing and flight testing is scheduled for the summer of 2012.

ACKNOWLEDGEMENTS

This project would not have been possible without the support, passion, and unwavering optimism of the Dean of the Clark School of Engineering, Dr. Darryll Pines. The team would also like to thank Dr. Inderjit Chopra and Dr. VT Nagaraj, who patiently sat through all the weekly team meetings for over 3.5 years, and provided much needed motivation and guidance at critical junctures. This paper is dedicated to all of Team *Gamera*, past and present; those 75+ students and friends who made this dream a reality.

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