

# Dirigible UAV Power Plant Design

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**Abstract**—Dirigibles have the ability to take off and land vertically, hover and maintain lift without consuming energy and can be easily deflated for packaging and transportation. As such, dirigibles are well suited for surveillance and surveillance missions such as rescue and aid operations after disasters. This paper reviews hybrid dirigible UAV design considerations and presents a novel hybrid power plant design. The hybrid power plant design consists of a 2-stroke 4cc glow engine in-line with a brushless DC motor/generator and variable pitch propeller capable of producing a maximum power output of 148.4W.

## INTRODUCTION

Dirigibles have several advantages over fixed wing and rotary wing aircraft. They have the ability to maintain lift without consuming energy making them ideal for long range and long endurance missions. This ability also allows them to take off and land vertically without the need for a runway and hover in place to monitor developments on the ground. Dirigibles can be easily deflated for packaging and transportation and then inflated on site before operation. As such, dirigibles are well suited for use as reconnaissance platform to aid rescue crews after disasters [1]–[5].

An endurance and payload comparison between fixed wing, rotary wing and dirigible UAVs is shown in Figure 1. These data were collected and combined from multiple sources [6]–[9]. UAVs that do not travel, such as aerostats, and upper atmosphere UAVs were excluded. Data were also excluded if inconsistent between publications or when only a range was provided. Based on the data in Figure 1, it can be seen that the majority of UAVs with payloads under 1 kg have a flight endurance of 1 hour or less. Furthermore, UAVs that have large payload and endurance tend to have large unit cost. Cost metrics can be used to compare the performance of the entire spectrum of UAVs [6]. A cost metric consisting of the cubed root of the products of range, endurance, and payload is applied for a baseline of existing technologies. Based on the performance results shown in Figure 2, it is clear that a robust UAV system is needed to meet the operation requirements of both long endurance and long range while maintaining a low unit cost.

This paper presents the design and testing for a novel hybrid power plant design for a UAV dirigible. First, power requirements and design considerations are discussed. Then an overview of the power plant design followed by the methodology and results from the experimental testing. The UAV design is then compared to existing UAVs on the basis of cost, payload, range and endurance.

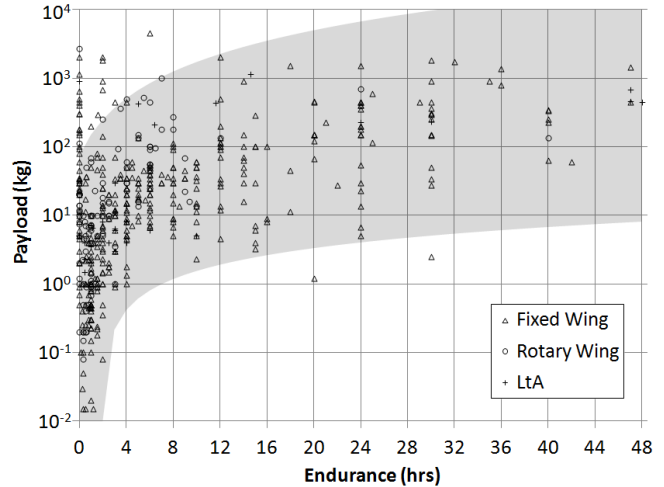


Figure 1: UAV Payload Capacity versus Endurance. Data was collected from both military and research agencies from several countries. These data were summarized from multiple sources [6]–[9].

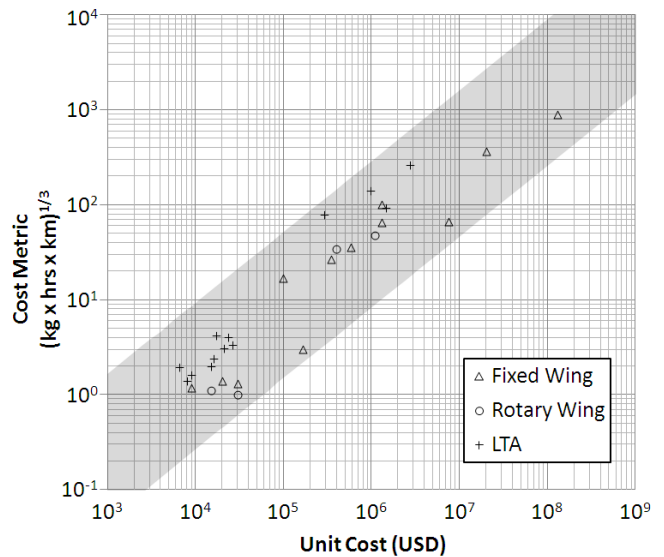


Figure 2: UAV Cost Metric (Payload x Endurance x Range) versus Unit Cost [6]–[9]

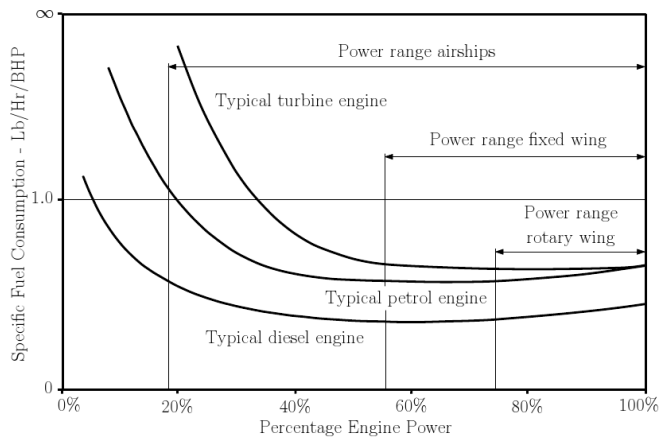


Figure 3: Specific Fuel Consumption for different aircraft types [10]

### Dirigible UAV Power Requirements

The propulsive power requirements of lighter than air (LTA) aircraft are far greater than of heavier than air (HTA) aircraft as LTA aircraft do not require propulsive power for lift. This presents a problem when selecting a suitable prime mover. Electrical power requirements for LTA aircraft can be over 65% total power and average cruise speeds compared to 15% for HTA aircraft [10]. Purely electric propulsion designs have significantly shorter flight endurance due to the lower energy density of electric power storage coupled with high electrical power requirements. Purely piston powered propulsion designs suffer from significant increases in specific fuel consumption at low engine power (during idling) and have a narrow peak efficiency range which makes varying the load on the engine undesirable. Furthermore, electrical energy storage is still required for avionics, therefore neither fuel or electric energy cannot be fully consumed during flight (the first depleted will limit flight endurance). The generally accepted ideal solution is to drive electric generators from piston powered propulsion engines [10], [11].

### Hybrid Power Plant Design

The proposed hybrid power plant consists of an engine, a brushless DC generator and a propeller connected in series as shown in Figure 4. This configuration provides the most flexible operating conditions as both fuel and electrical energy can be depleted simultaneously (maximizing flight endurance). The engine can be shut down during periods when propulsion or electrical generation is not required and the generator can be run in reverse to start the engine when required, eliminating the need for a separate starter motor. Starting and stopping the engine as required keeps the engine under constant load and maximum efficiency, and maintains the batteries in their useful operating range. Properly matching the engine and generator speed ranges can minimize specific fuel consumption of the engine. Maximum propeller efficiency can be achieved by implementing a variable pitch propeller. When the power plant is connected to the UAV, the engine is turned on according to the current flight

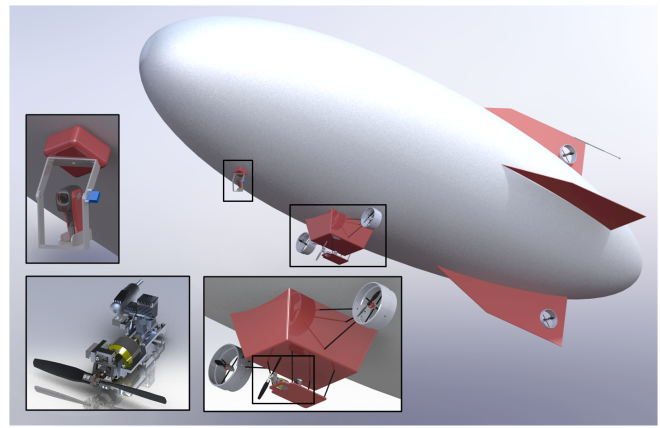


Figure 4: Dirigible design (middle), camera, GPS and inertial navigation system (left), hybrid power plant (lower left), and auxiliary electric propulsion (below)

conditions. The conditions can include distance remaining to target, UAV operating speed, opposing wind and the State of Charge (SOC) of the battery. This design can be adjusted for the following three scenarios:

- 1) Maximum engine efficiency - Minimizing engine fuel consumption and maximizing flight duration are paramount in this operating mode. The loading of the engine is held in its maximum efficiency zone by balancing the mechanical propulsion and electrical generation based on the current flight conditions, trip characteristics and SOC of the battery.
- 2) Maximum propulsion - This mode is used when propulsion is required but not electrical generation such as when the batteries are charged but the LTA needs to move to a position quickly. During this time, the batteries cells can be electrically disconnected and the propeller pitch can be adjusted to maximum thrust based on current airspeed.
- 3) Maximum electrical generation - This mode is used when electrical generation is required but not propulsion such as when the batteries need to recharge and the LTA is hovering in one place. During this time, the propeller pitch is adjusted to a feathered position and additional battery cells are electrically connected.

### Design Considerations

The maximum in-flight fuel usage for LTA aircraft is restricted by the maximum takeoff weight and the minimum landing weight [10]. To extend the in-flight fuel usage, it is assumed that air will be gradually collected to balance fuel depletion. For the purposes of this design, the maximum in-flight fuel usage will be limited to 3kg of fuel. If severe overpressure is detected, helium will be vented to prevent damage to the helium bladder. This method is ideal because it provides a means for altitude control and can regulate the dirigible's internal pressure to safe levels.

Another design consideration is the battery charging rate. The generally accepted charging rate of most lithium ion

rechargeable batteries is no more than one times the battery capacity. Hybrid designs benefit over purely electric designs in that most of the energy is stored in fuel which has a much higher energy density than a battery's energy density. Ideally, the battery capacity should be minimized to reduce the weight of the power plant. Since the battery capacity is limited by the magnitude of power it can accept and the duration it is rated to accept it, the battery was chosen based on the maximum electrical generation of the selected engine-generator combination. Recently, new generation lithium polymer batteries have been released that offer twelve times the capacity charging rate. This significantly lowers the battery capacity limitation and thus reduces the size and weight of the battery.

### Sizing

The initial sizing of the components was determined using the methodology proposed by Pant [12]. The iterative loop begins by estimating the helium volume storage of the airship, also known as the envelope. The envelope, air ballast and tail fin geometry, and the static lift were then calculated based on the volume estimate and the optimal aspect ratio. The optimal aspect ratio of airship length over diameter was selected to be 3.3 based on the minimum sum of form and skin drag on the streamlined National Physics Laboratory low drag airship body shape. Drag, total propulsion power, electric capacity and fuel weight were estimated based on the desired operating performance. The weights of the envelope, gondola, fins, and all sub-systems were estimated using preselected materials or weight factors modeled on existing LTAs [10], [12]. The work envelope is iterated until the difference of lift to weight (payload) converges to a satisfactory value [12].

## HYBRID POWER PLANT DESIGN OVERVIEW

### Engine

Three options for the prime mover include petrol engines, diesel engines and gas turbines. Gas turbines can be omitted based on the relative scale of the UAV being designed (under 2 hp). Engine selection effects specific fuel consumption and weight per unit power. For petrol engines these values are 0.46 lb/(HP-hr) and 0.85 kg/HP while for diesel engines these values are 0.37 lb/(HP-hr) and 1.025 kg/HP [10]. Diesel engines are more efficient per HP and have improved reliability over spark ignition engines. Model (Glow-plug) Engines operate similar to a diesel engine except for the fact that they have a heat filament to aid in combustion and that they use alcohol fuels rather than diesel fuel. A table of fuel properties is presented in Table I. Model engines are best suited for this design and are readily available in the required horsepower range.

These engines come in two or four stroke cycles. Two stroke engines have a higher power to weight ratio, a lower cost per HP, and a simple construction with fewer moving

<sup>1</sup>The purpose of castor oil in 2-stroke glow fuel is for lubrication. During normal operating, oil is not considered to burn during combustion and as such does not contribute to the lower heating value value of the fuel mix.

Table I: Fuel properties

Fuel Type	Density $\left[\frac{kg}{L}\right]$	Lower heating value $\left[\frac{MJ}{kg}\right]$
Petrol	0.745	43
Diesel	0.832	45.4
Ethanol	0.789	31.1
Methanol	0.792	19.9
Nitromethane	1.137	11.3
Castor Oil	0.961	0 <sup>1</sup>
15% Glow Fuel	0.874	15.0

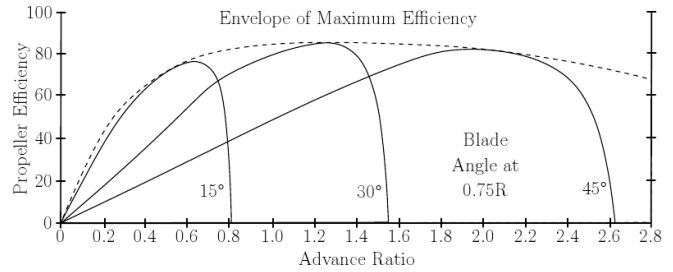


Figure 5: Propeller efficiency versus advance ratio for various propeller pitches [13]

parts. Four stroke engines have a higher fuel efficiency per HP, a longer engine life, a large range of peak engine performance, and tend to run quieter and cleaner. If the peak engine efficiency is matched with the generator output, and controlled in an on and off manner, then having a narrow peak efficiency range is sufficient. A two stroke OS 25LA model engine was chosen for its high power to weight ratio.

### Propulsion

The primary propulsion system consists of a variable pitch propeller connected to the model engine. The variable pitch propeller allows for the three different design scenarios proposed previously. The propeller pitch can be set to the feathered position to charge the battery pack without moving the aircraft. It can also be used to control the engine load for maximum engine efficiency when both generating electrical power and propelling. Alternatively, the propeller pitch can be optimized to maximize propulsion efficiency for a given engine speed when not generating electrical power.

In addition to the primary propulsion system, four additional brushless DC motors, connected to fixed pitch propellers, are used for low speed cruising when the engine is turned off, and for directional control while the UAV is hovering. The UAV's electric propulsion is shown in Figure 4.

### Starter/ Generator

The motor constant of a DC motor is determined from the number of turns and size of the coil. It can be shown that the rated power of the motor is inversely proportional to the motor constant. The motor constant dictates the ratio of rotational speed to voltage and current to torque. The most important consideration when using a motor as both a starter and generator is the selection of motor constant because

the optimal values for these two functions are contradictory. As a generator, the motor constant needs to be sufficiently large such that voltage is generated at a higher potential than the batteries. Most small electronic devices operate at 12V or lower and small model engines run at very high speeds (typically in excess of 10kRPM). As a starter, the motor constant needs to be sufficiently small such that the starting torque can overcome inertia and friction in the engine<sup>2</sup>. The torque required to induce a single turn in the engine was experimentally determined to be approximately 0.7 Nm using a pulley and incremental weights.

A common solution is to add a transmission stage or separate motors for each function, however this adds weight, complexity and non negligible frictional losses. The solution was to use a large electrical motor (with a lower motor constant) and to down convert the output voltage to a useable range when generating using a high efficiency switching buck converter.

The options for electric motors include induction, brushed DC, or brushless DC (a type of 3-phase synchronous motor). Brushless DC motors generate 3-phase AC when driven, therefore they require filtering and rectification. Brushless DC motors also need a specialized electronic speed controller. However, they benefit from higher efficiency and a high power to weight ratio over conventional brushed DC motors. They have excellent heat dissipation, low noise, low maintenance, and great longevity and reliability because there are no brushes to replace [14]. An AXI 4120 brushless DC motor was selected since high efficiency power electronic circuits for motor control, filtering, rectification and DC/DC conversion have advanced to a point where they can be easily and inexpensively assembled in a small form factor using open source designs.

The main disadvantage of a brushless DC generator is that conventional rectification methods cannot achieve the maximum power possible because of a distorted or unsuitable current waveform [15]. A method is proposed by Lee [15] to maximize the power density of a brushless DC generator by actively switching rectifier diodes with PWM signals. Although this method of rectification provides higher efficiencies and the same power stage used for driving the motor could be theoretically used in reverse, its control is complex and requires a high-speed digital signal processor to detect the back EMF and current waveforms. Incorporating a 20 million instruction per second digital signal processor on-board for the sole purpose of rectification is unfeasible therefore a full bridge passive diode rectifier was selected for its low cost, simple construction and lack of complex control.

Another concern regarding power generation is the power factor. Unlike most power generation applications, the brushless DC generator will experience low resistance ( $10^0\Omega$ ) and large operating speeds ( $10^3 \frac{rad}{s}$ ) leading to high inductance.

<sup>2</sup>Particularly when the engine is starting cold, there is an interference fit between the piston head and the cylinder. As the engine heats up during combustion this tolerance increases allowing it to move more freely. This ensures a proper sealing during combustion.

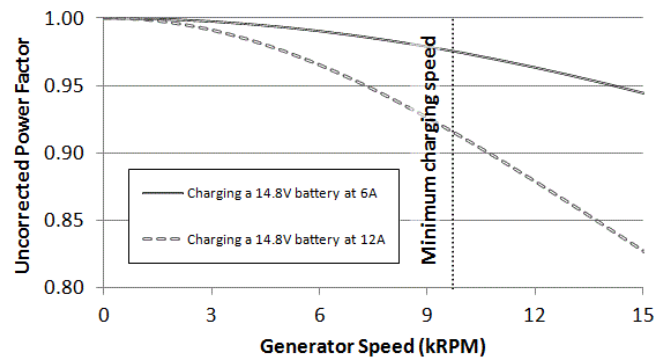


Figure 6: Uncorrected Power Factor

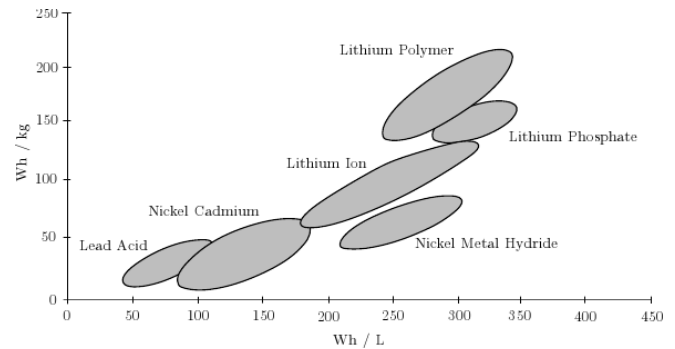


Figure 7: Energy densities of various battery compositions [16]

During high operating speeds, the power factor will begin to drift away from unity as the voltage and current become out of phase with each other as shown in Figure 6. The power factor can be corrected by adding a capacitor in parallel to the resistive load per phase of the generator. This type of power factor correction is only optimal (close to unity) for one operating speed therefore the power factor will decrease as the generator speed moves away from the corrected speed. Since the engine's peak efficiency occurs over a narrow speed range and the engine operation would be relatively constant at the optimal speed, passive power factor correction will be adequate. The results of experimental test on the power generator were used to determine the optimal engine/generator speed and select the power correction factor.

DC/DC conversion is also required in two separate cases on board the dirigible. First to regulate the output voltage of the generator to the working range of the battery charger (16.8V) and second to regulate the battery voltage down to 12V, 5V, and 3.7V sources used by the auxiliary components such as the on-board computer, electric propulsion motors and servo motors. A high efficiency step down (buck) controller circuit was selected for both situations.

### Energy Storage

A comparison of different battery chemistries on the basis of energy mass density and energy volume density (Watt-hours/Liter) is shown in Figure 7. Lithium polymer batteries are the newest generation of lithium batteries offering the

highest energy density compared to other types. They have no memory effect, a good life cycle, high energy efficiency [17]. The most important attributes of this battery are its fast charge and discharge rates. This is vital to hybrid designs as one of the power limitations of hybrid power plants is the charging current provided by the generator. The maximum charging rate for lithium polymer batteries is limited to one times the capacity. The battery capacity must be chosen as a compromise between maximizing charging rate and minimizing weight.

Lithium polymer batteries are not tolerant to over charging or over discharging which both lead to thermal runaway so they require an added protection circuit to prevent these conditions [17]. Battery damage and thermal runaway are associated with overheating. Maximum heat generation in a properly ventilated battery occurs during the final stages of charging (trickle charging) and during discharging (increases as the SOC is reduced). Charging a Li-Ion battery to 100% SOC, or discharging to 0% SOC will degrade its long term capacity [18]. Li-Ion operation SOC is usually limited to a smaller range, such as 30% to 70%. This reduces the useful battery capacity to only 40% of the fully specified capacity [18]. Therefore, the practical energy density of the battery is reduced. Although the useful battery capacity is a limitation of purely electric systems, hybrid systems have the advantage of maintaining the battery in its useful range by charging more frequently. This offers many advantages both for the battery and the efficiency of the system. As with all batteries, its life is extended by avoiding the damaging and inefficient periods of overheating shown in Figure 8. In combination with a hybrid system, keeping the battery within its useful range increases the effective energy density of the system when combined with fuel. Avoiding low power input trickle charge when the battery is near full SOC ensures that the loading on the engine is more stable and the engine is only used in its peak efficiency range. Avoiding near empty SOC prevents battery voltage fluctuations and voltage cutoff during discharging.

#### METHODOLOGY

The hybrid power plant shown in Figure 9 consists of a glow engine, a brushless DC generator, a controllable pitch propeller. The plant frame is fixed to a pressurized air bed that provides a virtually frictionless contact to the test bench. The static thrust of the propeller is measured by a cable connected to a digital scale. Fuel flow is measured by taking mass readings every 10ms. The glow plug and electronic speed controller are connected to a double throw power relay that switches between the electronic speed controller (starter mode) and the 3-phase rectifier (generator mode). If the rotational speed of the brushless DC motor (measured by the frequency to voltage converter) is below 3000RPM, the relay is switched to starter motor and the glow plug is powered. When generating, the electrical load of the battery and charger is simulated using a rheostat (variable resistance) set to the equivalent resistance of the charger and battery in series. The free stream air velocity represents the velocity of

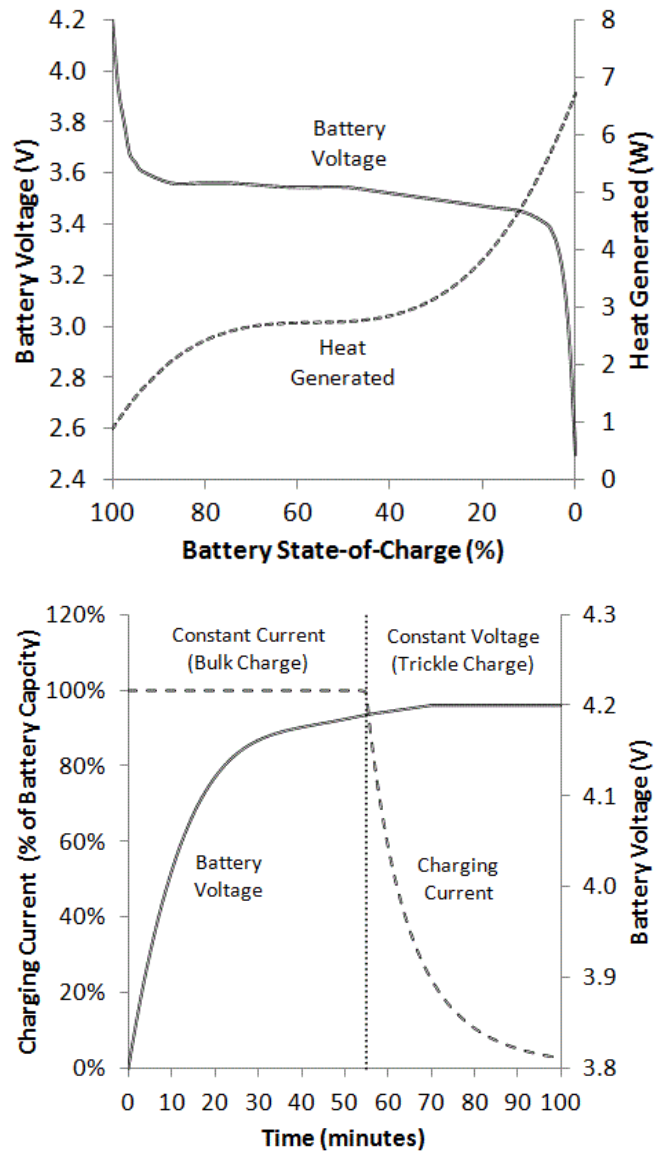


Figure 8: Typical Discharge (top) and Charge (bottom) Curves of a Lithium-Ion Battery [18]

the air entering the propeller. Tests were performed at five different free stream velocity speeds produced by an electric blower to simulate the effect of the dirigible traveling at those speeds.

Tests were performed to determine the power plant's useful power output, energy consumption and overall efficiency with respect to changing engine throttle, fuel mixture richness, propeller pitch, electrical load resistance, and free steam velocity. Table II contains a list of controlled variables and their ranges.

#### RESULTS

The recorded data points were segmented into groups according to engine speed, and averaged to produce the operating envelope shown in Figure 10. Data points below the engine's start-up speed (3000 RPM) were omitted. Useful

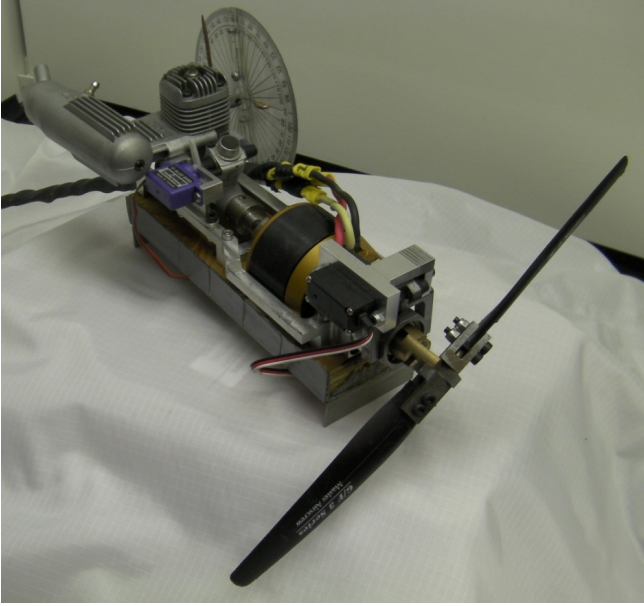


Figure 9: Experimental hybrid power plant

Table II: List of controlled variables and their operating ranges

Parameter	Minimum	Maximum	Increment
Engine Throttle	50% (half)	100% (full)	12.5%
Needle Value	360 (lean)	720 (rich)	30
Propeller Pitch	15°	45°	15°
Electrical Resistance	1.4	5.6	1.4
Free Stream Air Velocity	0 m/s	20 m/s	4 m/s

power was calculated based on the sum of propulsion and electrical power such that,

$$P_U = P_P + P_G$$

$$P_U = F_T \times v_f + V_g \times I_g$$

Where  $P_U$  is the total useful power produced [W],  $P_P$  is the propulsion power [W],  $P_G$  is the generation power [W],  $F_T$  is the propeller thrust [N],  $v_f$  is the free stream velocity in [m/s],  $V_g$  is the generation voltage [V], and  $I_g$  is the generation current [A].

Data points in the 98<sup>th</sup> percentile were considered to represent the useful power operating envelope. Overall system efficiency,  $\eta_O$ , was calculated as the ratio of useful power over input power,  $P_I$  [W]

$$\eta_O = \frac{P_U}{P_I}$$

The input power is defined by,

$$P_I = \dot{m}_F \times \rho_e$$

where  $\dot{m}_F$  is the mass flow rate of fuel [g/s] and  $\rho_e$  is the fuels energy density [W/g].

Based on the operating envelope, the engine was unable to reach it's optimal operating speed of 15000 RPM specified by the manufacturer due to the increase in torque caused

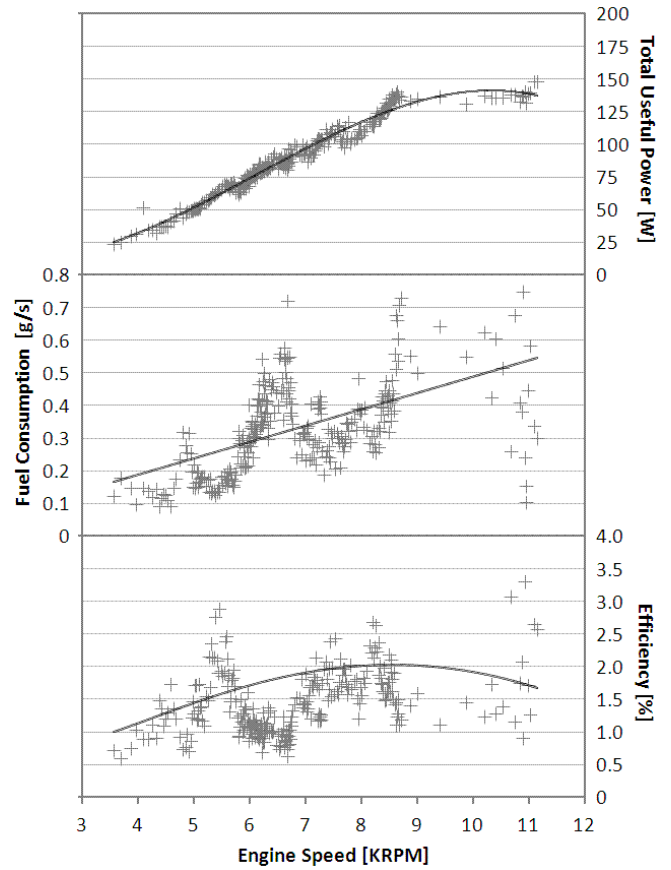


Figure 10: Engine operating envelope for the OS 25LA two stroke model aero engine

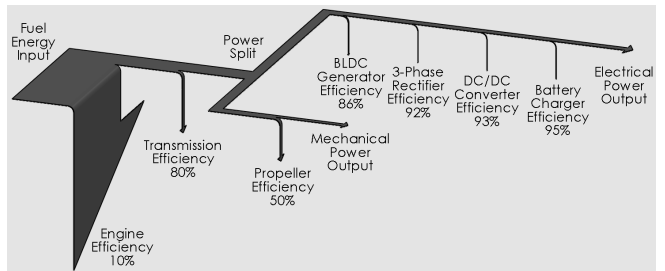


Figure 11: Summary of hybrid power plant losses

by friction bearings and the added inertia of generator and other rotating components. The useful power begins to plateau after 9000 RPM and the maximum useful output power achieved was 148.4W. In comparison, the engine's rated output given in the manual is 447.6W (7.4% engine efficiency at 0.4g/s fuel consumption of 15% nitromethane glow fuel). This difference can be attributed to the losses due to propeller and generator efficiencies (maximum of 50% and 85% respectively) and friction torque in bearings (the transmission efficiency is variable with engine speed but is roughly estimated to be 80%). A summary of these losses is shown in Figure 11. The engine's fuel consumption was much higher than expected at upwards of 0.4g/s at maximum efficiency which tended to lower overall efficiencies.

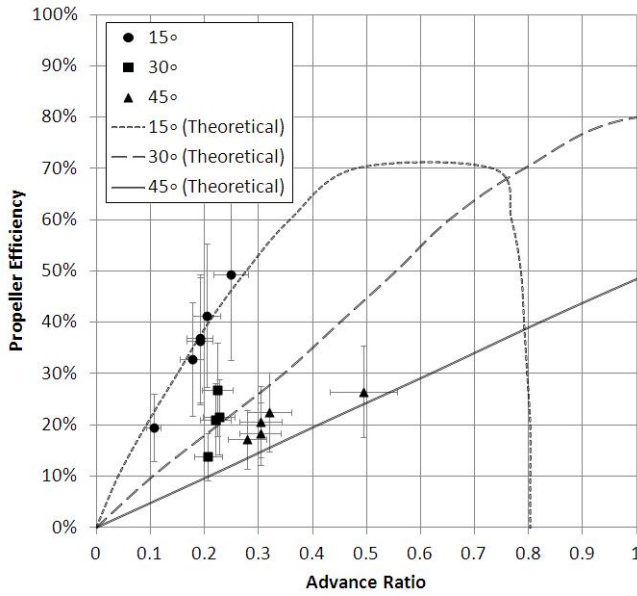


Figure 12: Propeller efficiency at  $3\Omega$  resistance

The propeller's efficiency for three pitch settings versus advance ratio are illustrated in Figure 12. Propeller pitch was measured at  $0.75R$  from the axis of rotation. The advance ratio is the ratio between the distance a propeller moves forward through the fluid during one revolution and is defined as,

$$J = \frac{v_f}{n_e \times d_p}$$

Where  $n_e$  is the engine speed [rev/s], and  $d_p$  is the diameter of the propeller [m].

Propeller efficiency values correspond well with theoretical values presented by McCormick [13] shown in Figure 5. Two separate methods were used to calculate propeller efficiency and compared. The first approach uses the classical definition for efficiency as the ratio of useful propulsion power out over power absorbed and was written as,

$$\eta_{P1} = \frac{P_P}{P_A} = \frac{F_T \times v_f}{\omega_e \times T_P}$$

Where  $P_P$  is the useful propulsion power [W],  $P_A$  is the power absorbed [W],  $\omega_e$  is the engine speed [rad/s], and  $T_P$  is the engine torque absorbed [Nm].

The propeller torque cannot be measured directly as it is a function of the engine torque, generator torque and frictional losses. Therefore, the propeller torque was estimated based on engine speed and propeller pitch using the following set of equations which were produced using propeller tables presented by Lesley [19],

$$C_T = 1.83 \times 10^9 * \theta^2 + 1.04 \times 10^8 * \theta + 1.70 \times 10^8$$

$$T_P = C_T \times \omega_e^2$$

Where  $\theta$  is the propeller pitch in inches.

The second method used to calculate propeller efficiency is based on disk actuator theory [20],

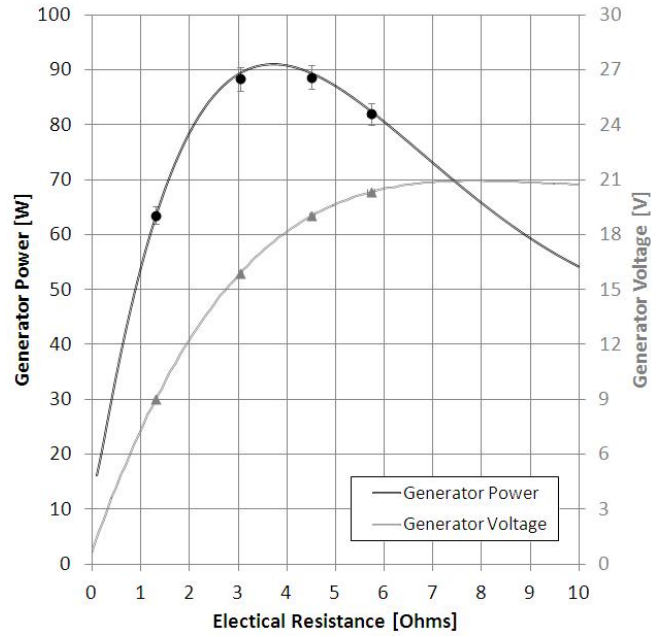


Figure 13: Generator power at  $15^\circ$  propeller pitch

$$\eta_{P2} = \frac{1}{1 + \frac{v_f - v_w}{v_f}}$$

where  $v_w$  is the velocity of the air in the wake of the propeller [m/s].

Both methods produced efficiencies within 10% however only the first method is presented in Figure 12 since it was considered to have lower cumulative error. Due to the size of the airship, flight speeds above  $10 \frac{m}{s}$  are unfeasible based on the total available propulsion power on-board. Therefore advance ratios above 0.3 are unfeasible. Based on Figure 12, propeller pitch will remain between 0 and 15 degrees to maximize the propeller efficiency for all foreseeable flight conditions.

The maximum generator power is shown in Figure 13. The electrical resistance represents the electrical load applied from the electrical propulsion motors, servos, and other on board electronics. Only electrical power produced with voltages above 14.8V can be used due to the battery voltage therefore, resistances below  $3\Omega$  are not useful. Maximum electrical generation is achieved between  $3\Omega$  and  $4.5\Omega$  of 90W. Above  $4.5\Omega$ , power begins to drop as the engine is no longer able to increase it's speed to increase the voltage and the current reduces following ohm's law.

The average current draw required by the brushless DC motor to start the engine was measured to be 35.7A (with a peak of 49.6A) at 14.8V which translates into 538.4W. However, the average time before the engine began driving the brushless DC motor was 0.28 sec leading to an energy draw of the battery of 41.9mWh. The servos used to vary the engine throttle and pitch angle drew 1.08W and 2.00W and were typically used only at start up for less than 5 seconds (1.5mWh and 2.8mWh, respectively). The glow

plug drew a constant 7.58W over 5 seconds resulting in a drain of 10.5mWh. The microcontroller used to generate the PWM signals is run continuously, but enters a power save mode when not receiving an input. Thus reducing its active consumption from 20mW to 1.2mW and can be neglected. The total energy required to start the engine once is 56.7mWh or about 0.06% of the battery's capacity.

The current design can run the glow engine for 2.08 hours on 3 kg of fuel at the maximum efficiency point. Given the 88.8Wh battery capacity on-board plus 90W regeneration and assuming an average of 50W power draw from electric propulsion and electronics results in an overall flight endurance of 5.52 hours. With 60W mechanical propulsion during engine on time and assuming 30W electric propulsion on average the maximum range of the airship (with zero net wind) is 123km.

The power and energy density of the glow engine hybrid system at the optimal operating point can be calculated for a given amount of fuel. The power density,  $\delta_P$ , is found by,

$$\delta_P = \frac{P_U}{\sum m_f + \sum m_v}$$

and energy density,  $\delta_E$ , is found by,

$$\delta_E = \frac{P_U \times t_r}{\sum m_f + \sum m_v}$$

Where  $t_r$  is the operating time,  $\sum m_f$  is the sum of fixed or dead masses such as the engine, motor and frame, and  $\sum m_v$  is the sum of variable masses such as fuel, the number or capacity of batteries or a combination of both. These two equations form the operational limits of each system which are represented by lines shown in Figure 14. The horizontal asymptote is the maximum power density and is governed by the maximum output power of the power plant considered. If the variable mass is infinitesimally small, maximum power density is achieved. The vertical asymptote is the maximum energy density and is governed by the energy density of the fuel source. If the power plant has an infinite supply of fuel or batteries, the maximum energy density is achieved, since the operating time depends on the amount of fuel or the total capacity of batteries available.

A point is plotted on Figure 14 for the current system given 3 kg of fuel. Given the electric motor and propeller efficiency and lithium polymer batteries as the current system, similar points can be constructed for a fully electric system and a gasoline hybrid system. Figure 14 indicates a 31% improvement in energy density with 3 kg worth of fuel over that of a fully electric system with 3 kg of batteries. Energy density is paramount over power density for long duration missions as the mass of the fuel becomes larger than the mass of the power plant. Considering this, further improvement is possible if a 4-stroke gasoline engine is used in the place of the 2-stroke glow engine. Gasoline has a 154% increase in energy density over 15% glow fuel and requires less oil in the mixture (which does not contribute towards useful work). A spark ignition would also provide practical benefits of reliable start up and ignition timing compared

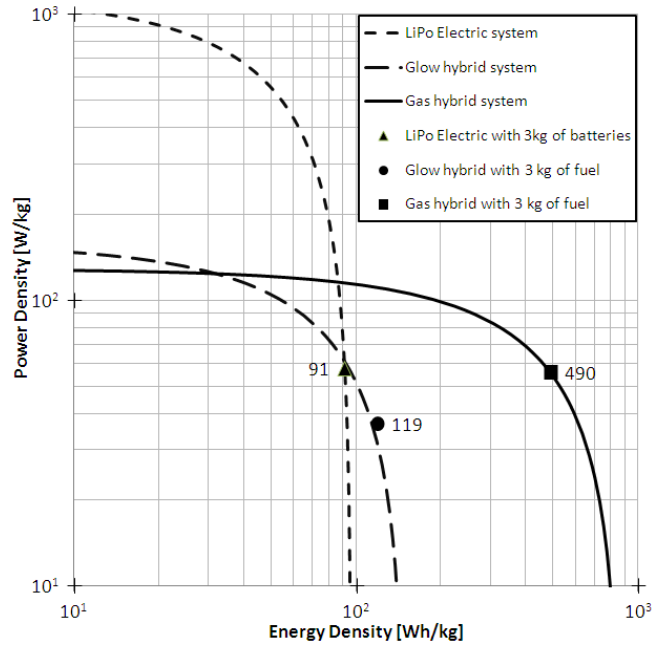


Figure 14: Power density versus energy density for electric, glow hybrid and gas hybrid systems

to a glow plug. Although 4-stroke engines generally weigh more than 2-stroke engines at the same power, they have significantly lower fuel consumption rates which becomes paramount when carrying over 1 kg of fuel.

The conservatively estimated overall cost for fabricating a single unit is \$5,000. The cost metric as presented in Figure 2 for this UAV design is 8.8. The average UAV cost metric at the same price point is 1.9. This represents a 363% increase compared to existing designs.

## CONCLUSION

The energy density of the purposed hybrid power plant design was proven to be higher than an equivalent purely electric system through experimental testing, despite sub-par engine performance. Utilizing a 4-stroke gasoline based engine such as the Saito fg-14b, which has a manual rated power output of 895.2W and fuel consumption of 0.096g/s (22.8% engine efficiency using gasoline with 20:1 synthetic oil mix), would increase overall efficiency substantially. A further 154% increase is expected for a similar design with implementation of this engine instead of the 2-stroke glow engine.

## REFERENCES

- [1] J. Rao, Z. Gong, J. Luo, and S. Xie, "Unmanned airships for emergency management," in *Safety, Security and Rescue Robotics, Workshop, 2005 IEEE International*, pp. 125–130, IEEE, 2005.
- [2] T. Fukao, A. Yuzuriha, T. Suzuki, T. Kanzawa, T. Oshibuchi, K. Osuka, T. Kohno, M. Okuyama, Y. Tomoi, and M. Nakadate, "Inverse optimal velocity field control of an outdoor blimp robot," in *Proc. of the 17th IFAC World Congress*, pp. 4374–4379, 2008.
- [3] H. Saiki, T. Fukao, T. Urakubo, and T. Kohno, "Hovering control of outdoor blimp robots based on path following," in *Control Applications (CCA), 2010 IEEE International Conference on*, pp. 2124–2129, IEEE.

- [4] R. Jia, M. Frye, and C. Qian, "Control of an airship using particle swarm optimization and neural network," in *Systems, Man and Cybernetics, 2009. SMC 2009. IEEE International Conference on*, pp. 1809–1814, IEEE, 2009.
- [5] P. González, W. Burgard, R. Sanz Domínguez, and J. López Fernández, "Developing a low-cost autonomous indoor blimp," *Journal of Physical Agents. Vol. 3, No. 1 (Jan. 2009). ISSN 1888-0258*, pp. 43-52.
- [6] R. Valerdi, J. Merrill, and P. Maloney, "Cost metrics for unmanned aerial vehicles," in *AIAA 16th Lighter-Than-Air Systems Technology Conference and Balloon Systems Conference*.
- [7] R. B. I. Limited, "Uav directory," 2010.
- [8] D. Defense, "Unmanned aircraft systems roadmap 2005-2030," tech. rep., Tech. rep., August, 2005.
- [9] D. Defense, "2009 worldwide uav roundup," tech. rep., Tech. rep., August, 2009.
- [10] G. Khoury and J. Gillett, *Airship technology*. Cambridge university press London, 1999.
- [11] A. Gawale and R. Pant, "Paper 2004-01-design studies of power plant system of non-rigid airships," *Aerospace Engineering Department, Indian Institute of Technology Bombay, Mumbai-400076*.
- [12] R. Pant, "A methodology for determination of baseline specifications of a non-rigid airship," *AIAA Paper*, vol. 6830, 2003.
- [13] B. McCormick, *Aerodynamics, aeronautics, and flight mechanics*. Wiley, 1979.
- [14] G. Rizzoni and T. Hartley, *Principles and applications of electrical engineering*. McGraw-Hill Higher Education, 2004.
- [15] H. Lee, *Advanced control for power density maximization of the brushless DC generator*. PhD thesis, Texas A&M University, 2003.
- [16] W. C. Ltd, "Battery and energy technologies," 2010.
- [17] M. Yoshio, R. Brodd, and A. Kozawa, *Lithium-ion batteries: science and technologies*. Springer Verlag, 2009.
- [18] G. Zimmer, "Battery management design for high power lithium battery stacks," tech. rep., Linear Technology, 2009.
- [19] P. Lesley, E, "Propeller tests to determine the effect of number of blades at two typical solidities," tech. rep., Stanford University, Daniel Guggenheim Aeronautical Laboratory, NACA Technical Note 698, 1939.
- [20] R. Fox, A. McDonald, and P. Pritchard, *Introduction to fluid mechanics*, vol. 7. John Wiley & Sons New York, 1985.