Berkeley Solar Drone

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1 Abstract

The problem of long-endurance flight has yet to be adequately solved with unmanned aerial vehicles (UAVs). Conventional powertrains are typically disadvantaged by limited capacities for non-renewable fuels, but in theory a renewable energy source would permit self-sustaining flight. However, most formal research to date concentrates on developing aircraft with immense wingspans, while overlooking miniature UAVs due to difficulties with effective downscaling. This team intends to bridge that gap by demonstrating multiple-day flight using an autonomous solar-powered UAV with a wingspan of $3m$ or less.

Meticulous power-saving techniques make continuous flight practical. Minimizing the mass of the airplane decreases the load on the motor, saving energy. Further efficiency relies on an embedded system that, with minimal overhead, can dynamically tune aircraft behavior for strategic power conservation, such as gliding, disabling non-critical electronics, and adjusting altitude. The objective for the UAV is to maintain a permanent station in the air without depending on persistent human direction.

Many applications would benefit from an inexpensive, autonomous, permanently airborne platform: weather tracking, emergency response communications, and high-altitude scientific research. Its smaller size, lower cost, and fewer maintenance requirements will allow the quick deployment of application-specialized drones in a sky-based network.

2 Challenge Description

Unmanned aerial vehicles (UAVs) offer unique potential as long-endurance platforms. Negating the complications of human physiology enables the possibility of uninterrupted flight, but so far the engineering of conventional UAVs has not fully realized this advantage. In particular, current powertrains remain inadequate for multiple-day flight.[1]

The powertrain encompasses the generation and delivery of power to the aircraft. Virtually all contemporary designs for production UAVs rely on a finite on-board energy source, either in the form of batteries or, more commonly, fuel for internal combustion engines largely inherited from manned aircraft. Consequently, miniature UAVs small enough to be man-portable are restricted to flight times of a few hours, and larger military UAVs demonstrate approximately 24 to 40 hours, depending on the configuration.[2] Short of tricky aerial refueling, the non-renewable nature of such sources unavoidably imposes an endurance limit on aircraft.

If one can develop a self-contained and inexpensive method to periodically restore energy while airborne, a UAV can be constructed for effectively continuous flight, curtailed not by fuel but by only the lifetime of the physical hardware.

The main benefit of a multiple-day flying platform lies in its extensibility with additional electronics. By adding the appropriate equipment, anyone can establish an application-specific infrastructure at low cost. Swiftly deployable platforms can act as instant ad-hoc communication nodes, invaluable for emergency response operations. Scientists can benefit from an "eye in the sky" during forest fires and after weather events. Space agencies can take advantage of maneuverable, low-maintenance atmospheric "pseudo-satellites."

3 Proposed Solution

As previously observed, the challenge of long-term flight fundamentally reduces to the issue of developing a suitable powertrain. The team's solution is a solar-powered fixed-wing UAV because it can most effectively generate power on its own, and the scope of this project focuses on the demonstration of multiple-day flight with such a design.

Furthermore, while solar-powered aircraft have long existed as a concept, most research and development to date involves designs with immense wingspans. For reasons of flexibility and practicality, a distinctive aspect of this project will be to demonstrate equivalent endurance capabilities using a miniature UAV, *i.e.*, with a wingspan of 3 m or less. This reduced scale poses its own unique set of issues that are expounded in the subsequent feasibility section.

To facilitate airworthiness and long endurance of the UAV, the powertrain must be mobile and low-maintenance, respectively. Key motivations in selecting a practical mechanism are thus compactness and functional simplicity. However, most renewable energy solutions fail to satisfy one or both requirements. A steam turbine, either solar or nuclear powered, requires unwieldy support equipment. A nuclear powered aircraft raises potential health and ethical concerns in the event of catastrophic failure. Hydrogen fuel cells currently suffer from low energy density and cannot sustain the power required for flight in a small space. A wind turbine counteracts the forward thrust generated by the motor, wasting energy.

Essentially, the only suitable device is an array of photovoltaic cells. In the air, the availability of sunlight presents an obvious source of energy, and the absence of moving parts in solar cells reduces the risk of mechanical failure and the need for maintenance.

Solar arrays, with an output directly proportional to area, require that the platform have broad, relatively flat, sun-exposed surfaces in order to generate sufficient power. A fixed-wing aircraft is most ideal for this purpose, providing the largest and most level surface area compared to helicopters and other novel fliers. The wing naturally accommodates the installation of solar cells, and additionally the greater aerodynamic efficiency of a fixed-wing aircraft reduces the power required for flight.

The principal drawback of photovoltaic cells is their inability to function in darkness, however. As a result, the challenge of implementing nighttime flight currently hinders mainstream acceptance of solar-powered UAVs.[1] The airplane thus requires an on-board energy reserve for periods when sufficient solar energy is unavailable.

Energy storage is provided by lithium-ion polymer batteries, in which increasing capacities have corresponded with decreasing cost and mass. During the day, excess power generated by the solar array recharges the batteries in preparation for night flight. On-board power management electronics handle gradual transitions between the solar and battery arrays during dawn and dusk. Such a system would detect a changing voltage from the solar array. When the voltage rises or falls below a given threshold, a switch transfers the power source from solar to battery or vice-versa. A bank of supercapacitors not only can smooth the transition but also provide emergency power if the solar array yield suddenly drops.

The lack of energy regeneration during the night prompts careful energy conservation techniques. Powering down non-essential electronics will help prevent unnecessary demands on the batteries. Decreasing the motor RPM, or turning it off completely and gliding, will reduce the power draw considerably. During the night, the plane must merely maintain its altitude using the energy in the batteries. To simplify the problem, the plane will employ an autonomous program to keep the plane bounded closely above the operators. Furthermore, such an autonomous program will allow the plane to manage its power consumption.

While the main focus lies on the powertrain, the project scope must necessarily be expanded to include additional subsystems required to support the proper operation of powertrain and of the airplane as a whole, but these subsystems should not be more complex than needed.

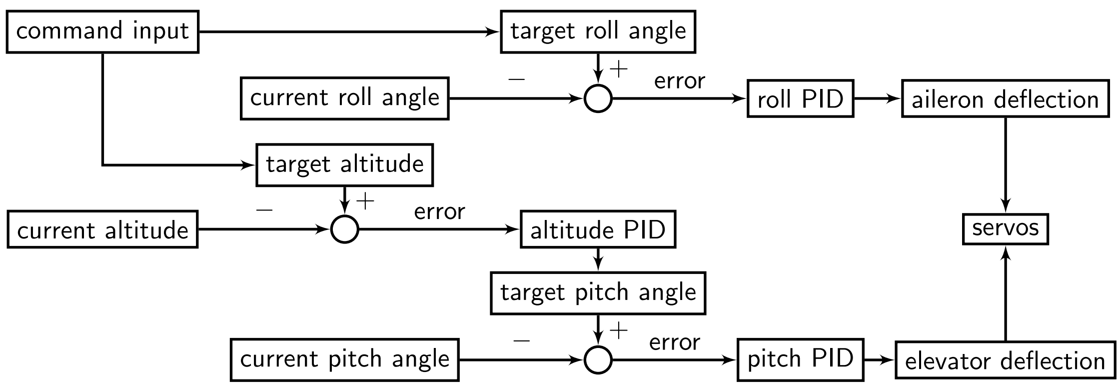
Adaptive power management is among several demanding control aspects that must be addressed using some degree of automation. The motivation for an embedded system is to automate functions that would be otherwise too tedious or risky for humans to remotely micromanage. Additionally, minimizing reliance on a ground station is preferable when communications can be easily disrupted by an unreliable wireless link. One practical case for automation here is an on-board autopilot operating by feedback.

Flight control functions can be separated into a hierarchy. The low-level autopilot directly handles flight dynamics such as attitude (orientation) and airspeed. To affect movement, output signals alter the deflections of the airframe's control surfaces and the motor throttle. At the core of the control loop is stability augmentation, concerned with compensating for disturbances and improving the dynamic response to steering commands provided by a higher-level guidance system; a yaw damper to reduce Dutch roll oscillations falls into this role. The next outer loop decomposes into an altitude controller, in terms of pitch, and a heading (direction) and velocity controller, in terms of roll, yaw, and throttle position, with the objective of being able to hold these parameters constant as necessary and to coordinate turns. Implementation-wise, the traditional proportional-integral-derivative (PID) approach is a well-established mechanism for feedback control, and as shown in Figure 1, the design subjects each controlled variable to a PID loop.

The high-level autopilot handles trajectory tracking and navigation. For the purposes of this project, the navigational requirements of the aircraft are relatively modest. A fixed holding pattern suffices to demonstrate flight endurance, and two classes of algorithms can be employed to adhere to predetermined ground tracks. The first class is a conventional waypoint guidance system, intended for moderate-range navigation and for directing the aircraft to a suitable landing site. The other class introduces the concept of a bounded airspace for short-range flight. Defined is a center location as well as a desired radius to maintain; the airplane continually executes a gentle banked turn to loop around that location, adjusting the ailerons if the actual distance begins to deviate outside a permissible range. In both cases, reference points are provided as GPS coordinates before or during flight, and the plane compares its own GPS values to these points as it moves.

Overall, the software implementing the control loop should be kept as simple as possible for ease of verification. Less software translates to fewer possibilities for failure and emphasizes the project's focus on operational efficiency. As software is readily modifiable, more elaborate functionality can

Figure 1: Subset of the autopilot control loop



be added later after covering the bare essentials for power management and flight control, if needed. The principle of minimalism is best described through the "worse is better" paradigm of Unix philosophy.

To facilitate flight testing and to provide a fail-safe in emergencies, the airplane will include a commercial 2.4 GHz receiver. A radio-controlled relay switch toggles a multiplexer that selects between autopilot and R/C signals. While normal flight can be handled by autopilot for convenience, takeoff and landing are more complex maneuvers best performed manually by a human via remote control. A more crucial role for the manual override is quickly permitting an operator to steer the airplane away from danger, and any unrecoverable software failure detected by a watchdog timer will cause a fallback to human guidance to safety.

A straightforward RF wireless data link, such as the one facilitated by Digi's XBee, will allow two-way communication between the airplane and the ground station, most useful for debugging. The plane can remotely receive commands and transmit telemetry data. The XBee abstracts away many of the complications of data transmission, even implementing an OSI Layer 3 protocol that includes error-correcting codes.

In an open, sunny, and calm environment, the airplane can demonstrate autonomous flight for the competition in May 2012. If limited to an enclosed space, or if weather prevents such a demonstration, then the plane can be displayed alongside recorded videos of flight.

4 Performance Measures

The endurance target set in the challenge definition shall be attained when the UAV demonstrates the capability for multiple-day flight. For solar-powered flight to remain self-sustaining, more energy must be captured and stored during the day than is consumed during the night, per the conservation of energy principle and inefficiencies inherent in the conversion process. More specifically for this project, multiple-day flight is defined as the ability to remain aloft for a complete 24-hour cycle, with the following conditions met:

- No net loss of energy stored in batteries across that interval. At the beginning and end of the 24-hour cycle, the voltage and current of the batteries are measured to check that the amount of stored energy remains equal at minimum.

- Minimum and maximum altitudes maintained at all times, except during takeoff and landing. During its flight, the altimeter is measured to see that the plane does not descend above or below a given range during normal flight.
- The average altitude across that interval is near the target altitude. The logged altimeter data will be checked; samples over multiple cycles can be analyzed for trends.

If the airplane can break even with energy usage and recovery in one 24-hour cycle, then it can be reasonably expected to last for another 24-hour cycle, barring drastic changes in flight conditions. Net loss of gravitational potential energy must also be avoided for total mechanical energy to be preserved, hence the altitude requirement.

As development gradually progresses, incremental tests will ensure that the airplane design remains on track to satisfy the challenge above. Testing the batteries without the solar panels will allow room for changes in the airframe should the capacity of the batteries prove insufficient. Once the batteries demonstrate the plane can remain in the air for the duration of one night, then solar cell testing can begin. Once both the batteries and solar cells are individually proven in flight, then long-term flight tests can commence.

- **Batteries test**: Battery power alone can sustain flight for at least the duration of one night on the winter solstice, descending with $\Delta h_n \leq \frac{h_{\min} - h_0}{t_n}$
- **Solar cell test**: The aircraft can fly and sufficiently climb in altitude on solar power alone: $\Delta h_d \geq 0$
- **Combined test**: The solar cells can fully recharge the batteries while powering normal flight: $\Delta h_d + \Delta h_n \geq 0$. The power consumption requirement that must be satisfied is $\int_{t_0}^{t_1} P dt \leq 0$, where $(t_0,\, t_1)$ represents one complete day-night cycle.

For flight control, the sensor suite must be evaluated on how accurately it can determine the aircraft's orientation, location, and velocity. The rate gyro and accelerometer are typically combined as a single package in an inertial measurement unit (IMU).

- **GPS**: absolute coordinates in geographic latitude and longitude, linear velocities relative to the ground
- **Rate gyro**: angular velocities in the three aircraft principal axes (yaw, pitch, roll rates)
- **Accelerometer**: linear acceleration in a reference frame relative to the Earth's surface
- **Barometer**: altitude, indicated airspeed

MEMS technology, while considerably miniaturizing sensors and reducing power consumption, involves a potential trade-off in accuracy. With regards to sensor performance, the primary concern is noise that leads to accumulated error. Since the gyroscope and accelerometer provide rates of change rather than absolute positions, errors from individual samples propagate when integrating over time. The increasing drift imposes an intermittent need for mutual calibration of sensors, with additional use of external sources such as GPS. However, GPS modules have a relatively slow update frequency (1 to 10 Hz) and limited resolution.

The following ground tests shall be used to gauge sensor accuracy:

- Compare GPS readings with USGS survey markers.
- Absence of disturbances should result in near constant readings.
- Compare initial and final calculations after the system is perturbed and returned to its original position.

Other solar UAV projects, such as NASA's Helios, QinetiQ's Zephyr, and Cocconi's SoLong, provide useful points of comparison. Most sources cite flight time, so measuring the flight time of this airplane is necessary.

The flight control system must also recover from errors gracefully, exhibit predictable latency, demonstrate the ability to fail safely in the event of a malfunction, and allow arbitrary manual override. These measures are largely qualitative, but still need to be assessed in the field.

Airworthiness tests will occur in sparsely populated areas to mitigate the risk of injury in the event of an accident. Additional flight tests conducted in various environments will establish the ability of the aircraft to manage power. Qualitative measures will arise from continuous testing and improvement.

5 Timeline & Milestones

A timeline can be found in the included spreadsheet. A Gantt chart is also included. For a more detailed timeline, refer to Appendix A.

6 Feasibility & Resources Available

A large body of knowledge exists for many aspects of this project, which allows this team to focus on power in particular. The support equipment to store and manage the power needed for multi-day flight justifies the solar array and the other electronics. Furthermore, many other UAV projects have solved the component problems of the plane's subsystem. There are numerous solar-powered UAVs to model after, and programs for autonomous flight are available to analyze. The main aspect of this project focuses on combining current solutions and configuring the UAV for multiple-day flight.

There exists a wealth of information on automating the flight of fixed-wing aircraft online, and mounting motors on the control surfaces comes naturally. Because solar cells cannot capture energy during periods of darkness, the aircraft must store any excess generated power in batteries on the plane. To remain in the air from day to day, the plane must generate more energy during the day than is used during the night. The mathematical feasibility of this power system receives treatment below.

6.1 Power

The concept of a solar-powered UAV is itself not novel. Serious interest has existed since at least the early 1980s, in particular a NASA contractor report examining the feasibility of a photovoltaic powertrain.[3] The NASA Helios project demonstrated some of the first long-term, high-altitude solar flights but suffered a premature end due to structural failure. The 22.5 meter wingspan QinetiQ Zephyr set the current world endurance record of 336 hours and 22 minutes (14 days) in July 2010.[4] Adam Cocconi, working with AC Propulsion, demonstrated a 48 hour flight time with the 5 meter wingspan SoLong plane, although requiring a constantly present human operator.[5] Finally, a senior MIT undergraduate project by Carl Engel and Adam Woodworth demonstrated a flight time of seven hours without batteries with a 3 meter wingspan, also lacking autonomous navigation.[6] This team also consulted local hobby aviation clubs, and members generally agreed on the feasibility of the project.

Multiple-day flight with a solar-powered UAV is certainly viable, although tricky, at the intended scale. This project addresses the addition of batteries as well as a high-end embedded processor to the airplane, thus increasing the concern about adequate power distribution. However, preliminary calculations indicate that careful power management will provide the plane with enough energy to remain aloft through the night.

André Noth's PhD dissertation, *Design of Solar Powered Airplanes for Continuous Flight*, is instructive with regards to the relationship between various aspects of aircraft design.[7] The following equations were adapted from his methodology.

Interdependencies between variables complicate the mathematical models used to predict the physical properties of the airplane. For example, adding more batteries increases total mass and thus the energy needed for propulsion, which again may require additional batteries to satisfy. The process of optimization essentially involves a fixed-point calculation: Certain parameters are constrained to desired values, and a temporary value (e.g. 1) is initially assigned to a single derived value (e.g. total mass, solar cell area, or power usage). The systems of equations are then iteratively solved until values no longer fluctuate and equilibrium is attained.

Equations 1 through 6 derive the contributions to the total mass of the airplane. Equation 1 adds the masses that, for any set of parameters, remain constant and depend on no other values, such as the payload mass m_{pld} and avionics mass m_{av}.

$$m_1 = m_{\text{av}} + m_{\text{pl}} \tag{1}$$

Equation 2 derives the mass of the airframe from the structural mass constant, which depends on the material k_{af}, the wingspan b, and the aspect ratio r, with the r and b taken to the power of x_1 and x_2, respectively. The values of x_1 and x_2 depend on the design of the airframe.

$$m_2 = k_{\text{af}}\, r^{x_2}\, b^{x_1} \tag{2}$$

Equation 3 determines the mass of the solar panels from the area of solar cells required A_{sc}, the solar cell mass per unit area k_{sc}, and the mass of the necessary enclosure and encapsulation k_{enc}.

$$m_3 = (k_{\text{sc}} + k_{\text{enc}})A_{\text{sc}} \tag{3}$$

Equation 4 derives the mass of the Maximum Power Point Tracker (MPPT), which allocates power usage by plotting the IV plot and determining the point for which the greatest power will be supplied from the solar cells. Although the design does not presently call for power point tracking, power generation efficiency may necessitate their inclusion. As with the other equations so far, it has its own coefficient responsible for relating its mass k_{mppt}, though it has many other dependencies. For example, it depends largely on A_{sc}, the maximum irradiance I_{max}, and the efficiencies of the solar cells η_{sc}, the curvature of the solar cells η_{cbr}, and the MPPT η_{mppt}.

$$m_4 = k_{\text{mppt}}\, I_{\text{max}}\, \eta_{\text{sc}}\, \eta_{\text{cbr}}\, \eta_{\text{mppt}}\, A_{\text{sc}} \tag{4}$$

Equation 5 addresses the mass of the batteries, determined by the power supply required. The mass depends on the length of the night T_{night} the efficiency with which the batteries can discharge η_{dchrg} and the overall mass coefficient for the batteries k_{bat}.

$$m_5 = \frac{T_{\text{night}}}{\eta_{\text{dchrg}}\, k_{\text{bat}}}\, P_{E_{\text{tot}}} \tag{5}$$

Equation 6 derives the mass of the propulsion group, including the motor, propeller, control surfaces, and other devices directly involved in propulsion. It depends on the electrical power available to sustain flight $P_{E_{\text{flight}}}$, and a mass coefficient for the propulsion group k_{prop}.

$$m_6 = k_{\text{prop}}\, P_{E_{\text{flight}}} \tag{6}$$

In order to obtain the total mass m_{tot}, combine the constituent masses.

$$m_{\text{tot}} = \sum_{i=1}^{6} m_i \tag{7}$$

To derive the mechanical power required for flight, consider the total mass of the aircraft and the design of the airframe. These two properties determine the aerodynamic effects of lift and thrust and thus determine the mechanical power. Prominent dependencies include m_{tot}, b, and r. However, the coefficients of drag and lift C_D and C_L, the gravitational acceleration constant for near surface calculations g, and the air density ρ also depend on more subtle equations. It is important to note that the coefficient of drag has two components: the airfoil drag coefficient $C_{D_{\text{afl}}}$ and the parasitic drag coefficient $C_{D_{\text{par}}}$, which are added together to arrive at C_D. Expressing the air density as a function of altitude would yield a more accurate figure, but because mechanical power increases with altitude, it is sufficient to derive only the maximum mechanical power using the air density at the highest desired altitude. Lack of FAA clearance restricts the airplane to a flight ceiling much lower than the target altitude.

$$P_{\text{mech}} = m_{\text{tot}}^{2/3}\, \frac{1}{b}\, \frac{C_D}{C_L^{2/3}} \sqrt{\frac{2rg^3}{\rho}} \tag{8}$$

To obtain the electrical power necessary for flight, consider the mechanical power and the efficiencies associated with its conversion from electrical power, including that of the motor η_{mot}, the motor controller η_{ctrl}, the gear box η_{grb}, and the propeller η_{plr}.

$$P_{E_{\text{flight}}} = P_{\text{mech}}\, \frac{1}{\eta_{\text{ctrl}}\, \eta_{\text{mot}}\, \eta_{\text{grb}}\, \eta_{\text{plr}}} \tag{9}$$

To calculate the total electric power used, add the power consumption of the avionics P_{av} and the power consumption of any payload attached to the aircraft P_{pld}, and scale by the efficiency of the step-down voltage converter. This voltage converter ensures safe operating ranges for the sensitive electronics.

$$P_{E_{\text{tot}}} = P_{E_{\text{flight}}} + \frac{1}{\eta_{\text{bec}}}(P_{\text{av}} + P_{\text{pld}}) \tag{10}$$

Finally, the derivation of the necessary solar cell area depends on $P_{E_{\text{flight}}}$, η_{sc}, η_{cbr}, η_{mppt}, the efficiency of the panels through various weather conditions η_{wthr}, the length of day T_{day}, the length of night T_{night}, the charging efficiency η_{chrg}, η_{dchrg}, and I_{max}. While the efficiency of commonly available solar cells η_{sc}, stays below 20%, higher quality cells have an efficiency of up to 22%. This calculation assumes a conservative estimate of 16.9%.

$$A_{\text{sc}} = P_{E_{\text{tot}}}\, \frac{\pi}{2\eta_{\text{sc}}\, \eta_{\text{cbr}}\, \eta_{\text{mppt}}\, \eta_{\text{wthr}}}\, (1 + \frac{T_{\text{night}}}{T_{\text{day}}}\, \frac{1}{\eta_{\text{chrg}}\, \eta_{\text{dchrg}}})\frac{1}{I_{\text{max}}} \tag{11}$$

Table 1 (Appendix B) contains the input values used for the calculations. After using a computer program (Appendix C) to calculate a fixed point for the equations and initial inputs, the model produces the following values for the properties of the plane:

$$
\begin{aligned}
m_{\text{tot}} &= 3.46\ kg \\
P_{\text{mec}} &= 9.94\ W \\
P_{E_{\text{mec}}} &= 14.93\ W \\
P_{E_{\text{tot}}} &= 25.69\ W \\
A_{\text{sc}} &= 0.71\ m^2
\end{aligned}
$$

With respect to self-imposed $5kg$ mass and $3m$ wingspan limit, the numbers do in fact support the feasibility of continuous flight at model scale. Firstly, a battery mass of $1.27kg$ translates into approximately eleven LiPo batteries, a reasonable number given their compact size. Also, the avionics and powertrain require a solar panel array of only $0.71m^2$, which fits adequately on a fixed-wing plane with a $3m$ wingspan and a $0.25m$ wing chord. Conservative estimates place the power consumption of the avionics at $6W$ and a $0.5kg$ electronic payload at $2W$. The addition of a payload also expands the margin for excess power draw without significantly affecting the performance of the plane. It bears mention that the these numbers are intended to represent a realistic worst-case scenario. For example, the value for the duration of night is based off of the winter solstice at a latitude significantly north of the competition site. Incorporating such ample margins produces greater confidence under more typical, moderate conditions.

Retailers already supply all necessary components and corresponding documentation, with the notable exception of high-efficiency solar cells. However, other student groups have succeeded in obtaining, mounting, and analyzing such solar cells for their projects, and this team will request their assistance. One campus group utilized solar cells from SunPower Corporation, which manufactures solar arrays with 22% efficiency and can supply more than $3W$ of power per $125\times125mm$ cell.[8] Extra solar energy obtained during the day can be used to climb in altitude, and this investment in gravitational potential energy permits strategic power-saving maneuvers during the night, such as gliding with the motor at a lower RPM.

Energy storage aboard the plane comes in the form of several lithium-ion polymer (LiPo) batteries in the fuselage. They feature a high energy density relative to their cost and size and can easily power the plane and its electronics. A 6000 mAh, 3.7 V LiPo battery fits a $20\times55\times55mm$ box and has a mass of only 110 g.[9] An Intel Atom processor demonstrated 19 hours of operation, sleeping 95% of the time, on a similar battery.[10]

6.2 Airframe

Utilizing a pre-existing airframe alleviates concerns over the complex aerodynamics involved. A store-bought radio control airplane allows immediate prototyping and simplifies modifications and repairs, as hobby shops typically carry spare parts. If a need for an in-house airframe arises, a number of faculty on campus with experience with designing and building lightweight airframes can assist this team.

Many R/C enthusiasts operate clubs in the vicinity, through which the team can seek guidance about performing flight tests with the airplane. An experienced pilot will be more capable of recovering the plane from a stall or a dive than the members of this team. In addition, local R/C clubs can provide access to open areas suitable for flying.

Relying on readily available expertise for assistance on the airframe allows the scope of the project to remain focused on solving the more central issues of power and navigation.

6.3 Avionics

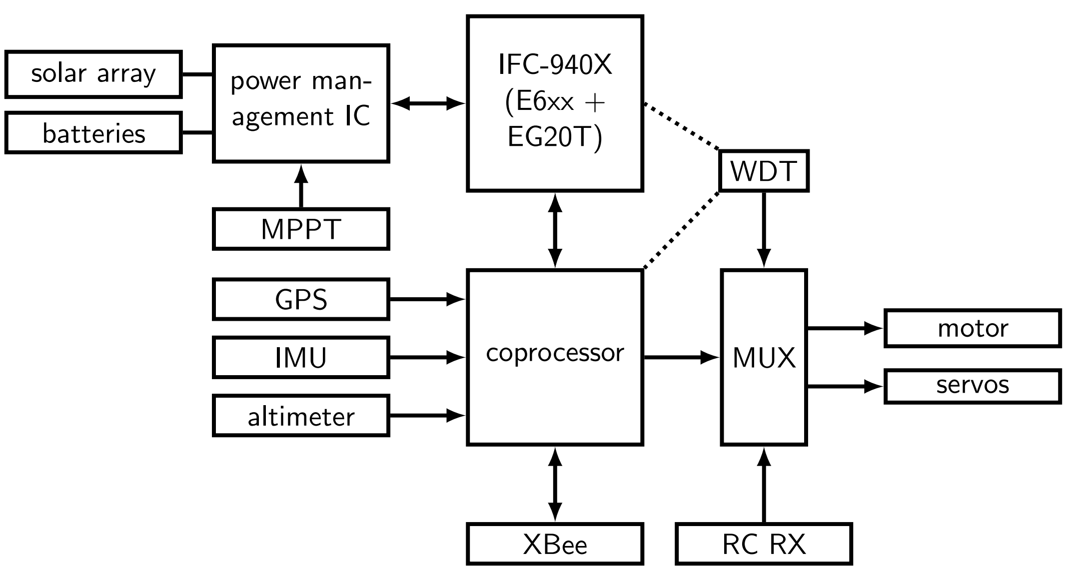
At the smaller structural scales considered in this project, the avionics potentially impose a significant overhead in proportion to the overall aircraft. Reducing power usage, even on the order of a few watts over several hours, allows for significant savings in battery weight, and the additional leeway assists with robustness in cases of decreased solar cell yield.

The Intel embedded platform, whose use is required by this competition, merits particular attention with respect to these concerns. The E6xx series of Intel Atom processors deliver superior computational performance relative to traditional microcontrollers but with the ramification of correspondingly greater power consumption. For the lower-end E620 model, datasheets provide an estimate of 3.3 W for the maximum thermal design power (TDP), defined by Intel as "the measured power generated in a component by a realistic application."[11] Additionally, the Intel chipset relies on the EG20T Platform Controller Hub to interface with a wide range of peripherals, which contributes a max TDP of 1.55 W as a discrete integrated circuit.[12]

Dynamic frequency scaling and undervolting are techniques that can assist with power conservation. Most crucially, suspending to ACPI state C3 (sleep) or C6 during periods of inactivity permits the system to subsist on less than 1 W of standby power. This entails a dual-processor strategy: Short-term flight control and telemetry are handled in real time by a lightweight coprocessor running continuously, and the E6xx is only awoken as necessary for more intensive batch computations, such as long-term navigation. An Atmel AVR microcontroller, for example, presents a viable coprocessor with a negligible footprint of approximately 0.2 W. Importantly, this arrangement readily aligns with the partitioning of low-level and high-level functions seen in the control hierarchy.

As an additional note, Intel deliberately incorporated PCI Express root ports on the E6xx package rather than a proprietary interconnect. Ideally the feature-rich EG20T would be substituted with a more modest I/O hub; however, this would require a substantial overhaul of the provided IFC-940x Qseven board, likely not realizable with this project's tight schedule.

Figure 2: Subsystems general architecture



7 Potential Concerns & Alternative Plans

Power constitutes the overriding concern with a solar powered UAV. Analysis of the mass of the airplane and its power requirements has already specified a recommended number of batteries, so premature depletion should not become a problem. To further mitigate these concerns, the plane will power down its motor while flying through the night, and the avionics will switch into ACPI sleep mode whenever possible. Should the model used become inadequate for the airplane, additional changes, like a customized fuselage, can further conserve power. Providing for an ample margin of safety in calculations should prevent extreme scenarios from arising. However, if the design fails to contend with this project's definition of continuous flight, then the plane will be configured to maximize flight time into the night until it exhausts its power, followed by a safe, controlled landing.

The team must address all risks of the plane flying into people, buildings, or the ground to prevent bodily injury, property damage, and loss of the airplane. During prototype stages, incremental testing of the plane and its avionics will ensure the control operates exactly as expected. Flight tests will occur manually before adding the processors to ensure airworthiness. This team will request the aid of experienced R/C pilots to demonstrate proper technique as well as methods to recover the plane from a stall or a dive. These techniques subsequently can be incorporated into the real-time systems. Avionics will undergo rigorous unit testing to ensure compliance with expected behavior before installation. Tests in the air will only follow after satisfactory ground testing and bench testing. Even while airborne, a manual override system in addition to the fail-safe will allow a human to take control and steer the airplane from potential trouble at any time.

However, no effort can completely mitigate the risk of an accident, so tests will occur away from populated areas to reduce the risk of injury and property damage. In a flat, unpopulated area, the team can also recover the plane with relative ease. Finally, a structural spare of the airplane will be purchased or built to ensure that work can continue in the event that the plane is destroyed or is damaged beyond repair. Should a catastrophic failure occur shortly before the competition, reconstruction can proceed quickly based on the documentation for the old plane. Finally, should the plane be damaged during its travel to the competition in May 2012, the team will perform its best attempt to repair the airplane and display its functioning components along with flight videos of any missing functionality.

However, even in the light of a last-minute catastrophe, this otherwise operational airplane would have demonstrated the ability for anyone to inexpensively produce or purchase a solar powered unmanned aerial vehicle. Adequate documentation would easily facilitate the production of another airplane. Once distributed, such a tool would call for the reconsideration of many applications in which human pilots or rocket launches were previously required. Its capability of multiple-day flight, combined with a powerful on-board computer and reasonable scale, will create new applications in many of today's fields and also open new horizons of its own.

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8 Appendix

A Detailed Timeline

A.1 Prototyping: *17 Oct 2011 – 22 Dec 2011*

A.1.1 Airframe

1. Research and purchase, and assemble: airframe, R/C transmitter and receiver, servos, motor and motor controller, batteries, telemetry equipment, sensor suite, basic electronics, spare parts
2. Integrate control surfaces, propulsion, and R/C to airframe
   - Ensure installation is sturdy
   - Verify configuration of equipment appears to meet power requirement
3. Test airworthiness under manual control; verify that airframe physically performs as expected
   - Mechanical integrity; durability
   - Reliable radio control
   - Gliding ability
   - Climbing ability (altitude)
   - Handling in adverse weather conditions
   - Airspeed
4. Verify avionics with test harness on ground
   - Create simulated conditions within avionics and verify response
5. Conduct design review of airframe and avionics subsystems
   - Verify alignment of project state with project objective
   - Determine whether significant design or goal changes are necessary
6. Integrate avionics load with airframe
   - Ensure installation is sturdy, connections complete and weatherproof
7. Verify operation of avionics *in situ* on ground
   - Simulate flight conditions and verify actuator response and data output
8. Test overhead of avionics with manual override engaged
   - Ensure aircraft's physical properties are not adversely affected by avionics
9. Test and verify long-term flight characteristics
   - Test ability of battery to supply power to motor
   - Test plane maneuverability with added avionics
   - Verify expected plane response to actual plane response to physical conditions
10. Disable override and test autonomous flight stability
    - Verify basic navigation
11. Test and verify fail-safe during flight
12. Integrate solar cells with airframe
    - Verify solar cell performance characteristics
    - Ensure torsion on wing does not damage brittle solar cells
    - Weatherproof panels as necessary

- Test short-circuit current and open-circuit voltage

13. Test solar-powered flight with manual override engaged
    - Verify battery recharging, motor power, and source switching
14. Test fully autonomous flight on solar power
    - Compare power load of avionics with theoretical models
    - Verify proper operation of all electronics
15. Conduct design review of completed aircraft
    - Verify alignment of project state with project objective
    - Determine whether design or goal changes are necessary
16. Attempt multiple-day solar flight

A.1.2 Avionics / Embedded System

1. Formalize real-time control requirements for avionics subsystem
    - Define exact roles and tasks for each component and contents of communication
    - Organize preliminary bill of materials
2. Determine interface and data bus requirements (UART, I^2C, etc.)
    - Relate E6xx and EG20T signals to pin assignments on the Qseven module connector
    - Determine physical interface and data-link protocol for networking the E6xx with the coprocessor
        - Identify software challenges (i.e., drivers, synchronization)
3. Design fail-safe
    - Design multiplexer to switch actuator control between autopilot and manual override
        - Accommodate trigger by either a radio-controlled relay or watchdog timer after repeated microprocessor faults
    - Incorporate conventional RC receiver
    - Design external watchdog timers (WDT)
        - Gauge if a software-based solution with a dedicated microcontroller is sufficient or if a commercial ASIC is necessary for reliability
        - Determine proper procedures to warm reset the E6xx, coprocessor, and peripherals (e.g., assert `RESET_B` and `PWROK` for the E6xx; alternatively, reset of E6xx and EG20T might be accomplished through the power management IC provided by the IFC940X board)
4. Power management
    - Determine how to generate and report accurate power statistics to microprocessors
    - Determine how to suspend the E6xx and EG20T (i.e., ACPI state C3) to save power and provide a reliable method for the coprocessor to induce timely wakeup (e.g., `WAKE_B` PCIe signal or `GPIO_SUS[4:1]` on the E6xx)
5. Define complete avionics hardware specification and configuration
    - Procure equipment
    - Test compatibility of peripherals with microprocessors (e.g., electrical characteristics)
    - Draw layout for custom carrier PCB once specific models for peripherals are selected

- Assemble an initial protoboard until PCB is finalized
- Measure power consumption of components and investigate possible approaches for reduction (e.g., undervolting, underclocking)

6. Establish software development toolchain for cross-compilation
   - Select final system platform based on hardware and real-time constraints (NetBSD, Linux with `PREEMPT_RT` patch, custom RTOS/exokernel)
7. Program coprocessor for real-time micromanagement (e.g., telemetry and flight control)
8. Design and program base station for telemetry and monitoring
9. Program E6xx for more computationally intensive tasks dealing with macromanagement (e.g., long-term navigation and power analysis)
10. Benchmark latencies; perform regular unit testing throughout development
11. Fabricate production carrier board and mount components

A.2 Review and Testing: *2 Dec 2011 – 1 Jan 2012*

1. Conduct major design review
2. Test completed prototype
   (a) Conduct flight tests
   (b) Analyze impact of design decisions
   (c) Factor results into production schematic

A.3 Production: *1 Jan 2012 – 30 Mar 2012*

1. Design and build production airframe
   (a) Research airframes; contact experts on airframe design
   (b) Design prototype airframes and simulate; select best model
   (c) Obtain components and construct airframe
   (d) Construct possible structural spare
2. Revise and construct production avionics system
   (a) Modify software to match new airplane
3. Test production design
   (a) Isolated ground testing
   (b) *In situ* testing
   (c) Flight testing
4. Begin final report from accumulated documentation

A.4 Review and Testing: *1 Apr 2012 – 4 May 2012*

1. Conduct major design review
2. Test completed production model
   (a) Conduct flight tests
   (b) Analyze results
3. Complete final report
4. Coordinate shipping logistics
5. Present completed product

B Tables

Table 1: Initial and tentative values for power calculations

C_L	0.8	Airfoil lift coefficient
$C_{D_{\text{afl}}}$	0.013	Airfoil drag coefficient
$C_{D_{\text{par}}}$	0.006	Parasitic drag coefficient
I_{max}	950 W/m^2	Maximum irradiance
k_{bat}	726545.455 J/kg	Energy density of lithium-polymer batteries
k_{sc}	0.32 kg/m^2	Mass density of solar cells
k_{enc}	0.26 kg/m^2	Mass density of encapsulation
k_{mppt}	0.00042 kg/W	Mass to power ratio of MPPT
k_{prop}	0.008 kg/W	Mass to power ratio of propulsion group
k_{af}	0.044852191 kg/m^3	Structural mass constant
m_{av}	0.2 kg	Mass of avionics
η_{bec}	0.65	Efficiency of step-down converter
η_{sc}	0.169	Efficiency of solar cells
η_{cbr}	0.9	Efficiency of the curved solar panels
η_{chrg}	0.95	Efficiency of battery charge
η_{ctrl}	0.95	Efficiency of motor controller
η_{dchrg}	0.95	Efficiency of battery discharge
η_{grb}	0.97	Efficiency of gearbox
η_{mot}	0.85	Efficiency of motor
η_{mppt}	0.97	Efficiency of MPPT
η_{plr}	0.85	Efficiency of propeller
N_{wthr}	0.7	Irradiance margin factor
m_{pld}	0.5 kg	Payload mass
r	10.0	Aspect ratio
P_{av}	8.5 W	Power of avionics
x_1	3.1	Airframe mass wingspan coefficient
x_2	-0.25	Airframe mass aspect ratio coefficient
P_{pld}	0.5 W	Payload power consumption
p	0.8 kg/m^3	Air density (2500 m altitude)
T_{day}	34200 s	Day duration
T_{night}	52200 s	Night duration
b	3 m	Wingspan

C Source Code

Noth's Equations Solver

```c
#ifndef _POSIX_C_SOURCE
//#define _POSIX_C_SOURCE 200809L
#endif /* _POSIX_C_SOURCE */
#include <stdio.h>
#include <math.h>

static float psol(float p, float m) {
    return 0.5 * 0.019 * 0.8 * p * 0.9
           * pow(pow(2.0 * m * 9.81 / 0.8 / p / 0.9, 0.5), 3.0);
}

int main(void) {
    /* Input variables */
    static const float
        C_L = 0.8,
        C_D_a = 0.013,
        C_D_p = 0.006,
        I_m = 950.0,
        k_bat = 726545.454545455,
        k_sc = 0.32,
        k_enc = 0.26,
        k_mppt = 0.00042,
        k_prop = 0.008,
        k_af = 0.044852191,
        m_av = 0.2,
        n_bec = 0.65,
        n_sc = 0.169,
        n_cbr = 0.9,
        n_chrg = 0.95,
        n_ctrl = 0.95,
        n_dchrg = 0.95,
        n_grb = 0.97,
        n_mot = 0.85,
        n_mppt = 0.97,
        n_plr = 0.85,
        n_wthr = 0.7,
        m_pld = 0.7,
        r = 10.0,
        P_av = 5.0,
        x_1 = 3.1,
        x_2 = -0.25,
        P_pld = 2.0,
        p = 0.873307,
        T_day = 52200.0,
        T_night = 34200.0,
        b = 3.0;
    /* Intermediate constants */
    float btmp, Ctmp, ptmp, gtmp, PPtmp, SCA1, SCA2;
    /* Derived variables */
    float m1, m2, m3, m4, m5, m6, m_tot,
        P_mec, P_E_mec, P_E_tot, A_sc;
    float tm1, tm2, tm3, tm4, tm5, tm6, tm_tot,
        tP_mec, tP_E_mec, tP_E_tot, tA_sc;
    /* Velocities */
    float v_max, v_min;
```

```
    float v_climb_max, v_climb_min;

    btmp = 1.0 / b;
    Ctmp = (C_D_a + C_D_p) / pow(C_L, 1.5);
    ptmp = 2.0 * r * pow(9.81, 3.0) / p;
    gtmp = n_ctrl * n_mot * n_grb * n_plr;
    PPtmp = P_av + P_pld;
    SCA1 = 2.0 * n_sc * n_cbr * n_mppt * n_wthr;
    SCA2 = 1.0 + (T_night / T_day / (n_chrg * n_dchrg));

    for (/* Initialize */
        (m1 = m2 = m3 = m4 = m5 = m6 = m_tot
            = P_mec = P_E_mec = P_E_tot = A_sc = 0.0),
        (tm1 = tm2 = tm3 = tm4 = tm5 = tm6 = tm_tot
            = tP_mec = tP_E_mec = tP_E_tot = tA_sc = NAN);
        /* Check fixed-point convergence */
        (m1 != tm1 || m2 != tm2 || m3 != tm3 || m4 != tm4
            || m5 != tm5 || m6 != tm6 || m_tot != tm_tot || P_mec != tP_mec
            || P_E_mec != tP_E_mec || P_E_tot != tP_E_tot || A_sc != tA_sc); ) {

        float mtmp;
        /* Update */
        tm1 = m1, tm2 = m2, tm3 = m3, tm4 = m4,
            tm5 = m5, tm6 = m6, tm_tot = m_tot,
            tP_mec = P_mec, tP_E_mec = P_E_mec,
            tP_E_tot = P_E_tot, tA_sc = A_sc;
        /* Calculate masses */
        m1 = m_av + m_pld;
        m2 = k_af * pow(r, x_2) * pow(b, x_1);
        m3 = (k_sc + k_enc) * A_sc;
        m4 = k_mppt * I_m * n_sc * n_cbr * n_mppt * A_sc;
        m5 = T_night / (n_dchrg * k_bat) * P_E_tot;
        m6 = k_prop * P_E_mec;
        m_tot = m1 + m2 + m3 + m4 + m5 + m6;
        mtmp = pow(m_tot, 1.5);
        /* Solve for unknowns */
        P_mec = mtmp * btmp * Ctmp * pow(ptmp, 0.5);
        P_E_mec = P_mec / gtmp;
        P_E_tot = PPtmp / n_bec + P_E_mec;
        A_sc = SCA2 / SCA1 / I_m * M_PI * P_E_tot;
    }
    /* Calculate velocities */
    v_max = pow(2.0 * m_tot * 9.81 / (C_L * p * 0.9), 0.5);
    v_min = pow(2.0 * m_tot * 9.81 / (C_L * 1.195 * 0.9), 0.5);
    v_climb_max = psol(p, m_tot) - (pow(m_tot * 9.81 * 2 / p / 0.9, 0.5)
                  / C_L * (C_D_a + C_D_p));
    v_climb_min = psol(1.27, m_tot) - (pow(m_tot * 9.81 * 2 / 1.27 / 0.9, 0.5)
                  / C_L * (C_D_a + C_D_p));

    printf("Total mass: %f\n"
        "Mechanical power: %f\n"
        "Electrical power for level flight: %f\n"
        "Total electrical power: %f\n"
        "Mass of batteries: %f\n"
        "Minimum area of the solar array: %f\n"
        "Minimum velocity at high alititude: %f\n"
        "Minimum velocity at low altitude: %f\n"
        "Maximum climb velocity (low altitude): %f\n"
        "Minimum climb velocity (high altitude): %f\n",
```

```
        m_tot, P_mec, P_E_mec, P_E_tot, m5, A_sc, v_max, v_min,
        v_climb_max, v_climb_min);
    return 0;
}
```