The Hybrid Tiger: A Long Endurance Solar/Fuel Cell/Soaring Unmanned Aerial Vehicle

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Abstract: The Hybrid Tiger is an Unmanned Air Vehicle currently in development at the US Naval Research Laboratory; it is designed to demonstrate long endurance (>2 d) and long range (>1000 nmi) in a relatively small (7.3 m wingspan, 25 kg GTOW) and tactically-relevant vehicle. The anticipated range and endurance are feasible due to a unique hybrid power train that incorporates a high specific energy (~1200 Wh/kg) PEM fuel cell system, high efficiency (+23%) solar arrays, and advanced autonomous soaring algorithms. Energy management is implemented onboard to coordinate the operation of each power subsystem and optimize the aircraft trajectory.

Keywords: solar, hydrogen, fuel cell, soaring, aircraft, unmanned, endurance, UAV, path planning

Introduction

The Hybrid Tiger is a Group 2 Unmanned Air Vehicle (UAV) currently in development at the US Naval Research Laboratory (NRL). The Hybrid Tiger is designed to demonstrate long endurance (>2 d) and long range (>1000 nmi) in a relatively small (7.3 m wingspan, 25 kg GTOW) and tactically-relevant vehicle. The anticipated range and endurance are feasible due to a unique hybrid power train that incorporates a high specific energy (~1200 Wh/kg) proton exchange membrane fuel cell (PEMFC) system, high efficiency (+23%) thin-film GaAs solar arrays, and advanced autonomous soaring algorithms. Energy management is implemented onboard to coordinate the operation of each power subsystem and optimize the aircraft trajectory. The Hybrid Tiger is a heavily modified version of the Ion Tiger UAV developed at NRL in 2009 to demonstrate fuel cell powered flight [1-4]. Ion Tiger is shown in Fig. 1 and Hybrid Tiger is shown in Fig. 2.

Aircraft which achieve long endurance by harvesting energy from the environment are not a new idea; Solar Impulse 2 [5], Zephyr [6], and Atlantik Solar [7] are prominent examples. Solar Impulse 2 and Zephyr are designed to fly at altitudes above 3,000 m where winds are consistent and few clouds obscure the sun. The Hybrid Tiger, in contrast, is a smaller and more robust vehicle which can fly at lower altitudes and endure a wider range of weather conditions. The increased mass of robust structures make storing sufficient solar energy to fly through the night infeasible, so the Hybrid Tiger cannot fly indefinitely like a pure solar electric aircraft. However, the Hybrid Tiger's hybrid electric propulsion system can exploit any available sunlight *and* operate in cloudy conditions by relying on the stored Hydrogen and PEMFC to supplement solar power, albeit at the cost of reduced range and endurance. Furthermore, by flying in the convective boundary layer of the atmosphere (below 3,000 m), the Hybrid Tiger can harvest energy from the atmosphere by exploiting thermals and other rising air.



Figure 1. The Ion Tiger UAV, predecessor of Hybrid Tiger.



Figure 2. CAD model illustrating key energy-related elements of the Hybrid Tiger design.

Fuel Cell System: The PEMFC system has a traditional stack topology with a liquid cooling loop and produces up to 625 W at an efficiency of >40% (LHV of H₂). [4, 8] The 53 L hydrogen fuel tank stores 1221 g H₂ at 5,000 psia and 25°C.

The fuel tank is a Type-III aluminum lined, composite overwrapped pressure vessel which weighs < 8 kg empty. A single stage pressure regulator reduces the H₂ pressure to 15 psig for consumption by the PEMFC system. The overall specific energy of the PEMFC and fuel tank is ~ 1200 Wh/kg, which is more than five times greater than Li-Ion batteries (~ 200 Wh/kg).

Solar Arrays: The Hybrid Tiger carries five thin-film GaAs solar arrays (four on the wing and one on the tail) and each has its own maximum power point tracker (MPPT). The array was divided this way to accommodate manufacturing variations between sub-arrays and differences in solar irradiation as the aircraft changes orientation with respect to the sun during maneuvers.

The solar arrays are co-molded with the wing and tail composite skins during vehicle fabrication to produce an integrated structure with a smooth surface. Total solar array system weight is 1.0 kg, approximately 5% of the vehicle gross take-off weight (GTOW).

Autonomous-Soaring: Algorithms that identify and exploit rising air to gain altitude are being employed to harvest energy from the atmosphere. Onboard algorithms use existing autopilot sensors to measure vertical wind motion, identify thermal updraft structures, and guide the aircraft into position to gain free altitude with the motor off [9].

Prior experimentation with auto-soaring techniques demonstrated +5 hours of endurance during the daytime with a sailplane [10] or offsetting over 50% of average propulsion energy over a multi-hour flight [11]. Soaring behaviors are integrated with the power management system to best leverage the energy capture opportunity balanced with the mission constraints.

Long Distance Path Planning: An algorithm that solves the task of energy (fuel) optimal trajectory planning between any two points in 4D space (3D position and time). The approach utilizes a prior given weather forecast of 3D wind and solar irradiance to produce the optimal path and the commanded airspeed along the path. The resulting trajectory serves as a reference of the achievable optimal performance of the vehicle along the route.

Drivetrain Efficiency: While the PEMFC system stores energy efficiently and the solar arrays and auto-soaring algorithms gather energy, another important contributor to the performance of Hybrid Tiger is the efficiency of its drivetrain. A variable pitch propeller (VPP) coupled to a sixphase brushless DC motor ensures that electric power is converted to thrust at maximum efficiency over a wide range of airspeeds and throttle settings. A full authority digital engine controller (FADEC) uses predetermined maps to look up the optimal VPP and motor configuration for the current flight conditions and throttle setting.

Airframe: The Hybrid Tiger is a high-wing monoplane with a large lift/drag ratio of ~21:1 designed to fly efficiently at 15 m/s. A spread-tow carbon fiber and foam sandwich composite skin construction enables robust and lightweight

structures. The airframe is <30% of total takeoff mass, despite being designed for +6G ultimate loads. The wing and tail planforms are designed for high active solar area fractions, and the high-wing and T-tail reduce the likelihood of shading during maneuvers. Aerodynamics of the wing are highly tailored for low propulsion power required at a cruise speed reasonable to handle moderate environmental winds. The fuselage is direct from Ion Tiger [1-4] and the majority of available internal volume is dedicated to hydrogen storage.

Hybrid System Integration & Strategy

A major design constraint on long endurance (>12 h) pure solar electric aircraft is storing sufficient energy to fly through the night and having excess solar energy capture to recharge quickly during the daytime. The efficiency limits of practical photovoltaic technology and the specific energy limits of Li-ion batteries are major design drivers for such vehicles. The need to deploy large areas of solar array and lift large battery mass generally leads to designs with structures that are large and fragile.

The Hybrid Tiger, in contrast, does not attempt to store solar energy. Any energy gathered by the solar arrays offsets power production by the fuel cell to reduce the rate of fuel consumption. In some circumstances (clear skies, mid-day, and low latitude) there may be surplus solar power, in which case the Hybrid Tiger flies faster toward a range goal or climbs to store the energy in an "altitude battery". The combination of reduced fuel consumption during daylight hours and high specific energy storage by the PEMFC system to continue flying at night enables this robust, long range and endurance vehicle.

Custom power management and distribution (PMAD) electronics integrate power from the solar arrays and fuel cell, and supply power to hotel loads and the propulsion system. A small 32 Wh Li-ion battery pack supplies power for the avionics in the event of an emergency, such that the aircraft can maintain control during descent and landing. A passive, voltage-staging approach is used to ensure all of the available solar power is absorbed before consuming finite hydrogen fuel resources via the PEMFC; the MPPTs provide power at 45 V, which is higher than the 31-45 V range of the fuel cell, which is higher than the 23-29 V range of the battery.

Energy-Optimal Path Planning

Flying within the convective boundary layer of the atmosphere creates several types of inhomogeneity in the energy environment. For example:

- Clouds cause the distribution of solar energy to vary both spatially and temporally, in addition to the diurnal cycle.
- Wind direction and magnitude vary both spatially and temporally. Winds are significant because they can



Figure 3. Example comparing great circle (blue dots) and energy optimal (red dots) routes through a wind field where favorable winds are red and unfavorable winds are blue. The optimal route also considers solar irradiance.

increase or decrease energy consumption, depending on the relative wind direction and vehicle trajectory.

• Rising (or sinking) air intensity varies spatially and temporally. Convective updrafts (i.e. thermals) form, drift, and dissipate as they interact with wind and the conditions which create them change.

The inhomogeneity of the energy environment presents an opportunity from a path planning perspective. Given a nonuniform distribution of energy sinks and sources, it is unlikely that the energy-optimal route for an energy harvesting vehicle will be the geographically shortest route. Simulations carried out at NRL and by partners at the Naval Postgraduate School (NPS) have indicated that significant energy savings can be realized by planning vehicle trajectories with energy in mind. The energy optimization problem has been cast as fuel consumption minimization over a flight between two fixed locations, but other formulations are possible as well. For example, the fight time could be minimized while respecting a constraint on the amount of fuel consumed so that sufficient fuel remains to carry out a mission upon arrival. The path planning process is decomposed into a global path planning problem and a local path planning problem to leverage different sources of environmental data and attack the problem at different scales.

The global path planner (GPP) uses weather forecasts produced by the NRL COAMPS numerical weather simulation [12] which include wind (u,v,w) and solar irradiance as functions of time and geographic position, on a 9 km and 3 h grid, produced in 6 h intervals. The GPP uses a Hybrid Tiger model to estimate the energy balance along a proposed path between two locations, given the predicted environment. The optimization task is formulated as a two point boundary value problem with an analytically synthesized optimal control laws which minimize energy consumption along the route; the analytical form of the solution allows for computationally efficient onboard implementation of the algorithm. The result, returned as the C^1 continuous polynomial, is discretized by a series of global waypoints with metadata describing the anticipated vehicle state (time of arrival, fuel remaining, etc.) at each waypoint.

Figure 3 presents an example that illustrates the resulting optimal route (red dots, x_t h flight) in comparison with the route along the great circle (blue dots, $1.51x_t$ h flight) between the initial and final position of the aircraft. The wind along the routes unfolds as the UAV flies along the optimal route. The wind direction and magnitude are color coded with red representing tail wind and the blue representing the headwind. The result illustrates that the optimal route heavily leverages wind in the desired direction of flight.

The local path planner (LPP) uses local observations of wind and solar irradiance to exploit energy harvesting opportunities and reduce energy expenditure [13]. The LPP drives the minute-by-minute operation of the Hybrid Tiger in response to environmental features that have too small a spatial or temporal resolution be captured by the weather forecast. The ultimate goal of the LPP is to fly the Hybrid Tiger to the next global waypoint and arrive with the aircraft in the anticipated state or in a state that improves the global prediction of the GPP solution. This gives the LPP some leeway to operate the Hybrid Tiger outside of the global path in search of improved energy harvesting opportunities or reduced energy expenditure, so long as it arrives at the next global waypoint on time and with sufficient energy. For example, the LPP can stop forward progress to gain altitude via autonomous soaring, trading free energy for time along route.

Energy management software is implemented onboard on an Odroid XU4 board computer. Disparate software functions such as the GPP and LPP were wrapped into Robot Operating System (ROS) nodes to facilitate parallel development and robust interactions through a publish/subscribe model.

Vehicle Energy Simulation

A detailed Hybrid Tiger simulation was developed for component sizing, performance estimation, and energy management strategy analysis. The simulation steps through a flight in 1 min increments, calculating the vehicle energy balance and state at each step. Fuel cell performance measurements are used to relate fuel cell electrical power production to fuel consumption rate, and detailed solar array models predict solar power production as a function of solar irradiance and array temperature. A vehicle drag model estimates propulsion power consumption as a function of vehicle weight, airspeed, altitude, load factor, etc. Energy management behaviors are captured by the simulation, such as climbing to store surplus solar energy. The simulation can assume user-defined environmental conditions such as wind field, temperature profile, and celestially determined solar irradiance, or use COAMPS weather forecast data to simulate in a realistic environment.

Simulation results include metrics such as the fraction of total energy supplied by the solar arrays, fuel cell average efficiency, and fuel remaining as a function of time. The relationship between diurnal variation in solar irradiance and the rate of fuel consumption is evident in the results. For example, along a route near $32^{\circ}N$ with takeoff on the summer equinox, the fuel tank fill fraction curve is flat for 2-3 h in the middle of each day indicating the solar arrays produce sufficient power to satisfy all vehicle power consumption during those periods. In simulations at moderate latitudes, the solar arrays supply ~20% of the energy consumed in a flight.

Conclusions

The Hybrid Tiger UAV is projected to achieve long range and endurance through a combination of high specific energy storage, energy harvesting from the environment, energy management, and energy-aware path planning. Flight testing of the full hybrid power system is anticipated in 2018 followed by a maximum endurance flight in 2019.

Acknowledgements

The authors thank DoD Operational Energy Capabilities Investment Fund for supporting this work, the USMC Expeditionary Energy Office for supporting development of solar-soaring algorithms at NRL, and the NRL 6.2 Base Program system for supporting basic research programs in fuel cells, solar co-molding integration, and autonomous soaring algorithm development.

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