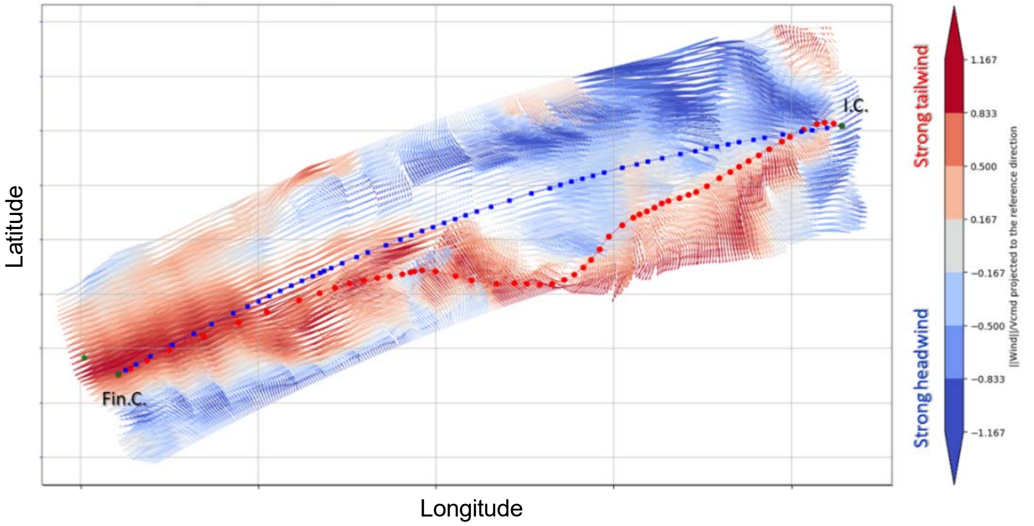

**Figure 3.** Example comparing great circle (blue dots) and energy optimal (red dots) routes through a wind field where favorable winds are red and unfavorable winds are blue. The optimal route also considers solar irradiance.

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 non-uniform 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°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.

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