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

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Background:
Fuel Cell Propulsion, Soaring, and Solar

Ion Tiger PEM Fuel Cell UAV

Ion Tiger: NRL's first "practical" fuel cell powered UAV

- 16 kg, 5.7 m wingspan autonomous air vehicle
- Gaseous H_2 fuel: 22 L at 5,000 psi and 25°C → 500 g
- Liquid H_2 fuel: 19.8 L at 20 psi and 22 K → 1300 g
- Unofficial flight endurance records – 26 h (GH_2) and 48 h (LH_2)

Ion Tiger demonstrated the feasibility of fuel cell UAV propulsion with high performance H_2 storage

ALOFT soaring UAV

Solar SBXC

Auto-soaring

- Harvest energy from atmosphere by climbing in rising air
- Key is *autonomously* finding and exploiting rising air
- Can yield long flights with little energy input – e.g. 70 mi w/o motor!

Integrated Solar

- NRL has unique co-cured solar panel integration process
- Nearly "free" flight during daylight – overnight difficult for tactical vehicles

Solar and soaring experiments have demonstrated day-long flights with little to no net energy consumption

Next Step: The Hybrid Tiger Unmanned Air Vehicle

Goal: Demonstrate synergistic range and endurance benefits by integrating fuel cell propulsion, soaring, solar harvesting, and optimal path planning

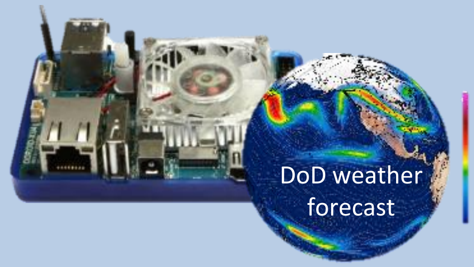
Exploit Multiple Energy Sources

Photovoltaics

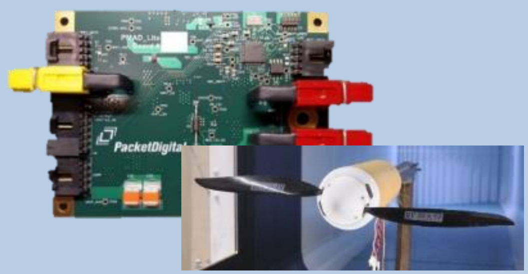
Fuel Cell & H_2 Fuel Storage

Autonomous Soaring

Maximize Performance



Novel Energy Optimization Algorithms



Real-Time Energy Management & High Efficiency Components

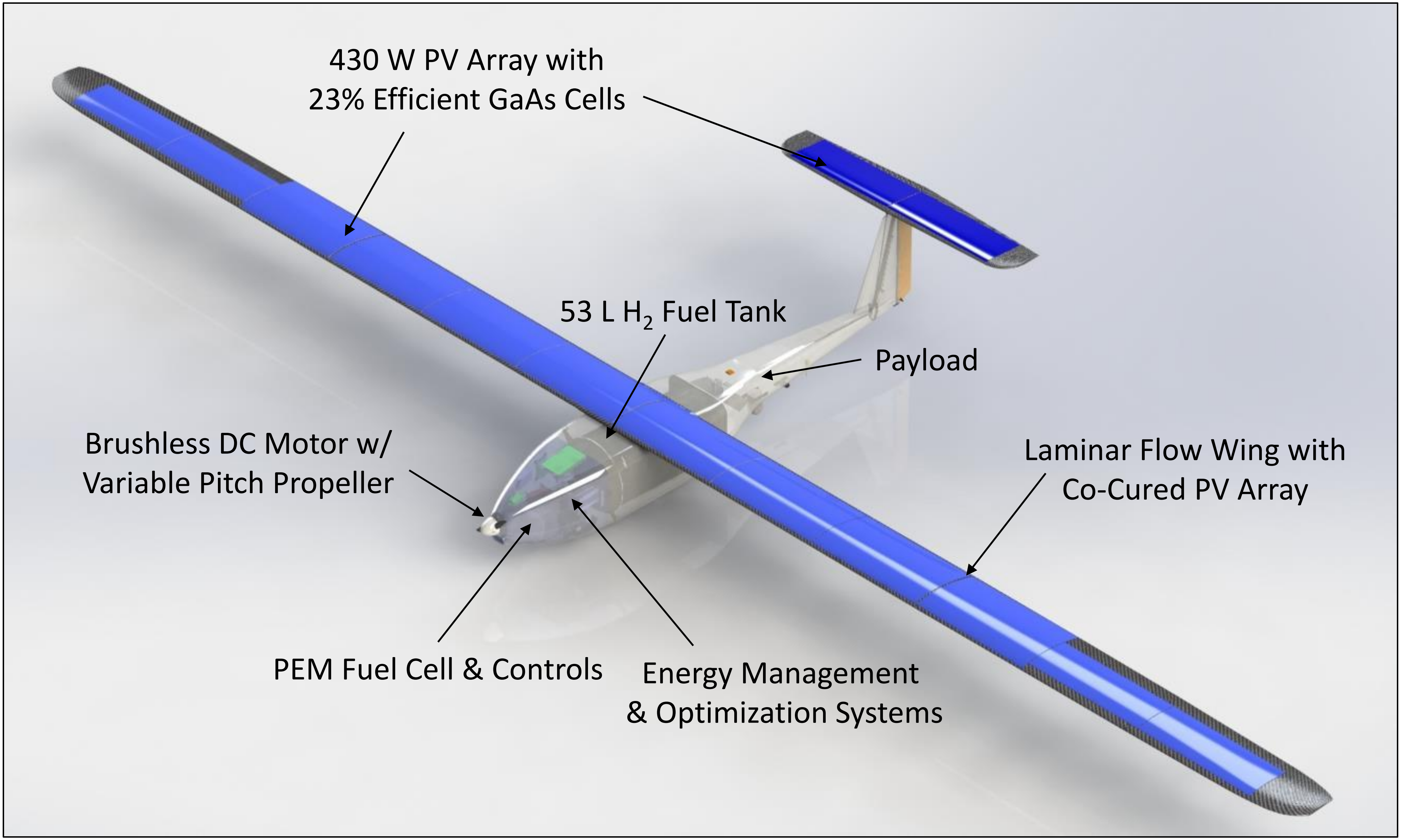
Integrated System: Hybrid Tiger

Group II UAS with Multi-Day Endurance

Main Challenges

- Automatically identifying how best to exploit the environment
- Robust integration of technologies with software-heavy focus
- Lightweight and energy efficient aircraft design

Hybrid Tiger Vehicle Design



Fuel Cell Propulsion

Fuel Cell
- PEM system from Protonex Technology Corp.
- Liquid cooled with external radiator
- Maximum output ~625 W net

H_2 Storage
- 53 L carbon overwrapped, Al lined Type III pressure vessel
- 13.6 wt % H_2 storage at 5,000 psi
- Lightweight single stage pressure regulator

PEM Fuel Cell / Solar Hybrid

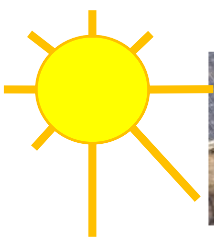
Specific energy is energy/mass:

Li-Ion battery:	250 Wh/kg
Fuel cell system*:	2800 Wh/kg
Solar day 1**:	1600 Wh/kg
Solar day 2:	3200 Wh/kg

Fuel cell enables solar array to capture "free" energy on following day. Each additional day increases *system* specific energy & endurance.

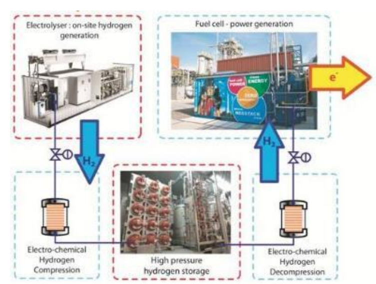
Conceptually, the H_2 could be produced locally by energy harvesting:

Source of Electricity



PV Solar Array

Hydrogen Generation System



Hybrid Tiger

* Incremental weight with fuel and tank, assuming 500 W fuel cell is sunk cost.
** Roughly 22% efficient PV cell for 12 h cosine day at 1000 W/m² peak.

Solar Energy Harvesting

Solar Arrays

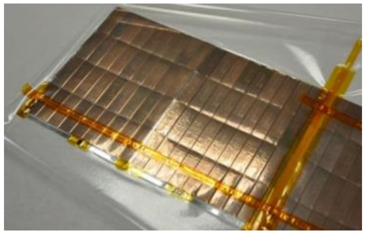
- 23% efficient GaAs cells co-cured in composite wings by NRL
- Multiple arrays enable independent max power point tracking
- Maximum output ~600 W (AM1.5 conditions)
- Weight: 600 g (~ 1 kg installed)

SBXC UAV with solar integrated by NRL

Maximum Power Point Trackers

- Small, lightweight, and efficient buck/boost with 20 Hz tracking
- I,V, and T data passed to power manager
- Distributed with arrays to minimize wire weight

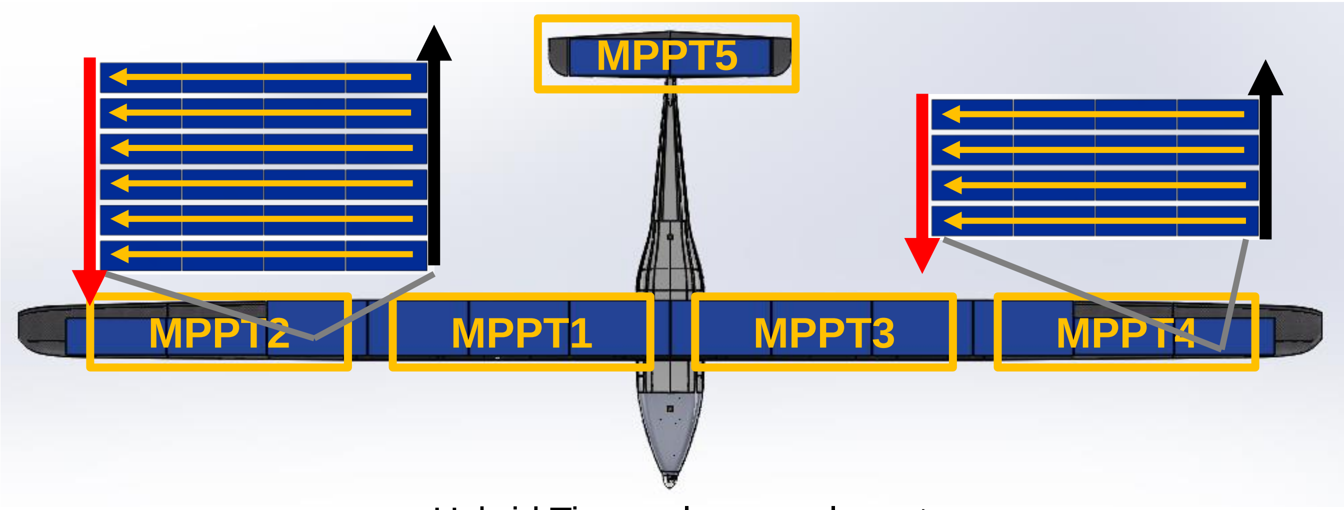
MPPT



Cells prior to integration

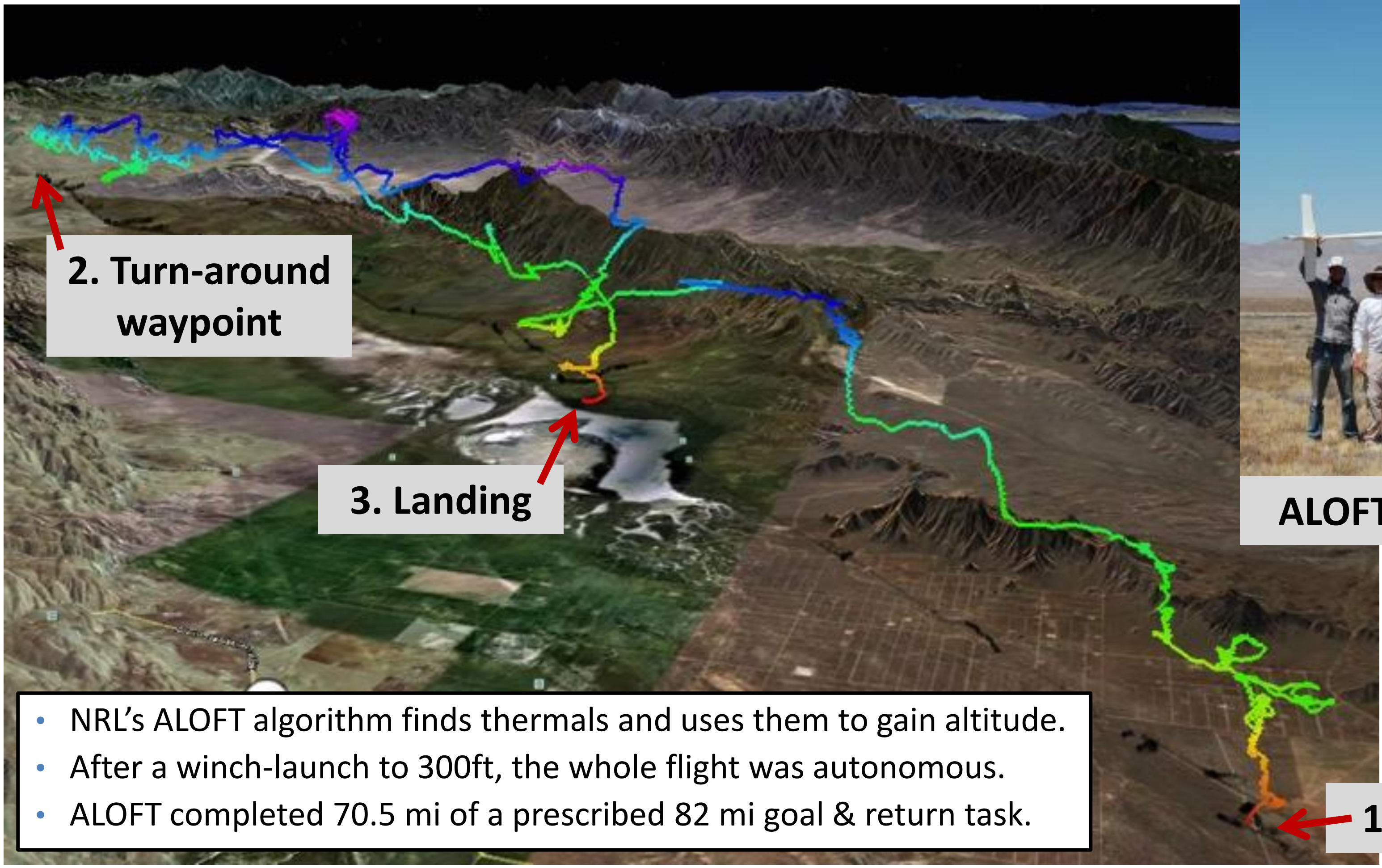
Smart Battery

- 7s Li-Ion pack with cell balancing, smart charging, and SOC reported
- For emergencies only unlike most solar air vehicles



Hybrid Tiger solar array layout

Autonomous Soaring

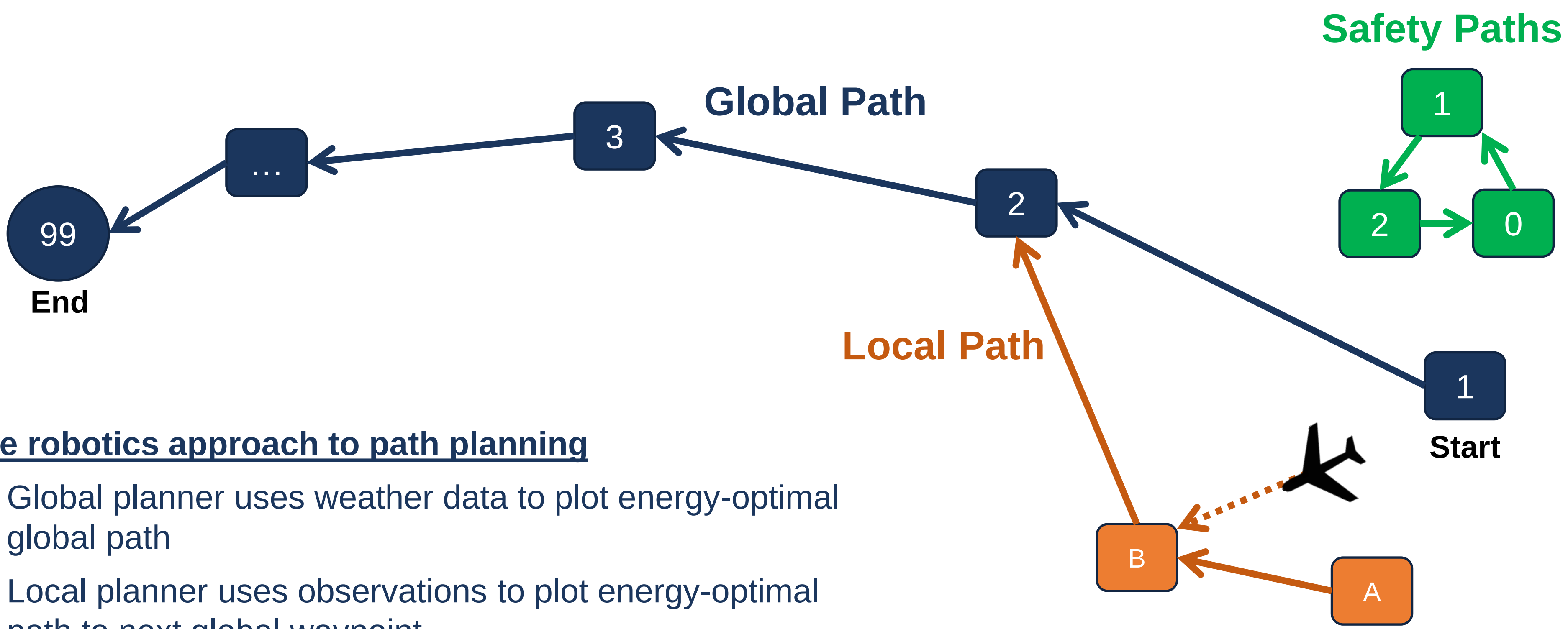


- NRL's ALOFT algorithm finds thermals and uses them to gain altitude.
- After a winch-launch to 300ft, the whole flight was autonomous.
- ALOFT completed 70.5 mi of a prescribed 82 mi goal & return task.

ALOFT sailplane

70.5 mi along prescribed course in 4.5hr, <u>all without a motor</u>.

Energy-Optimal Path Planning



Use robotics approach to path planning

- Global planner uses weather data to plot energy-optimal global path
- Local planner uses observations to plot energy-optimal path to next global waypoint

Global planner exploits large-scale features: regional wind & solar

Local planner exploits small-scale features: thermals & clouds

Two optimization problems

- Min fuel consumption with time upper bound
- Min time with fuel lower bound

Global optimum is not guaranteed, but seems to be a good approximation

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Energy-Optimal Path Planning: GPP

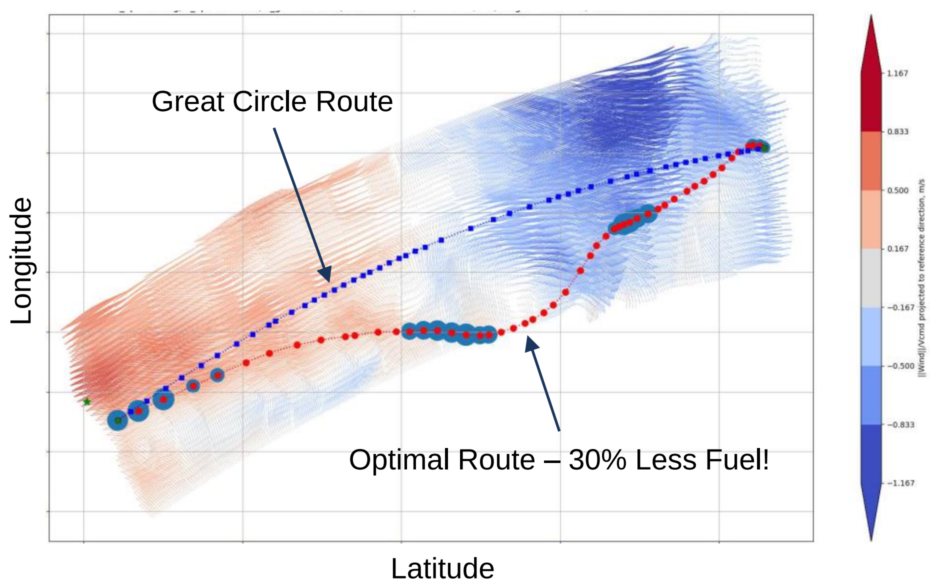
Solution Process

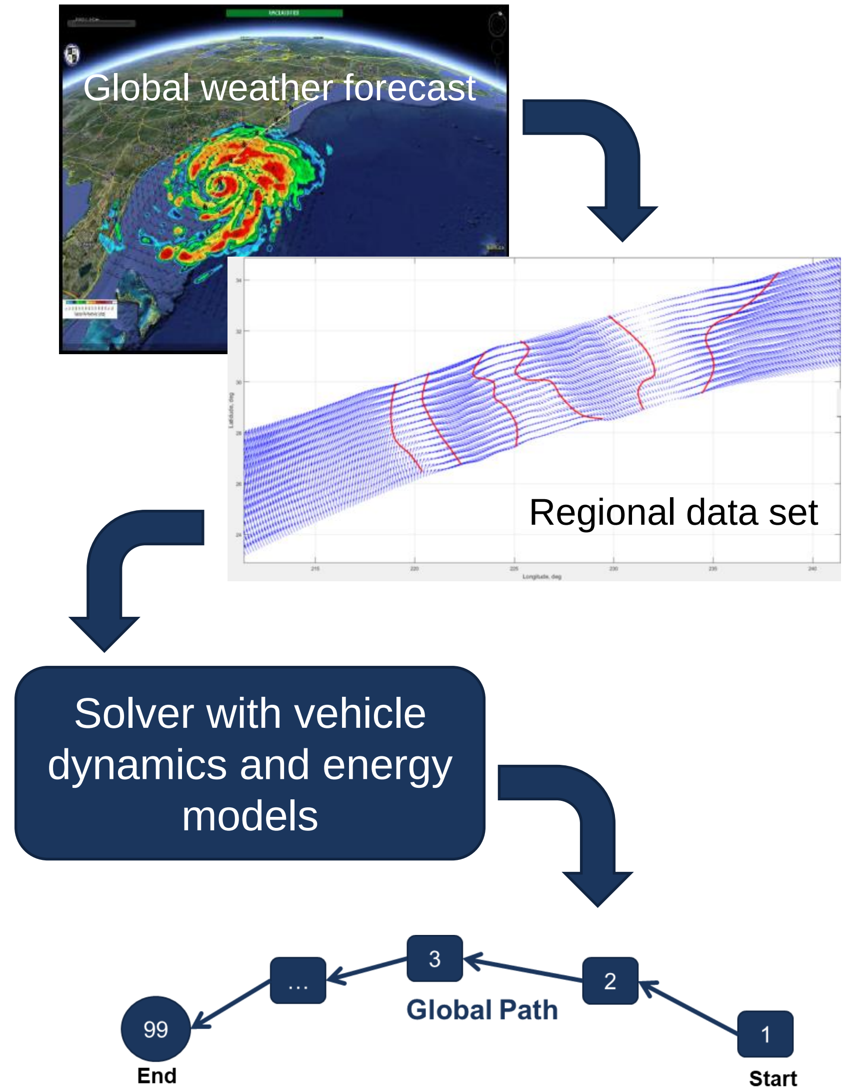
- Navy COAMPS model yields wind & solar flux on 9 km grid
- Use vehicle dynamics and energy models to simulate flight; wrap optimization solver around simulation

Result

- Series of global waypoints with metadata: altitude, speed, and **vehicle energy** targets
- Substantial energy and/or time savings – varies with weather

Global Path Planner Results





Energy-Optimal Path Planning: LPP

LPP Goals

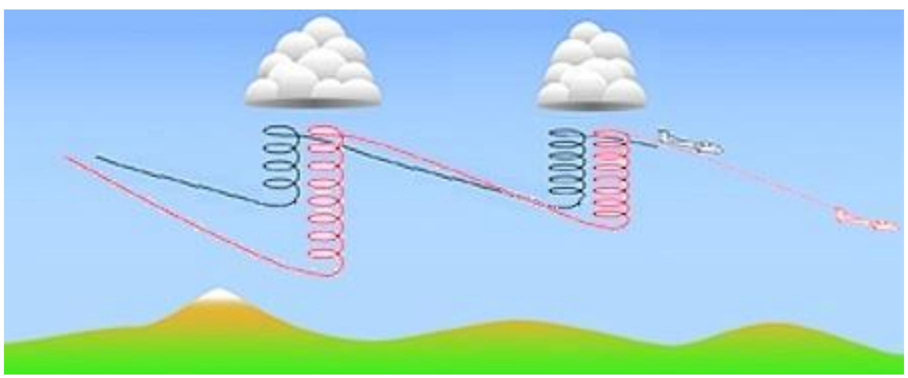
- Manage **flight path**, **altitude**, and **power balance** to reach next GPP waypoint with at the expected time with at least the proscribed **energy**.
- Exploit rising air to **reduce energy expended** or improve speed.
- Manage speed & altitude during solar interruptions to **maximize average speed** without consuming H_2.

LPP Optimization Process

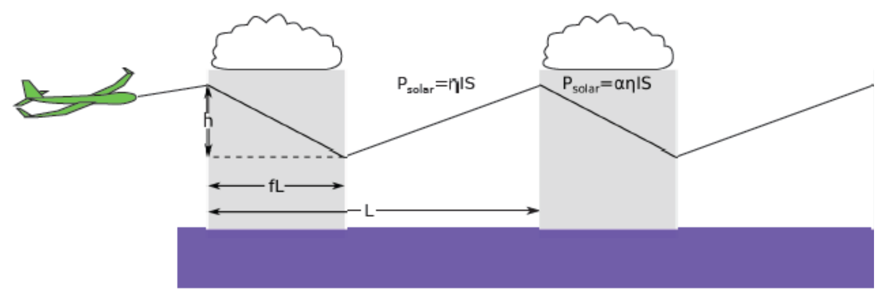
- Objective function: Maximize

$$\dot{e}_{total} = w_z + v_a\left(\frac{T}{mg} - \frac{C_L}{C_D}\right) + \dot{e}_{batt} + \dot{e}_{FC} + \dot{e}_{PV}$$

- $\dot{e}_{total}$: total power expenditure
- w_z: updraft input
- v_a: airspeed selection and T: thrust selection
- $\dot{e}_{PV}$: PV power considering aircraft attitude



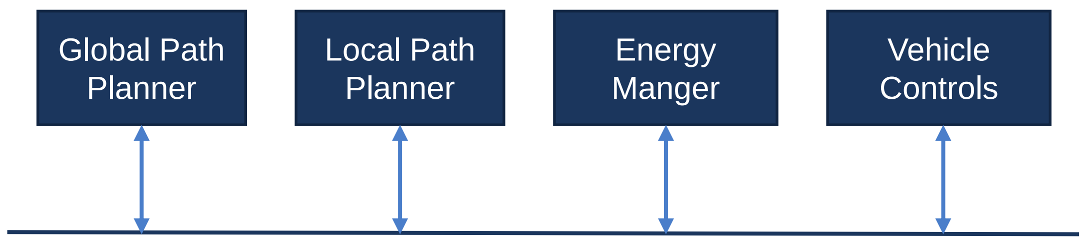
Traditional McCready theory: speed to fly



Considering influence of solar harvesting

We can treat sunny regions like rising air and shaded regions like sinking air to incorporate solar harvesting in speed to fly calculations

Putting It All Together



ROS Network Controlling the Hybrid Tiger

ROS

Odroid Board Computer

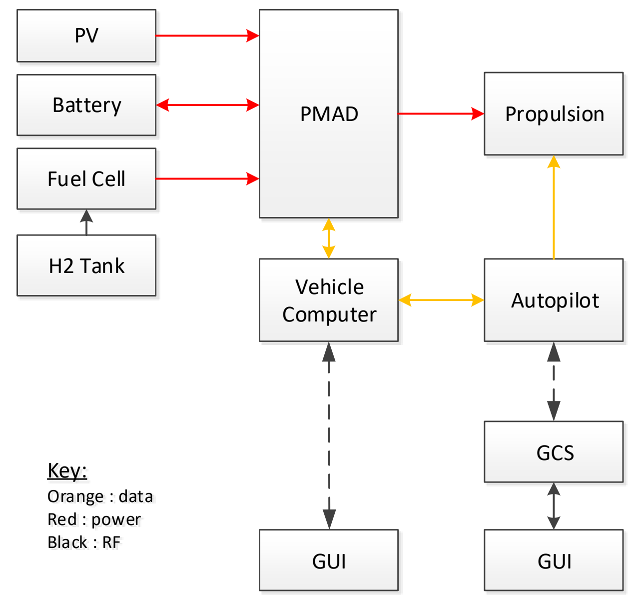
Power Management and Distribution Board

Software

- Subsystems are ROS nodes or operated by them
- “Supervisor” state machine coordinates interactions of GPP, LPP, and power management

Hardware

- Power management electronics integrate power from solar arrays, fuel cell, and emergency battery.
- A variable pitch propeller consumes power efficiently, and the electronics limit power consumption to operate the fuel cell efficiently.



Energy subsystem interconnections

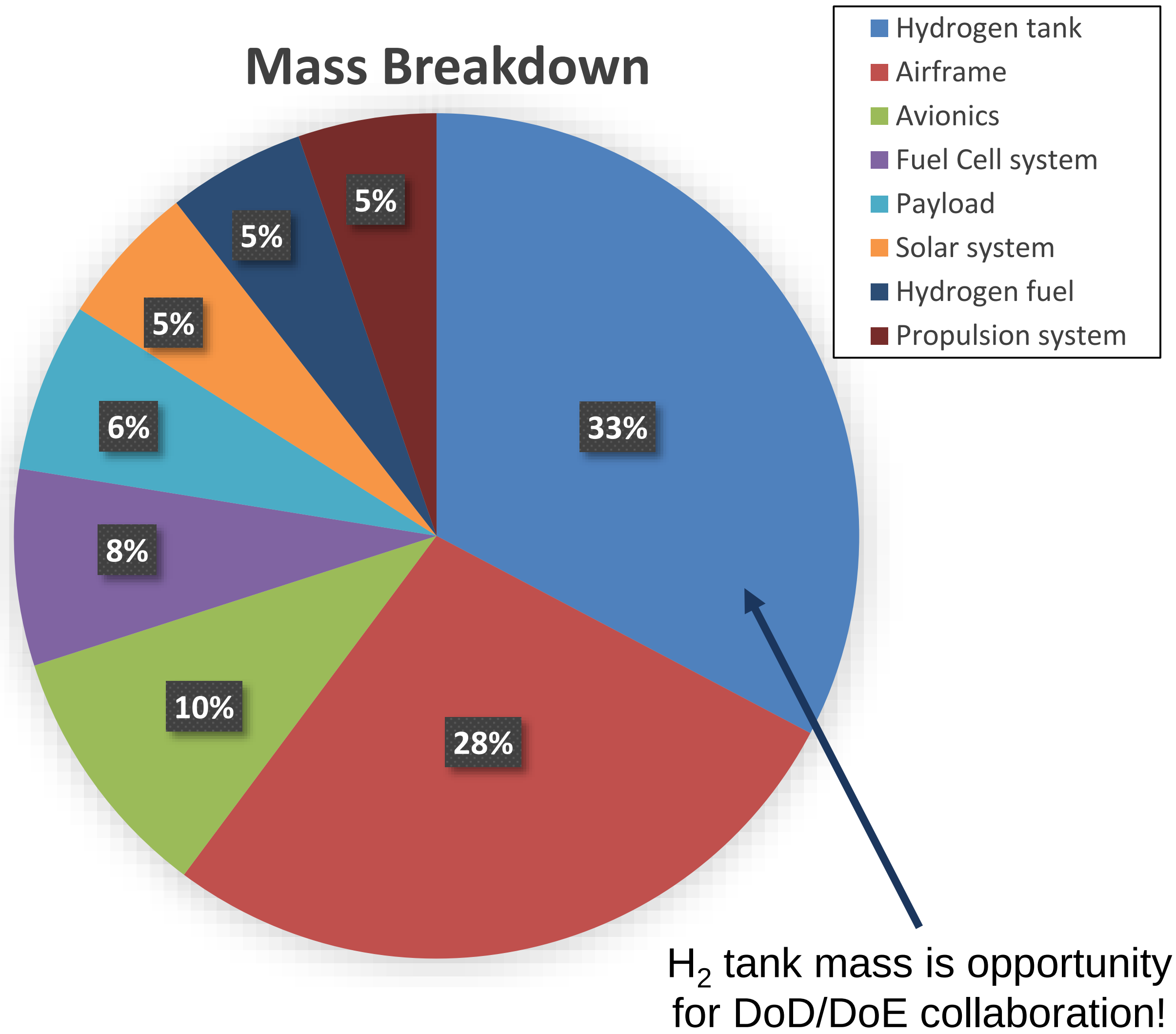
Hybrid Tiger Mass Breakdown

Major masses contributors:

- 33% is empty H_2 tank alone!
- 28% airframe is on the low side, but achieved with good design.
- 17% is avionics and payload.

Energy Sources:

- 5% solar mass provides **one-third** of total energy consumed.
- 5% hydrogen mass provides **two-thirds** of total energy consumed.



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Conclusions and Looking Forward

Conclusions so far:

- Major simulation effort has paid off in improved design and schedule
- Opportunities for improvement include fuel tank mass and system-level integration & optimization
- Small performance improvements (efficiency, specific energy, etc.) add up quickly

Looking forward:

- First flight planned for early summer; battery electric and then spiral in hybrid systems
- Continue to leverage DoD and DoE investments in fuel cells, solar (PV) conversion, H_2 storage, weather prediction and optimized energy harvesting
- Apply the lessons learned from Hybrid Tiger to other platforms

Questions?