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: NRL’s first “practical” fuel cell powered UAV
- 16 kg, 5.7 m wingspan autonomous air vehicle
- Gaseous H₂ fuel: 22 L at 5,000 psi and 25°C → 500 g
- Liquid H₂ fuel: 19.8 L at 20 psi and 22 K → 1300 g
- Unofficial flight endurance records – 26 h (GH₂) and 48 h (LH₂)

Ion Tiger demonstrated the feasibility of fuel cell UAV propulsion with high performance H₂ storage

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 & H₂ Fuel Storage
- Autonomous Soaring

Maximize Performance
- Novel Energy Optimization Algorithms
- Real-Time Energy Management & High Efficiency Components

Integrated System: Hybrid Tiger

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

Group II UAS with Multi-Day Endurance
Hybrid Tiger Vehicle Design

- 430 W PV Array with 23% Efficient GaAs Cells
- 53 L H₂ Fuel Tank
- Payload
- Brushless DC Motor w/ Variable Pitch Propeller
- PEM Fuel Cell & Controls
- Laminar Flow Wing with Co-Cured PV Array
- Energy Management & Optimization Systems
Fuel Cell Propulsion

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

H₂ Storage
- 53 L carbon overwrapped, Al lined Type III pressure vessel
- 13.6 wt % H₂ 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 H₂ could be produced locally by energy harvesting:

Source of Electricity

Hydrogen Generation System

Hybrid Tiger

PV Solar Array

* 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)

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

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

SBXC UAV with solar integrated by NRL
Cells prior to integration

Hybrid Tiger solar array layout
Hybrid Tiger UAV | 5
Autonomous Soaring

70.5 mi along prescribed course in 4.5hr, all without a motor.

- 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.

- 1. Launch
- 2. Turn-around waypoint
- 3. Landing

ALOFT sailplane

@ DOE AMR Inter-Agency Session
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
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

- Great Circle Route
- Optimal Route – 30% Less Fuel!
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
  \[
  \dot{e}_{total} = w_z + v_a \left( \frac{T}{m g} - \frac{C_L}{C_D} \right) + \dot{e}_{batt} + \dot{e}_{FC} + \dot{e}_{PV}
  \]
  - $\dot{e}_{total}$: total power expenditure
  - $w_z$: updraft input
  - $v_a$: airspeed selection and $T$: thrust selection
  - $\dot{e}_{PV}$: PV power considering aircraft attitude

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

H$_2$ tank mass is opportunity for DoD/DoE collaboration!
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, H₂ storage, weather prediction and optimized energy harvesting
• Apply the lessons learned from Hybrid Tiger to other platforms