Guidance and Control of an Autonomous Soaring Vehicle with Flight Test Results

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Background

- Many UAVs have similar mission constraints to birds and sailplanes.
  - Surveillance
  - Point to point flight with minimal energy
  - Increased ground speed
- Birds use atmospheric energy to hunt, forage, and migrate thousands of miles.
- Manned sailplanes rely solely on atmospheric energy
  - 2,000km (1,200mi) maximum distance.
  - Cross-country speeds in excess of 160kph (100mph)
Background:
Energy sources for Unmanned Vehicles

• Fossil fuel
  – Advantages: cheap, high specific power, COTS engines
  – Disadvantages: pollution, noise, must re-fuel, cannot start & stop easily

• Solar Electric
  – Advantages: Quiet, renewable, easy to start & stop, no pollution.
  – Disadvantages: Lower specific power, more expensive, climate and weather dependant

• Atmospheric Energy
  – Advantages: Free, strong, quiet, does not require special hardware
    (although advanced algorithms may require faster processor)
  – Disadvantages: Climate and weather dependant, usually limited to lower altitudes (h<10Kft), requires maneuvering which may upset sensor measurements

• Best use of atmospheric energy is to augment other sources of energy.
Background: Alan Cocconi

- Alan Cocconi flew the Solong UAV for 48hr using solar energy on June 1-3, 2005
  - Span = 15.6ft
  - Weight = 28.2lb
  - “The energy budget requires riding thermals.”
  - Cocconi also stated that the pilots/UAV operators were exhausted after 48hr of flying.
  - Moving map display with aircraft path was used by the pilots to soar in thermals.
John Wharington first proposed autonomous soaring for UAVs in 1998.

- Recursive learning was used to center updrafts. Neural networks were used to identify updraft positions.
- Algorithms were too computational intensive for real-time use.
- Framework for updraft modeling, simulation, and autonomous soaring was provided.
Test Hardware

- Cloud Swift Aircraft
  - Span: 4.26m (14ft)
  - Weight: 6.58kg (14.5lb)
  - Stall speed: 18kt
  - Mission speed: 25kt
- Piccolo Plus Autopilot
  - Weight: 212g (7.5 oz)
  - Sensors:
    - Rate gyros
    - Accelerations
    - Static & total pressure
    - GPS position & velocity
- Custom software developed for this project
Flight Test, Guidance and Control for Thermal Soaring
Flight Test Plan

Soaring research flights
- 4,000ft AGL altitude restriction
- Conducted on the edge of Rogers Dry Lakebed
- August – October, 2005
Flight Test Results

• 23 updrafts were autonomously detected and used
• Average height gain was 172m (567ft)

• Play cloudSwift_flt08_pr.mp2v
Thermal State Estimation

Diagram:

1. \( \dot{E} \)
2. Latitude
3. Longitude

Coordinate transformation

1. \( E \)
2. \( P \)
3. \( q_1 \)
4. \( q_2 \)
5. \( P_{th} \)
6. \( q_{th} \)
7. \( r_{th} \)
8. \( w_{th} \)

Drift correction
Updraft position estimation
Updraft velocity estimation
Updraft radius estimation

\( P_{th} \)
Thermal Drift Estimation

- Drift velocity was estimated from previous values of energy rate.
- Drift was used to define a new reference frame that is moving with the thermal.
Thermal Radius Estimation

- Thermal radius was estimated by iteratively fitting an assumed thermal velocity distribution to the energy rate measurements.

\[ W_{\text{pred}} = (W_{\text{th}} + V_e) e^{\left( \frac{S}{r_{\text{th}}} \right)^2} - V_e \]

\[ \dot{E}, \text{ m/s} \]

Distance to estimated thermal center, m
Thermal Position Estimation

- Position was estimated by finding the position centroid of the measured energy rate.
- Advantages: Low computational cost, no tuning required, robust to variations in thermal size.
- Disadvantages: Bias toward the center of the measurement set.

\[
X_{th} = \frac{\sum X \cdot \dot{E}^2}{\sum \dot{E}^2}
\]
Flight Test Results

- Soaring flight in light lift shown.
- Two small thermals encountered.
- Thermal centering performance could be improved.
  - Energy rate estimation delay.
  - Slow down when soaring.
- Altitude gain = 300ft
**Mode Logic**

- Simple mode logic was able to determine when to soar and when to search.
  - **Input:**
    - Total energy rate
    - Total energy acceleration
  - **Output:**
    - Soaring on/off
- **Possible improvements:**
  - Quicker estimate of aircraft energy
  - Additional mode that would allow the UAV to “Investigate” the thermal before moving on.
Flight Test Results

- Highest climb in a single updraft shown.
- 844m (2770ft) altitude gain.

Play: cloudSwift_flt12_up2.igc
Flight Test Results
Flight Test Results
Flight Test Results

• Multiple thermals were used to soar autonomously for over an hour.
• Flight was limited only by actuator battery capacity.
• Altitude time-history is similar to that of migrating birds.
Concluding Remarks

- A guidance and control method was developed to detect and exploit thermals for energy gain.
- Latency in energy rate estimation degraded performance.
- The concept of a UAV harvesting energy from the atmosphere has been shown to be feasible with existing technology.
Questions?