BOOM AND RECEPTACLE AUTONOMOUS AIR REFUELING USING A VISUAL PRESSURE SNAKE OPTICAL SENSOR

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AUTONOMOUS REFUELING

outline of presentation

- AERIAL REFUELING
- VISUAL PRESSURE SNAKE SENSOR
- AUTONOMOUS AIR REFUELING SYSTEM
- BOOM AND VEHICLE MODELING
- CONTROLLER DEVELOPMENT
- SIMULATION EXAMPLE
- CONCLUSIONS & FUTURE DIRECTIONS
REFUELING
probe and drogue
REFUELING SEQUENCE

approach
REFUELING SEQUENCE

transfer fuel
VisNav APPLICATION

autonomous probe and drogue aerial refueling

6 DOF navigation solution:

- \((X_c, Y_c, Z_c)\): Object Space coordinates of sensor
- \([C]\): Transformation from Object Space to Image Space
VisNav APPLICATION

autonomous probe and drogue aerial refueling

Valasek et. al, 2002-2006
REFUELING
boom and receptacle

- Boeing (1940s)
- Operator maneuvers boom with ruddervators
- Pilot responsible for station-keeping
- Quick connection
- High flow rate of fuel
- Drag penalty on tanker
- Buffet
- Frequent disconnects in turbulence
AUTONOMOUS REFUELING

recent work

- Sensing systems
  - Differential Global Positioning System (2003 Speyer et al.)
    - Passive systems (visual servoing, pattern recognition)
    - Active systems (VisNav)
  - Combined systems

- Controllers
  - Model-following control (2002 - 2006 Valasek et al)
  - $H_\infty$ control (2004 Campa et al)
  - Differential games, adaptive control (2004 Stepanyan et al)
AUTONOMOUS REFUELING
considerations and options

- DGPS particularly useful for distant tanker/UAV separations or gross positioning movements

- Local Positioning System (LPS) is required for close-in navigation
  - DGPS limited in
    - accuracy
    - bandwidth
    - dropouts

- Optical-based navigation systems offer promising alternative
  - Multipath reflections minimized by restricted field of view
  - High bandwidth, Signal-Noise (S/N) ratio
  - Redundant set of sensors
    - robustness and flexibility
RESEARCH OBJECTIVE

● “Develop a reliable and robust Aerial Refueling System which automatically steers the boom on a manned tanker aircraft into the refueling receptacle on an unmanned receiver aircraft, in light and moderate turbulence”

● Components of the Aerial Refueling System
  1. Relative Position Sensor
  2. Boom Trajectory Tracking Controller
  3. Receiver Aircraft Station-Keeping Controller
  4. Autonomous Refueling Supervisor
AUTONOMOUS REFUELING

*proposed operational concept*
CLASS II/III REFUELING DEMONSTRATION

triangle boom concept

- Primarily conceived for refueling unmanned air vehicles.
- Suitable for speeds lower than a hose and drogue system could operate.
- Receiver probe is guided into triangle boom, in a probe and drogue system.
VISUAL PRESSURE SNAKES

- Color Statistical Pressure Snakes (Smith and Schaub)
  - HSV Color Space
  - \[ E = \int_0^1 \left[ E_{\text{int}}(S(u)) + E_{\text{pres}}(S(u)) \right] du \]
  - \[ E_{\text{pres}} = \rho \left( \frac{\partial S}{\partial u} \right)^\perp (\epsilon - 1) \]

- Numerically efficient for Real-Time applications
  - Running on 800 MHz PC-104 computer at 25-30 Hz (640x480)

- Robust to lighting variations
SNAKES SYSTEM

sensor example
SNAKES SYSTEM

*target on receiver*
SNAKES SYSTEM

visual snake feature extraction

- Target Shape moments of inertia -- Green’s Theorem
  \[ M_{ij} = \int \int x^i y^j \, dx \, dy \]
  \[ \int \int \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dx \, dy = \int P \, dx + Q \, dy \]

- Target Center of Mass
  - Determines relative heading to target

- Principal Axis Dimensions
  - Assuming target shape is known….
  - Relationships between inertias and axes sizes
  - Axes determine range to target
    - Pin-hole Camera Model

\[ l = \sqrt{\frac{3I_1}{A}} \]
\[ h = \sqrt{\frac{3I_2}{A}} \]
SNAKES SYSTEM
forced perspective

- Desire particular visual target shape
- Use Forced Perspective
  - paint target on 3D surface so that it appears “correct” to the camera

Small errors introduced if receiver is not in position/orientation
SNAKES SYSTEM

performance

- Ideal Test Case
  - Crisp image boundaries
- Center of Mass = Heading to Target
  - 0.1 pixels (1 \(\sigma\))
- Principal Axis Lengths = Range
  - 0.3 pixels (1 \(\sigma\))
- Heading more precise than range
SNAKES SYSTEM

performance

- At nominal position/orientation…. (10.7 m. range)
  - 0.3 cm uncertainty in heading
  - 1.1 cm uncertainty in range
  - ie., long, thin “uncertainty cone”
SNAKES SYSTEM

hardware

- PC-104 computer (All hardware is COTS)
  - 800 MHz Pentium III
  - Frame-Grabber card
  - Digital Camera
- Volume:
  - 20 cm x 15 cm x 15cm
- Power:
  - < 100 W DC power
SNAKES SYSTEM

tanker boom model

- CHARACTERISTICS
  - Rigid body
  - 2 rotational DOF (pitch and yaw)
  - 1 translational DOF (extension)
  - Dimensions and masses from Soujanya et. al.
BOOM CONTROLLER

optimal PIF-NZSP-CRW

- COMMAND SYSTEM WITH CONTROL RATE WEIGHTING

- NZSP command:
  \[ \lim_{t \to \infty} y = y_m = Hx^* + Du^* \]

- integral of command error:
  \[ \dot{y}_1 = y - y_m \]

- control rate weighting:
  \[ u_1 = \dot{u} \]

\[
\begin{align*}
\tilde{x} &= x - x^* \\
\tilde{u} &= u - u^* \\
\tilde{u}_1 &= u_1 - u_1^*
\end{align*}
\]

\[
\begin{align*}
\ddot{x} &= A\dot{x} + Bu + y_1 \\
\ddot{y}_1 &= H\dot{y}_1 + Du_1 \end{align*}
\]
BOOM CONTROLLER

optimal PIF-NZSP-CRW

- COMMAND SYSTEM WITH CONTROL RATE WEIGHTING

- cost function:

\[ J = \frac{1}{2} \int_{0}^{\infty} \{ \tilde{x}^T Q_1 \tilde{x} + \tilde{u}^T R \tilde{u} + \tilde{r}_1^T S \tilde{r}_1 + y_1^T Q_2 y_1 \} dt \]

\[ J = \frac{1}{2} \int_{0}^{\infty} \begin{bmatrix} Q_1 & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & Q_2 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{u}_1^T S \tilde{r}_1 \end{bmatrix} dt \]

- control law:

\[ u_1 = (u_1^* + K_1 x^* + K_2 u^*) - K_1 x - K_2 u - K_3 y_1 \]

- LQR gains
- VKF state estimator
BOOM CONTROLLER

optimal PIF-NZSP-CRW

\[ E \]

\[ K_3 \]

\[ K_2 \]

\[ K_1 \]

\[ D \]

\[ H \]

\[ y_m \]

\[ \dot{y}_1 \]

\[ y_1 \]

\[ u_0 \]

\[ x_0 \]

\[ y \]

\[ \dot{u} \]

\[ u \]

\[ x \]

\[ \text{system} \]

\[ \text{optimal PIF-NZSP-CRW BOOM CONTROLLER} \]
V/STOL CAPABLE UCAV

60% SCALE AV-8B HARRIER
- Manned systems removed

LINEAR MODELS

PHYSICAL CHARACTERISTICS
- Gross weight = 13350 lbs
- Wing area = 533 ft$^2$
- Wing span = 46.2 ft
- Aerodynamic chord = 11.53 ft
- Inertias
  - $I_{xx} = 16425.9$ slug-ft$^2$
  - $I_{yy} = 26000.3$ slug-ft$^2$
  - $I_{zz} = 54284.1$ slug-ft$^2$
  - $I_{xz} = 0$
SNAKES SYSTEM

simulation examples

- **OBJECTIVE**
  Demonstrate autonomous refueling using simulated Visual Pressure Snake sensor.

- **SPECIFICATIONS**
  - Already in steady-state trailing formation (end game docking only)
  - Accuracy 0.2m
  - docking speed < 1 m/sec

- **TEST CONDITIONS**
  - 250 kts /6000m
  - Dryden light/moderate turbulence
  - Receiver initial offsets
    - x = 0.5m
    - y = 0.5m
    - z = 0.5m

Station keeping controller uses GPS for sensing, LQR controller for positioning maintaining within 3D refueling box: 0.25m x 0.75m x 0.5m
SNAKES SYSTEM
forced perspective video

Seen by Camera
NUMERICAL EXAMPLE

Still Air

receptacle to boom tip errors

![Graph showing error in Still Air receptacle to boom tip errors over time.](image-url)
NUMERICAL EXAMPLE

Still Air sensor output position estimates

![Graph showing sensor output position estimates for Still Air](image)
NUMERICAL EXAMPLE

boom displacements, rotations, rates

Still Air

\[ \psi_{\text{Boom}} \text{ (deg)} \]

\[ \theta_{\text{Boom}} \text{ (deg)} \]

\[ \text{Length}_{\text{Boom}} \text{ (m)} \]

\[ \dot{\psi}_{\text{Boom}} \text{ (deg/s)} \]

\[ \dot{\theta}_{\text{Boom}} \text{ (deg/s)} \]

\[ \dot{\text{Length}}_{\text{Boom}} \text{ (m/s)} \]
NUMERICAL EXAMPLE

Still Air

receiver UAV states
NUMERICAL EXAMPLE

Still Air  receiver UAV control effectors
NUMERICAL EXAMPLE

receptacle to boom tip errors

Light Turbulence
NUMERICAL EXAMPLE

sensor output position estimates

Light Turbulence

![Graphs showing sensor output position estimates](image-url)
NUMERICAL EXAMPLE

receptacle to boom tip errors

Moderate Turbulence
NUMERICAL EXAMPLE

sensor output position estimates

Moderate Turbulence

[Graph showing sensor output position estimates with X, Y, and Z coordinates over time.]

Doebbler, et. al. 2006 - 6504 - 37 Aerospace Engineering
CONCLUSIONS

- **CAPABILITY**
  - Accurate relative positions and attitude data at 30 Hz from 50m+
  - Steering of boom into receptacle for light and moderate turbulence

- **FEATURES**
  - Compatible with legacy refueling systems
    - small, low power sensor
  - Can be made effective in poor weather/lighting conditions
  - Wide field of view, no moving parts
  - Recovers and resets well from interruptions
FUTURE DIRECTIONS

- SENSOR IMPROVEMENTS
  - Direct sunlight operation
    - Appears feasible; to be demonstrated

- MODELING AND CONTROL IMPROVEMENTS
  - Flexible boom
  - Improved boom tracking controller
  - Tanker flowfield

- SIMULATION IMPROVEMENTS
  - UMBRA real-time hardware-in-the-loop development code
QUESTIONS?