Robust Trajectory Tracking Controller for Vision Based Probe and Drogue Autonomous Aerial Refueling

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Outline of the Presentation

- Autonomous Aerial Refueling.
- Components:
  1. VisNav Sensor
  2. Trajectory Generation Module
  3. Reference Observer
  4. Trajectory Tracking Controller
- Numerical Simulation Results
- Conclusions
- Future Research
Motivation

- Develop a system that will enable UAVs to perform autonomous aerial refueling (AAR)
  - Increase range and loiter time capabilities
  - Decrease size, weight, and per-unit cost
- Critical technologies
  - Sensors
  - Controller
  - Supervisory system
  - Refueling equipment
Aerial Refueling

Boom-Receptacle Method
- Preferred method for small, agile aircraft
- Small lightweight equipment
- No human operator required on the tanker aircraft.

Probe-Drogu Method
A Challenging Task
Problem Statement

- “Develop an Aerial Refueling System to dock the refueling probe of an unmanned receiver aircraft into a non-stationary drogue suspended from an unmanned tanker aircraft.”

- Components of the Aerial Refueling System
  2. Trajectory Tracking Controller.
Relative Navigation: Approaches

- **Global Positioning System**
  - Measurement Accuracy ~ 1 cm to 2 cm
  - Problems: lock-on, integer ambiguity, and low bandwidth present challenges for application to in-flight refueling.

- **Visual Servoing with Pattern Recognition**
  - Not reliable in all lighting conditions.
  - Computational power.

- **VisNav: Vision Based Cooperative Navigation**
VisNav Cooperative Vision

“Optical sensor with active structured beacon lights that provides an accurate, high speed 6-DOF navigation solution for the mid to end game docking maneuver.”

- Pattern recognition problem effectively eliminated.
- Update rate of 100 Hz and high precision under optimum conditions.
- Feasible at current level of optical sensing technology
- Concept validated with hardware in laboratory experiments and in outdoor experiments in presence of sunlight.
- Range up to 100 m. Accuracies
  - ~ 1cm/0.25 deg at 30m
  - ~ 1mm/0.05 deg at 0.5m
- Beacon signal modulation and optical filtering
- Real-time beacon selection/intensity control
- Very wide field of view, no moving parts.
- Distributed beacons, Very large operating space, redundancy.
The VisNav System

VisNav sensor

Active Beacon Array

“Image Space”

beacon commands

“Object Space”

6 DOF navigation solution:

- $\mathbf{X}_c, \mathbf{Y}_c, \mathbf{Z}_c$: Object Space coordinates of sensor
- $\mathbf{C}$: Transformation from Object Space to Image Space
The VisNav System

Estimate 6-Dof relative information between the receiver aircraft and the drogue from sensor readings.
(Gaussian Least Squares Differential Correction)
Outdoor Hardware Experiment
Central Idea
Reference Observer based Tracking Controller (ROTC)

1. VisNav Sensor
   Relative Position
   \( X, Y, Z \)

2. Trajectory Generation
   Generate Smooth Reference Trajectory
   in terms of
   \( X, Y, Z \)

3. Reference Observer
   Estimate the entire 12 state vector
   \( X, Y, Z, u, v, w, \phi, \theta, \psi, p, q, r \)
   for the reference trajectory

4. State Feedback Controller
   Full State Feedback Controller
   to track the Reference States

Reference Observer based Tracking Controller (ROTC)
Reference Trajectory Generation

- **Stage I**
  - Gross positioning based on initial offset
  - Lateral and vertical alignment

- **Stage II**
  - Track drogue motion in the end game.

- Ref Trajectory:
  Inertial positions $X_r, Y_r, Z_r$
Need for the Reference Observer

- Controller Used: Full State feedback Controller, entire state vector
  \(X, Y, Z\), \(u, v, w\), \(\phi, \theta, \psi\), \(p, q, r\)
  is available for feedback.

- What \(u_r, v_r, w_r\), \(\phi_r, \theta_r, \psi_r\), \(p_r, q_r, r_r\) \(\rightarrow\) \(X_r, Y_r, Z_r\)

- The reference observer estimates the states and the control inputs that the plant should follow to track the desired reference trajectory.
Reference Observer based Tracking Controller (ROTC)

- **Plant:**  
  \[
  \dot{x} = Ax(t) + Bu(t) \\
  y = Cx(t) + Du(t) \\
  x(t) = [X, Y, Z, u, v, w, \phi, \theta, \psi, p, q, r] \\
  y(t) = [X, Y, Z]
  \]

- **Find**  
  \[u(t)\] to drive \(y(t) \rightarrow y_r(t)\)  
  \[y_r(t) = [X_r, Y_r, Z_r]\]

- The reference dynamics will have the form  
  \[
  \dot{x}_r = Ax_r(t) + Bu_r(t) \\
  y = Cx_r(t) + Du_r(t)
  \]
Tracking Controller

- **Error Dynamics**
  \[ \tilde{x} = x - x_r, \quad \tilde{u} = u - u_r \]
  \[ \dot{\tilde{x}} = A\tilde{x}(t) + B\tilde{u}(t) \]
  Control Law: \[ \tilde{u} = -K\tilde{x} \]
  In terms of original variables
  \[ u = (u_r + Kx_r) - Kx \]

- But \( u_r, x_r \) are unknown.

- The Reference Observer estimates \( u_r, x_r \) from \( y_r \)
Reference Observer

- Augmented Reference Dynamics

\[
\begin{bmatrix}
    \dot{x}_r \\
    \dot{u}_r
\end{bmatrix} =
\begin{bmatrix}
    A & B \\
    0 & 0
\end{bmatrix}
\begin{bmatrix}
    x_r \\
    u_r
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    I
\end{bmatrix}
\dot{u}_r
\]

- Output Injection Observer

\[
\begin{bmatrix}
    \dot{x} \\
    \dot{\hat{u}}
\end{bmatrix} =
\begin{bmatrix}
    A & B \\
    0 & 0
\end{bmatrix}
\begin{bmatrix}
    \hat{x} \\
    \hat{u}
\end{bmatrix} +
L\left\{y_r - [C & 0]
\begin{bmatrix}
    \hat{x} \\
    \hat{u}
\end{bmatrix}\right\}
\]

- By suitable pole placement the observer can be made stable
ROTTC Block Diagram

- $y_d$
- $y_{rel} + \eta_1$
- Reference Trajectory Generation Module
- $y^* - \eta_1 + \eta_3$
- Observer
- Controller
- Plant
- Full state feedback
- Feed-forward
- $\hat{u}$
- $\hat{x}$
- $u$
- $y$
- $\eta_2$
- $\eta_3$
- $\eta_1$
Reference Observer Based Tracking Controller

- Stability of the combined Observer Controller system using Separation Principle.

- Frequency Domain Stability Robustness and Performance Robustness analysis using Singular Value Plots.
Numerical Simulation

- Linear model of an unmanned air vehicle UCAV6
- 60% scale AV-8B Harrier aircraft

- Flight condition: Altitude=6000 m, $V_0=128.7$ m/s
- Dryden Light Turbulence ($\sigma$-gust=1)
- High Fidelity VisNav Simulation.
- Receiver Position relative to the Drogue
  - 30 m behind, 15 m below, 15 m to the right
Linear States

\[ \delta X (m) \]
\[ \delta Y (m) \]
\[ \delta Z (m) \]
\[ \delta v (m/s) \]

\[ \delta v (m/s) \]

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Veritas Fugae

STAR VISION

Technologies
Angular States

\[ \delta \phi (\text{deg}) \]
\[ \delta \theta (\text{deg}) \]
\[ \delta \psi (\text{deg}) \]
\[ \delta \rho (\text{deg/s}) \]
\[ \delta \sigma (\text{deg/s}) \]

Time (s)

Observer
Plant
Aerodynamic Angles

\[ \delta \alpha (\text{deg}) \]

\[ \delta \beta (\text{deg}) \]

Time (s)
Control & Control Rates
Docking End Game

![Graph showing the performance of a docking system over time.](image-url)
Projection of probe-drogue trajectories in Y-Z plane
Docking Animation

Distance to Dock = 30.1
VisNav Estimate Error
Beacon Drop Outs

Discontinuities in VisNav solution in high turbulence due to beacon dropouts

![Graph showing Xc error (ft) vs. time (s)]
Comparison: Tracking
NZSP v/s ROTC

- X (m)
- Y (m)
- Z (m)
Comparison: Tracking Error
NZSP v/s ROTC
Conclusions

- Proposed and Validated a novel Reference Observer Based Tracking Controller
- Observer-Controller system: stable.
- Stability and Performance Robustness: VisNav sensor noise, state feedback sensor noise, light turbulence due to wind gusts, high frequency unmodeled dynamics.
- Tracking error was reduced by 75% as compared to a NZSP Controller. (Reduction in lag in the tracking)
- Probe tip within a 5 cm radius circle around the center of the drogue in the presence of light turbulence.
Future Research

- Flow field effect of the tanker aircraft
- Accurate model of the drogue dynamics. (flight test data)
- Investigation of discontinuities in the VisNav solutions due to beacon dropouts
- Actively control drogue to enable docking in higher levels of turbulence
- Fight test demonstration of the vision sensor and controller
  - air-to-ground
  - air-to-air refueling demonstration.
Thank You

Questions or Comments