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


Global Hawk

Aerial Refueling

Boom-Receptacle Method

Probe-Drogue Method

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

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
  1. Sensing Relative Position.
  2. Trajectory Tracking Controller.

Relative Navigation : Approaches

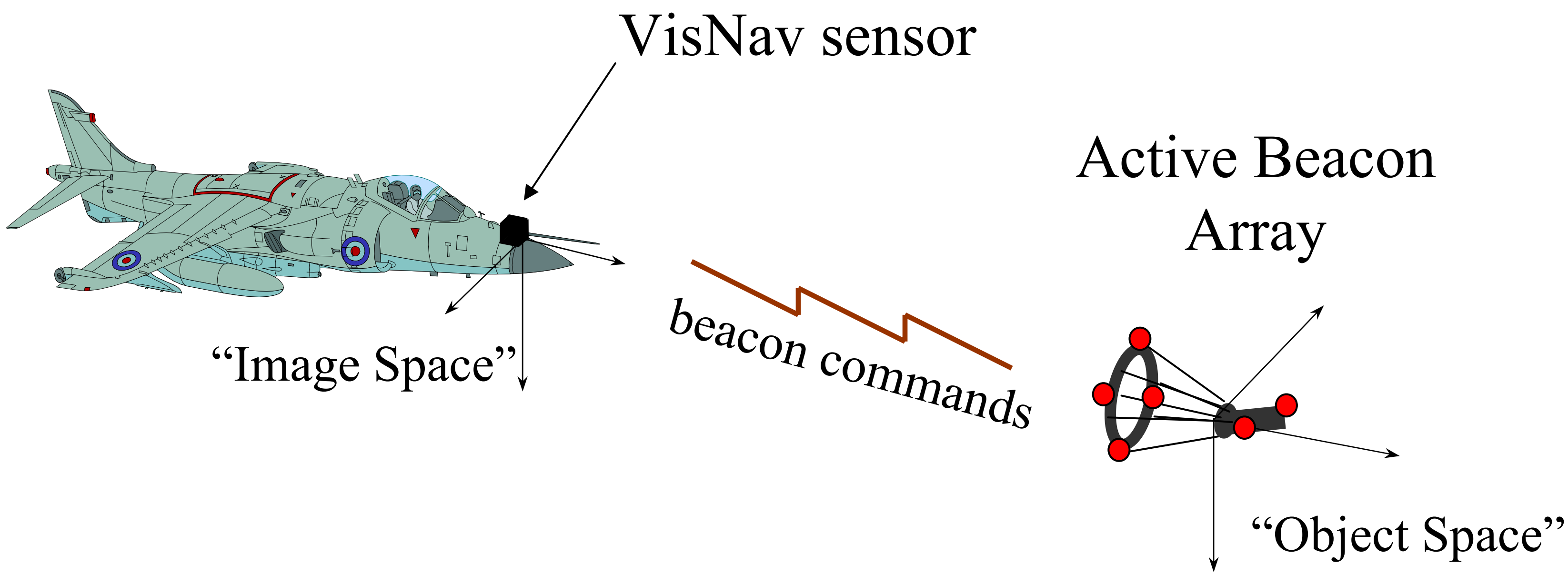
- Global Positioning System
  - Measurement Accuracy ~ 1 cm to 2 cm
  - Problems: lock-on, integer ambiguity, and low bandwidth present challenges for application to in-flight refueling.
- Visual Servoing with Pattern Recognition
  - Not reliable in all lighting conditions.
  - Computational power.
- 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.

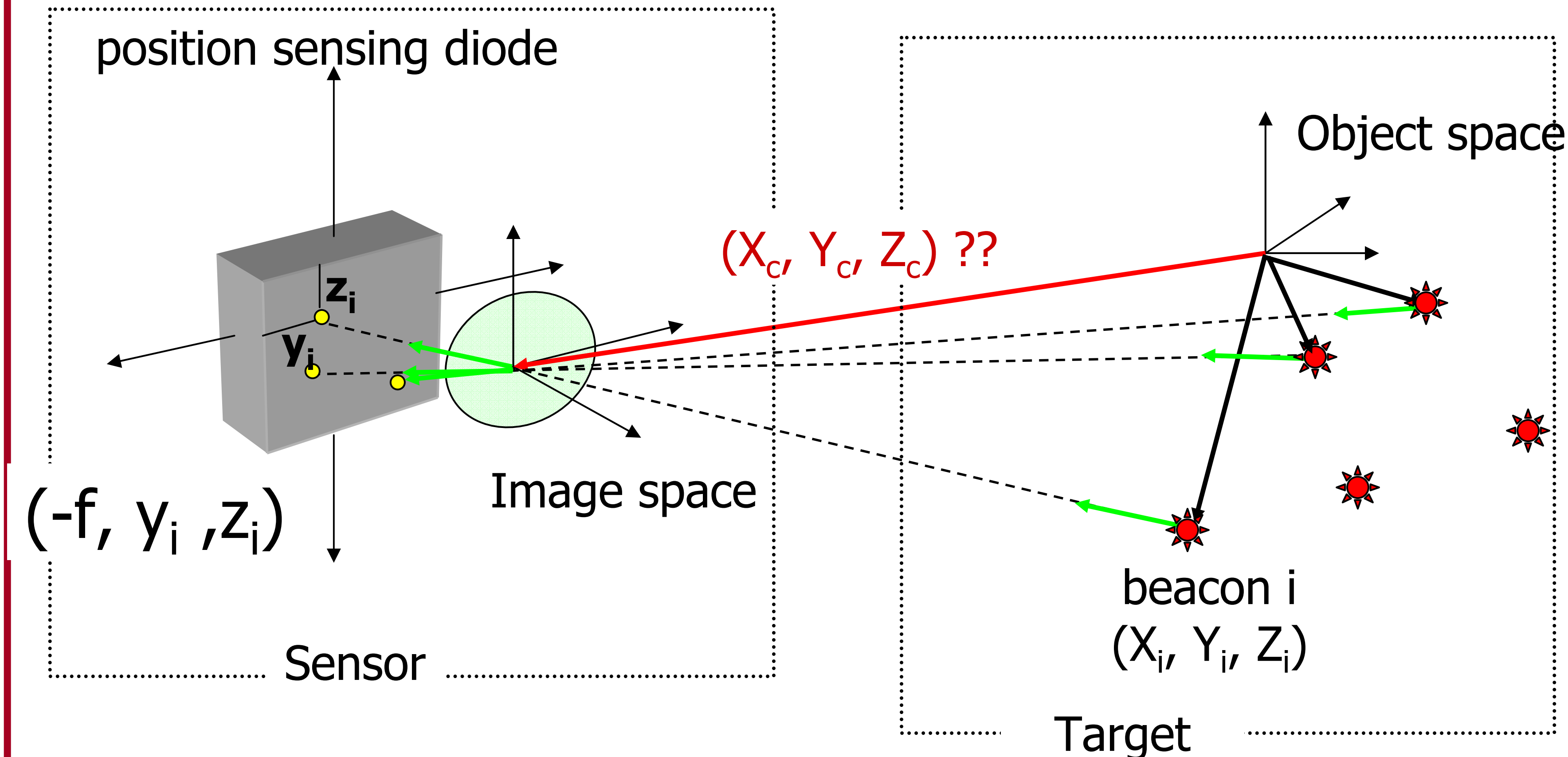
The VisNav System



6 DOF navigation solution:

- (Xc, Yc, Zc): Object Space coordinates of sensor
- [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

$X, Y, Z \quad u, v, w$

$\phi, \theta, \psi \quad p, q, r$

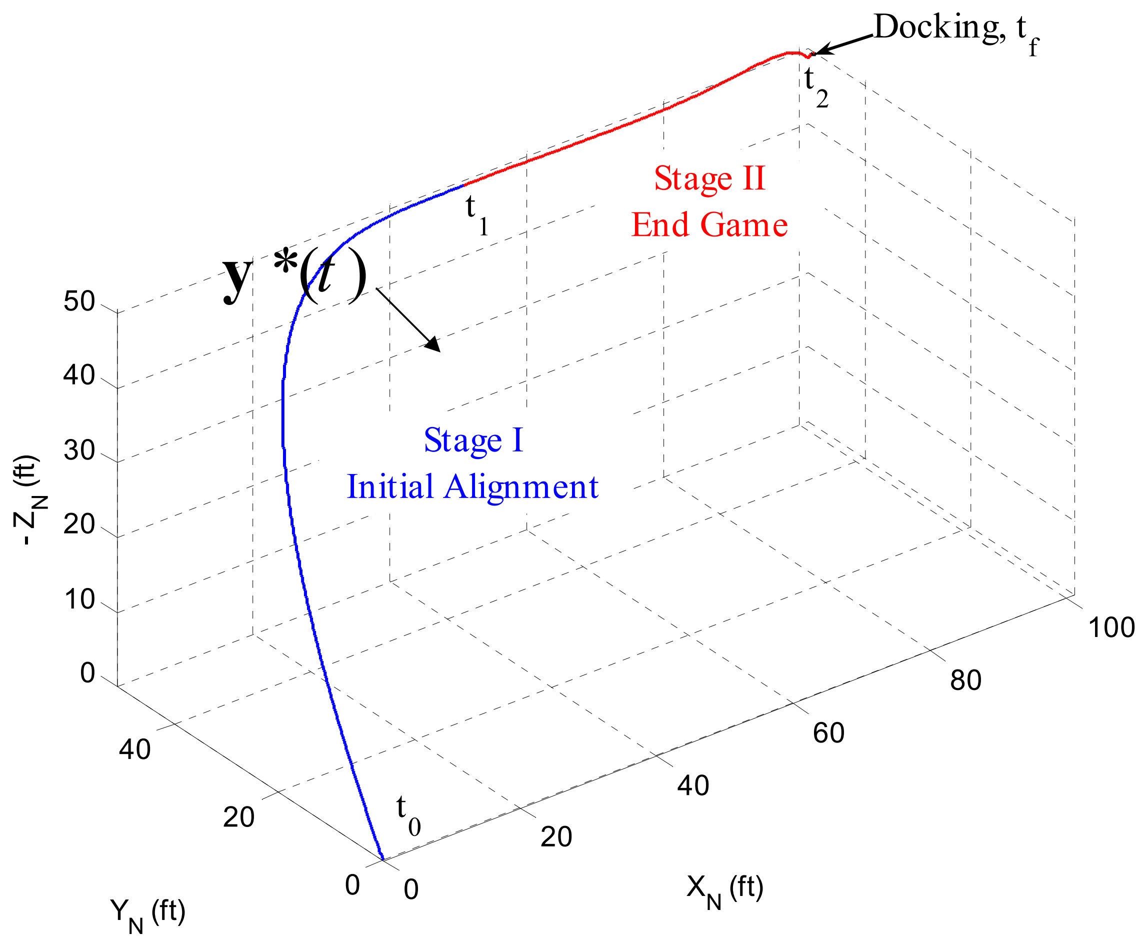
for the reference trajectory

4. State Feedback Controller

Full State Feedback Controller to track the Reference States

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

  $X, Y, Z \quad u, v, w \quad \phi, \theta, \psi \quad p, q, r$

  is available for feedback.

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

- 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: $\dot{x} = Ax(t) + Bu(t)$

  $y = Cx(t) + Du(t)$

  $x(t) = [X, Y, Z \quad u, v, w \quad \phi, \theta, \psi \quad p, q, r]$

  $y(t) = [X, Y, Z]$

- 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

  $\dot{x}_r = Ax_r(t) + Bu_r(t)$

  $y = Cx_r(t) + Du_r(t)$

Veritas Fugae

STAR VISION TECHNOLOGIES

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

  $$\mathrm{u} = (u_r + Kx_r) - Kx$$

- But u_r, x_r are unknown.
- The Reference Observer estimates u_r, x_r from y_r

Reference Observer

- Augmented Reference Dynamics

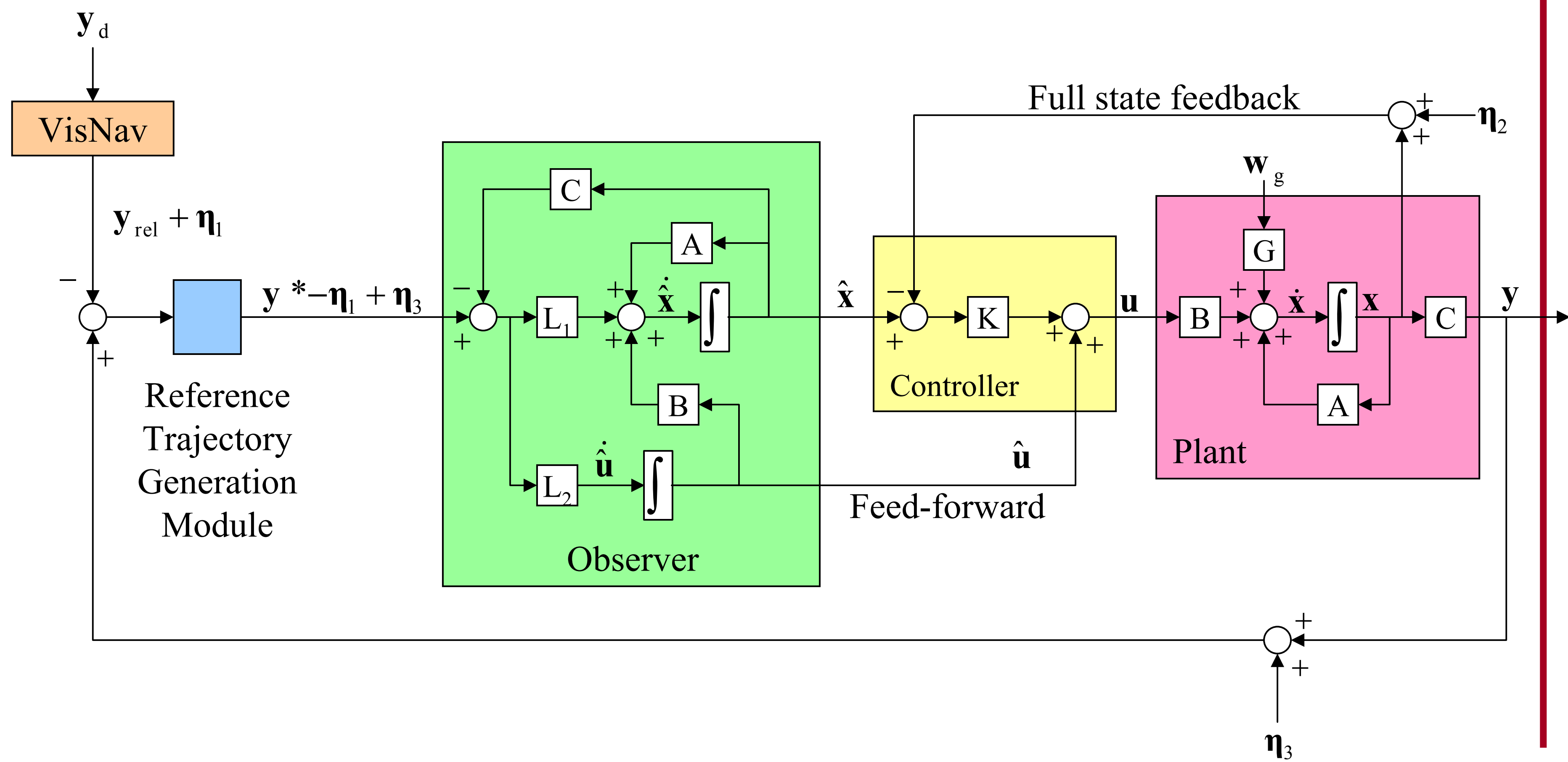
$$\begin{bmatrix} \dot{x}_r \\ \dot{u}_r \end{bmatrix} = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_r \\ u_r \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} \dot{u}_r$$

- Output Injection Observer

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

- By suitable pole placement the observer can be made stable

ROTC Block Diagram



Reference Observer Based Tracking Controller

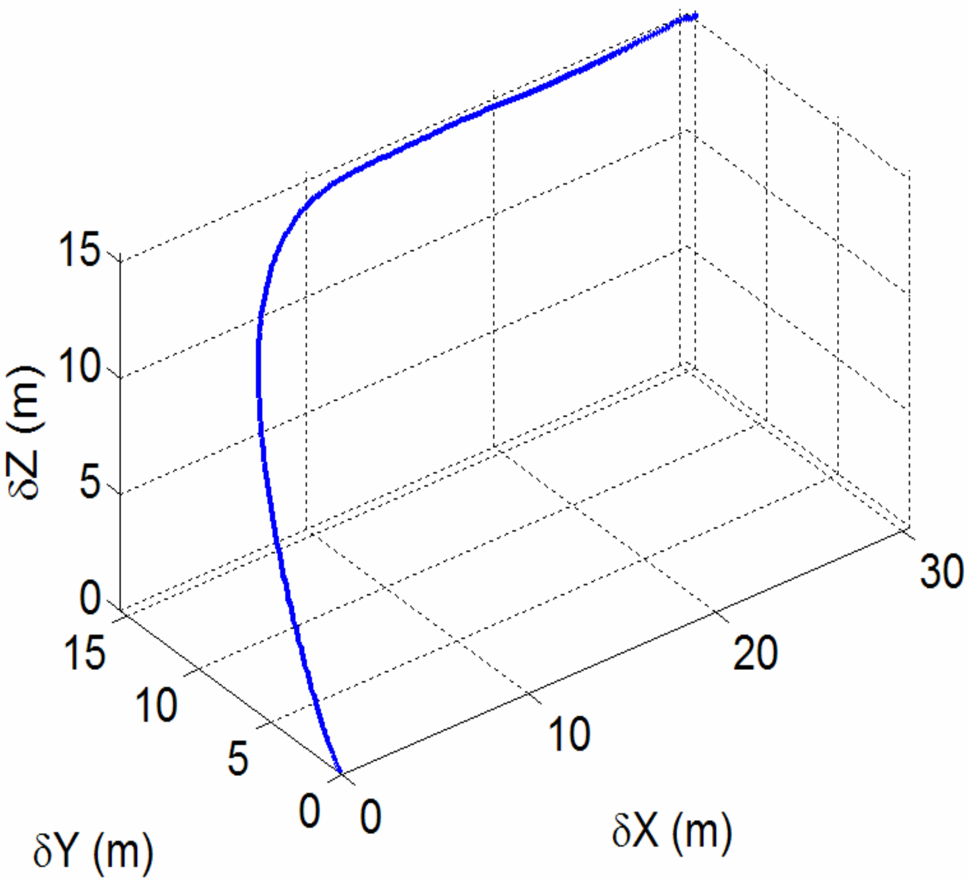
- Stability of the combined Observer Controller system using Separation Principle.
- Frequency Domain Stability Robustness and Performance Robustness analysis using Singular Value Plots.

Numerical Simulation

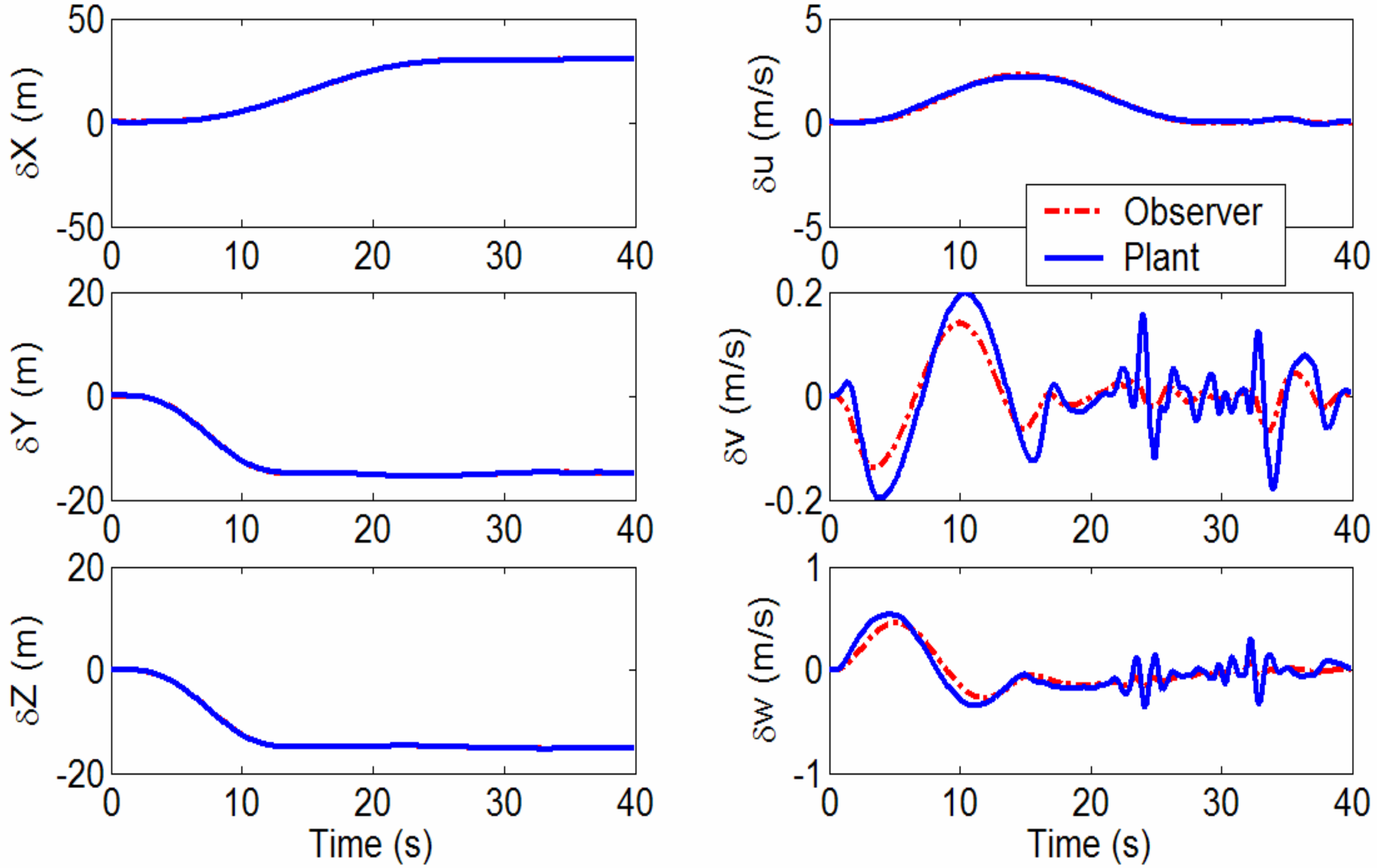
- linear model of an unmanned air vehicle UCAV6
- 60% scale AV-8B Harrier aircraft

- Flight condition : Altitude=6000 m, V0=128.7 m/s
- Dryden Light Turbulence (σ-gust=1)
- High Fidelity VisNav Simulation.
- Receiver Position relative to the Drogue
  - 30 m behind, 15 m below, 15m to the right

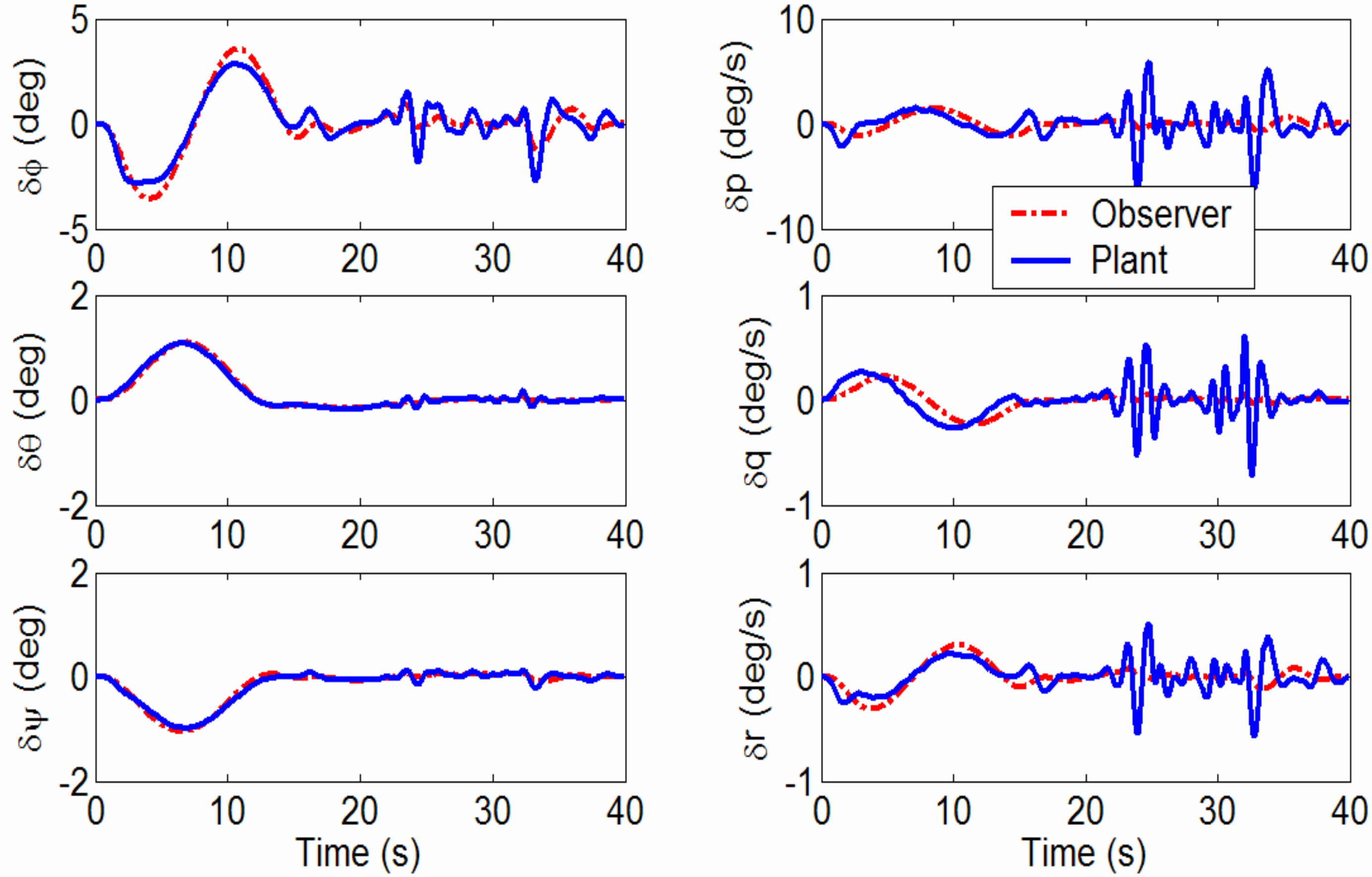
Relative Trajectory



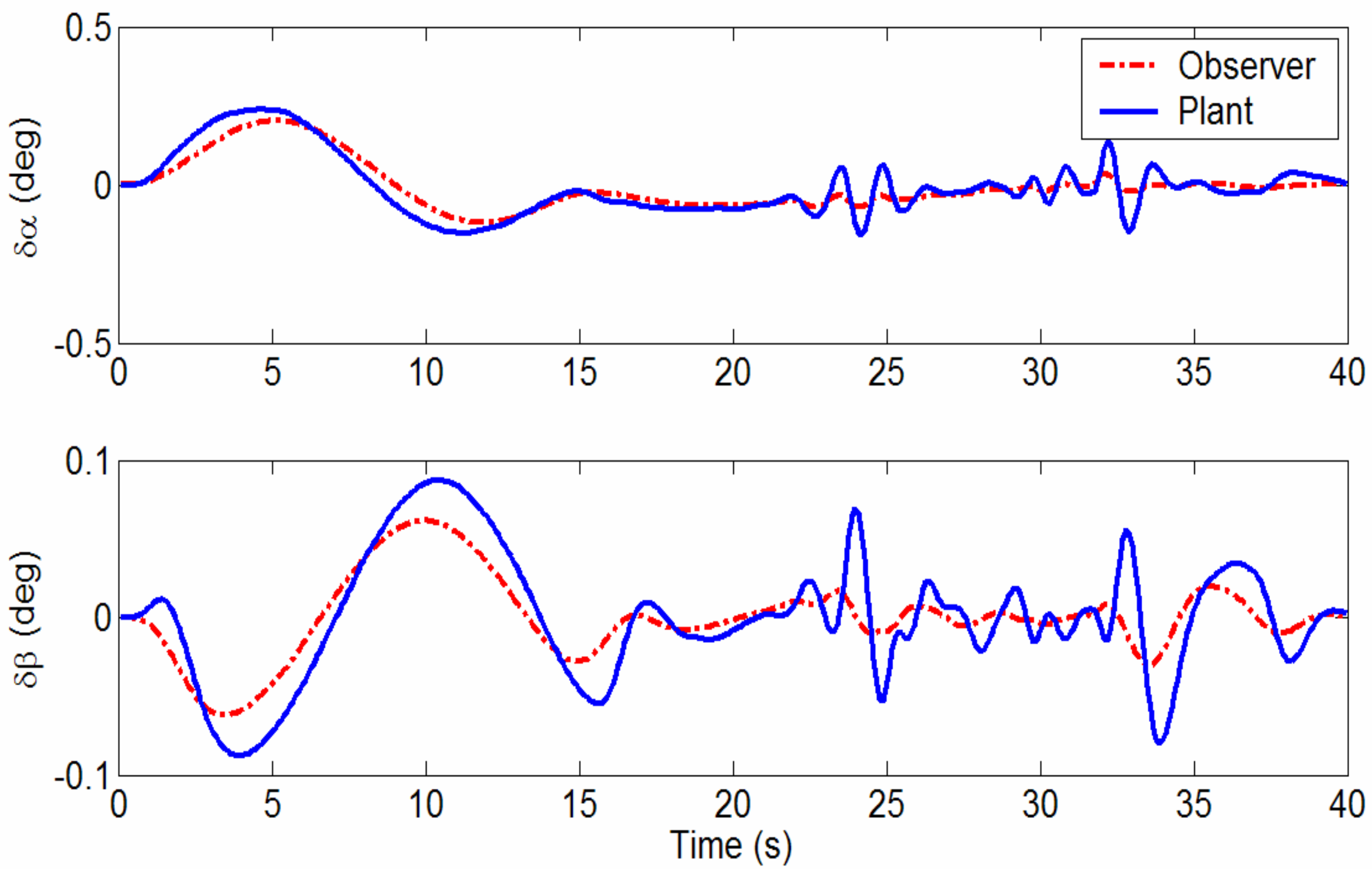
Linear States



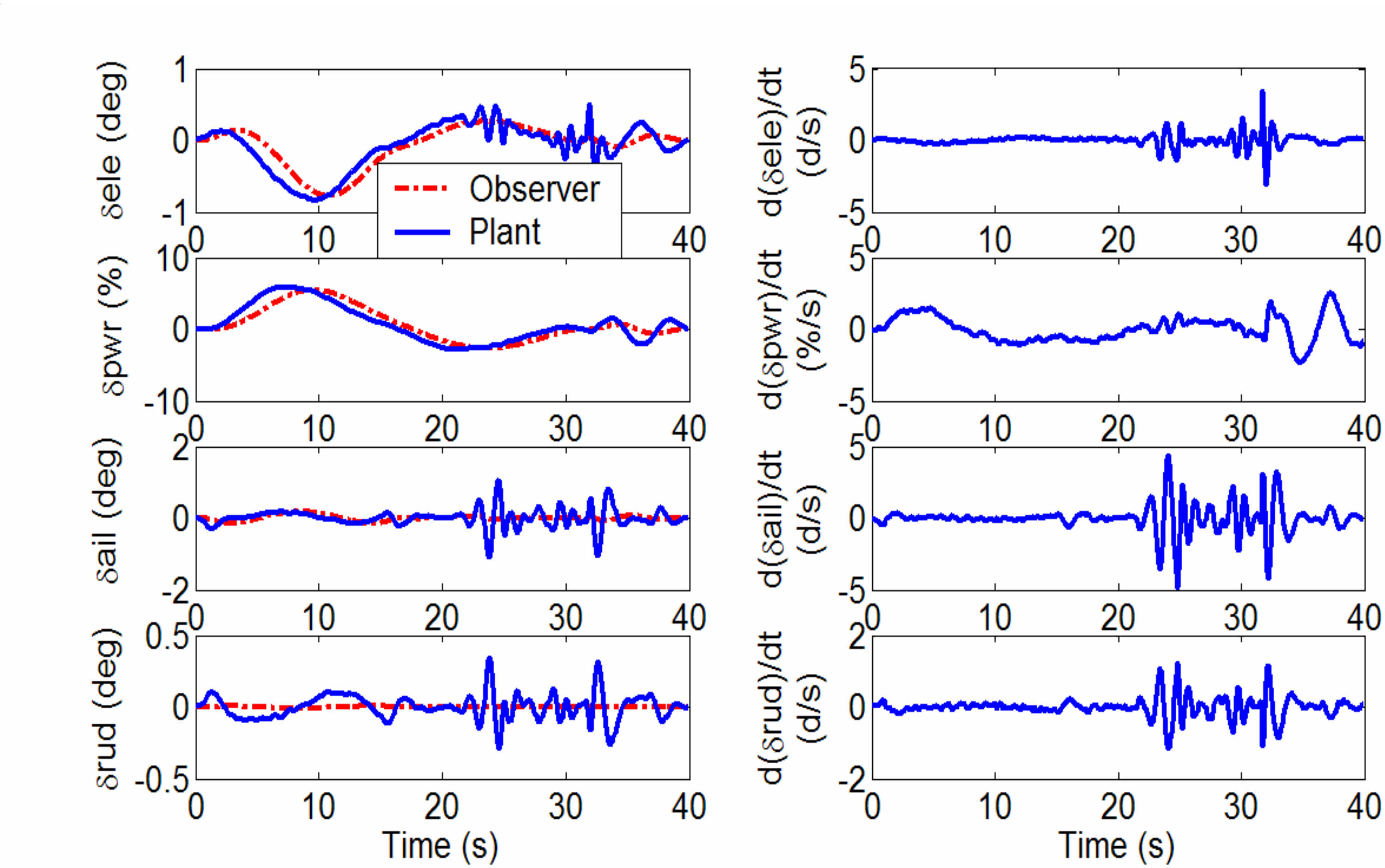
Angular States



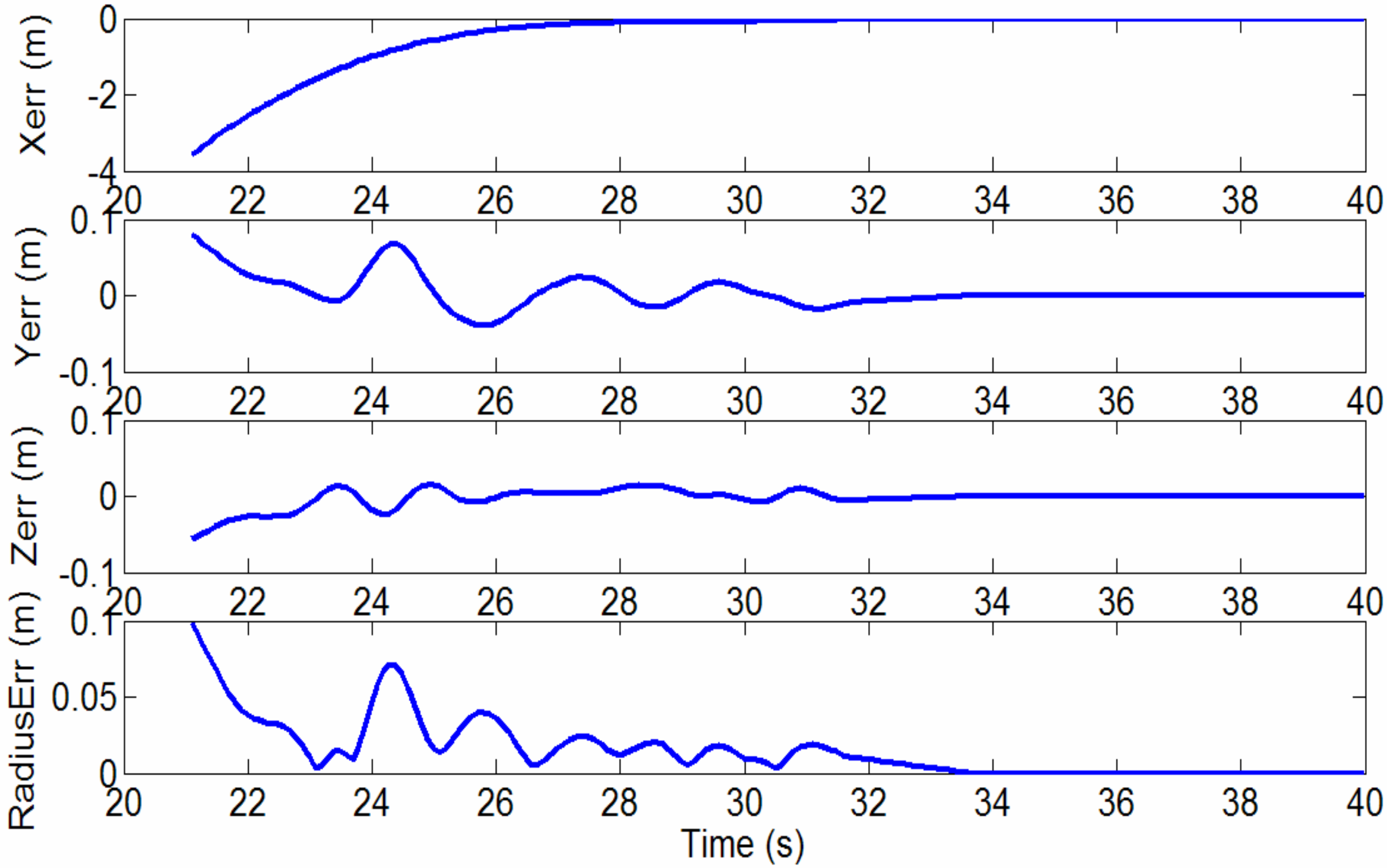
Aerodynamic Angles



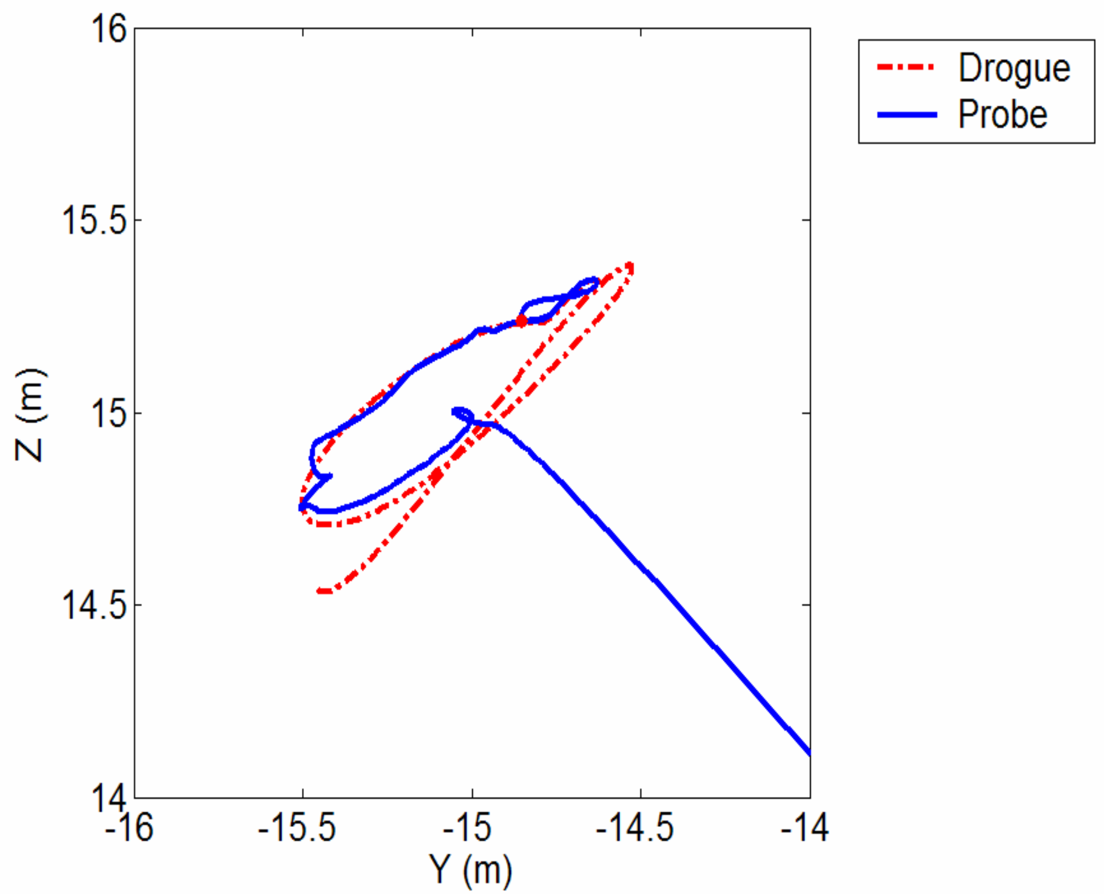
Control & Control Rates



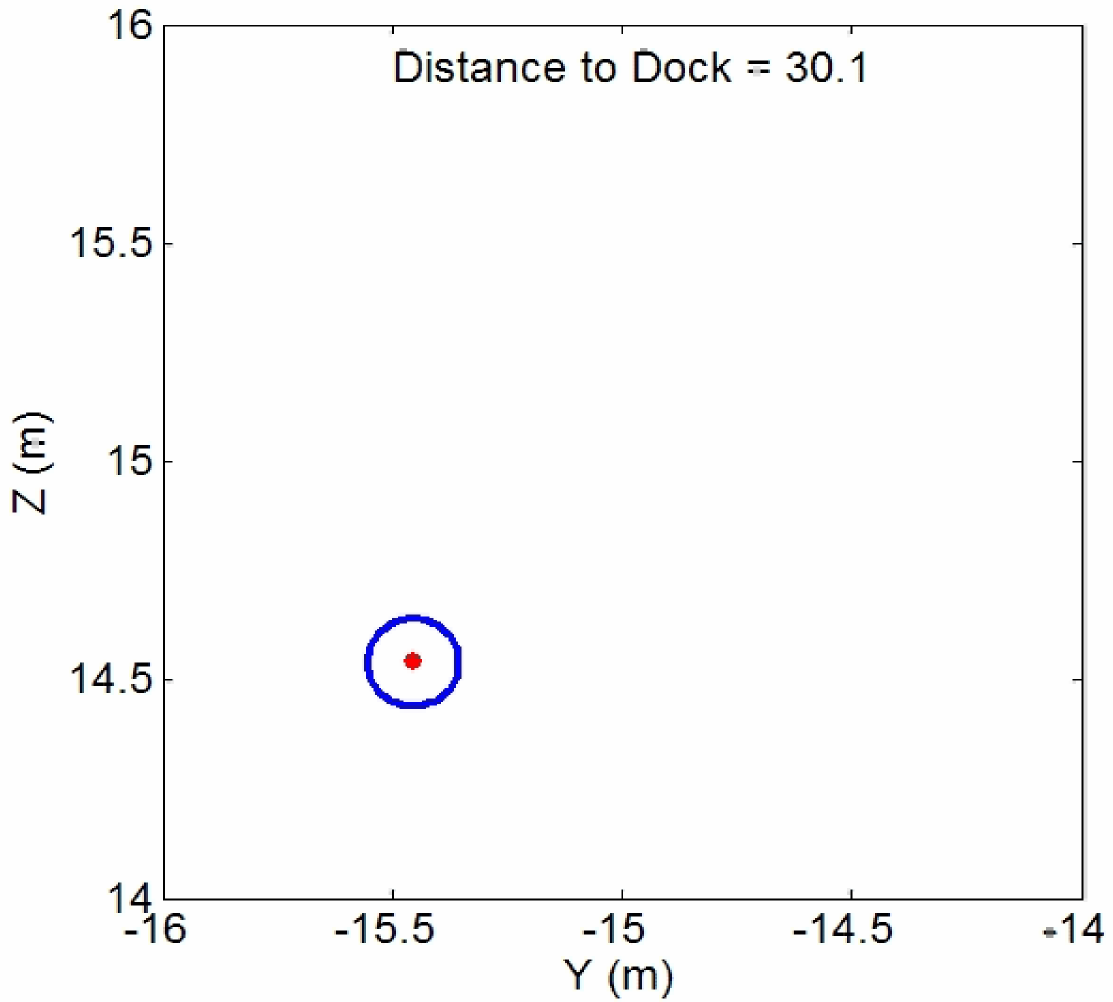
Docking End Game



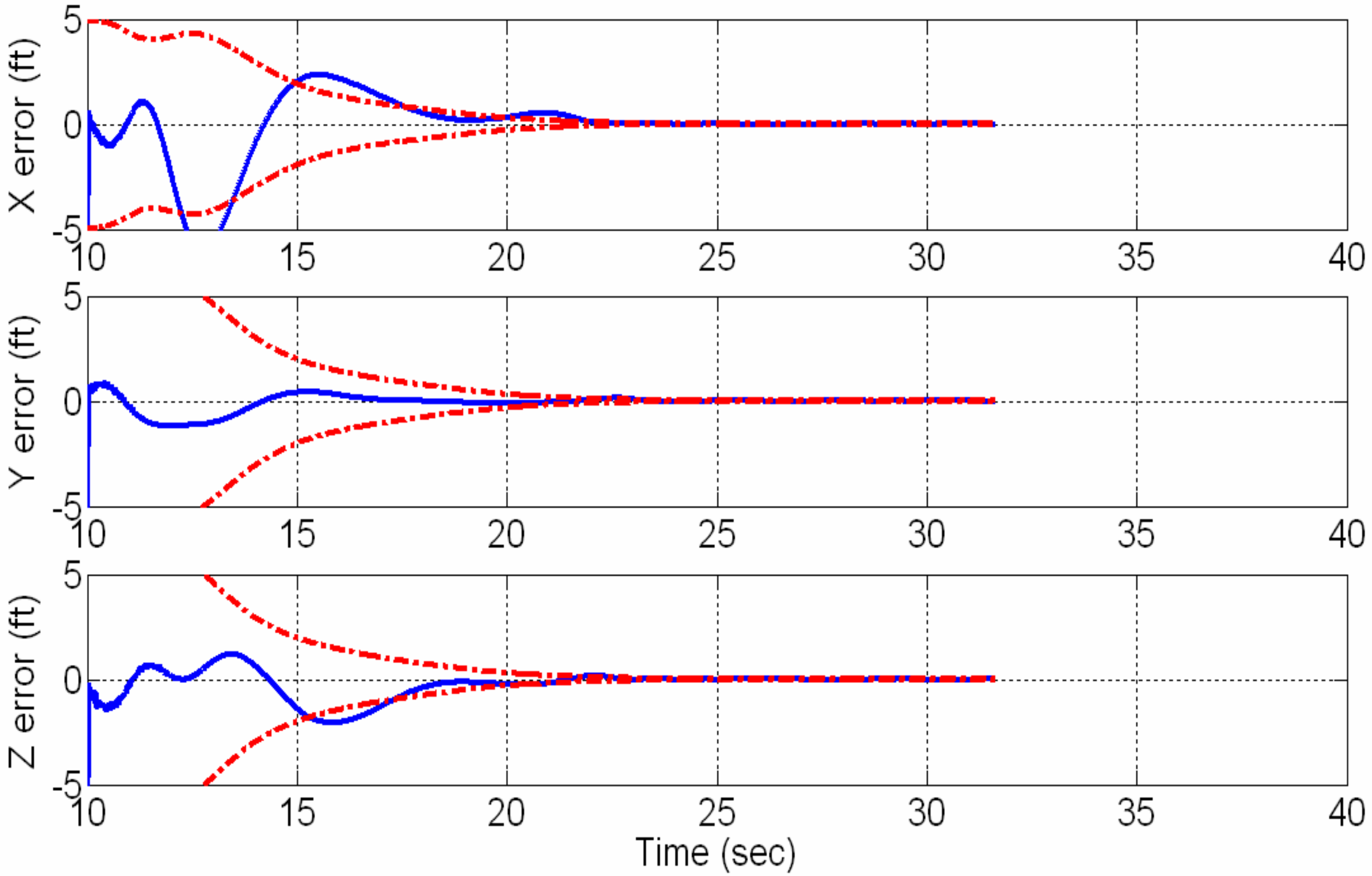
Projection of probe-drogue trajectories in Y-Z plane



Docking Animation

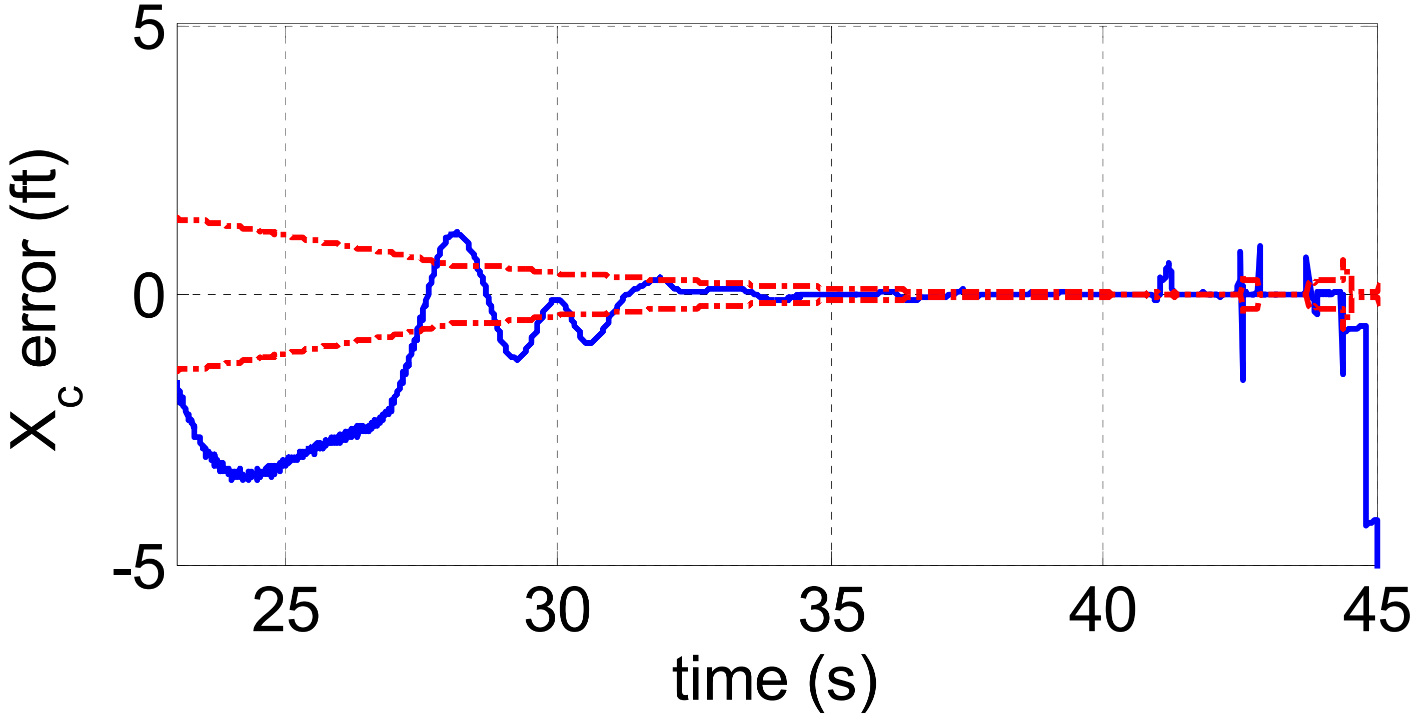


VisNav Estimate Error

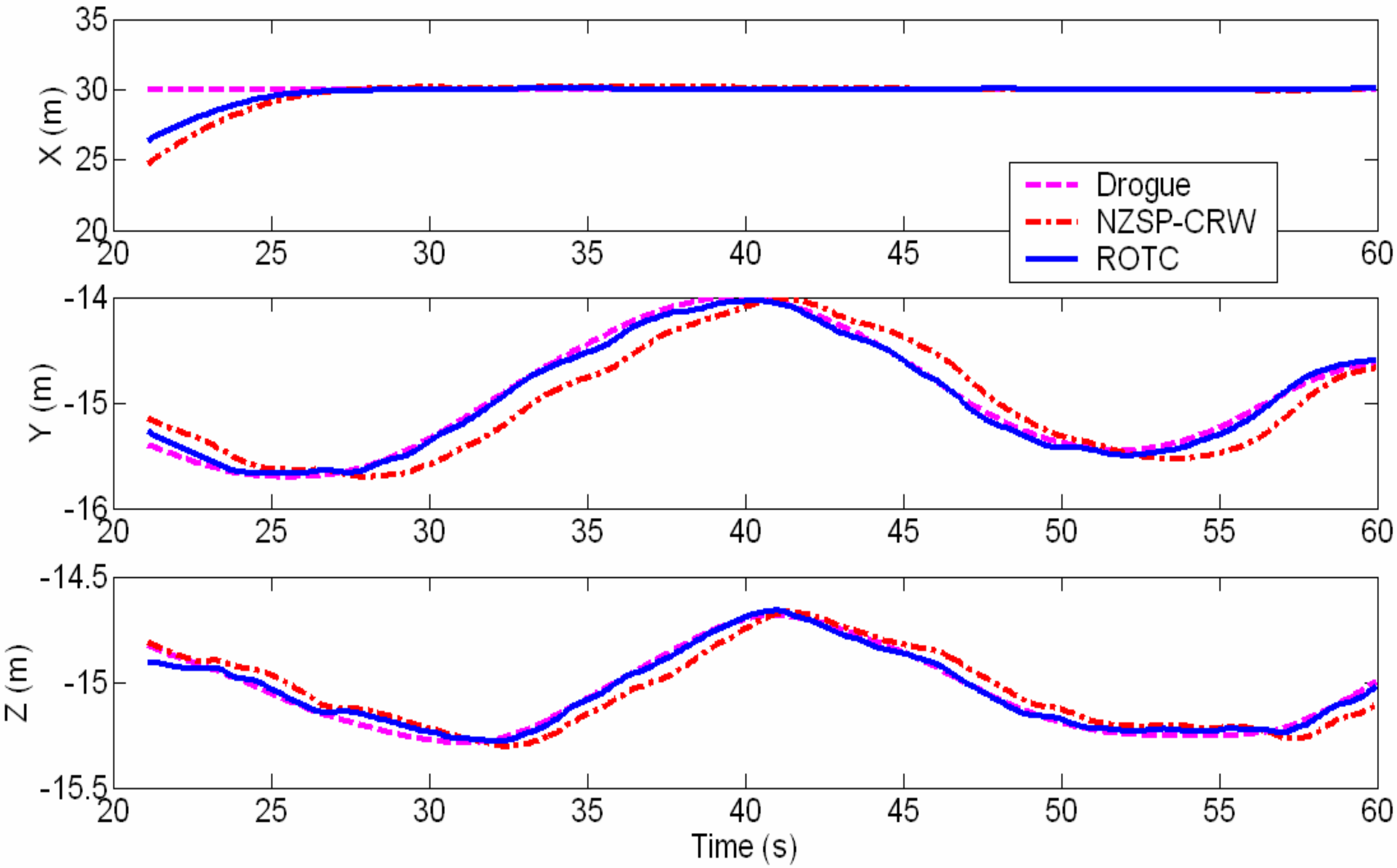


Beacon Drop Outs

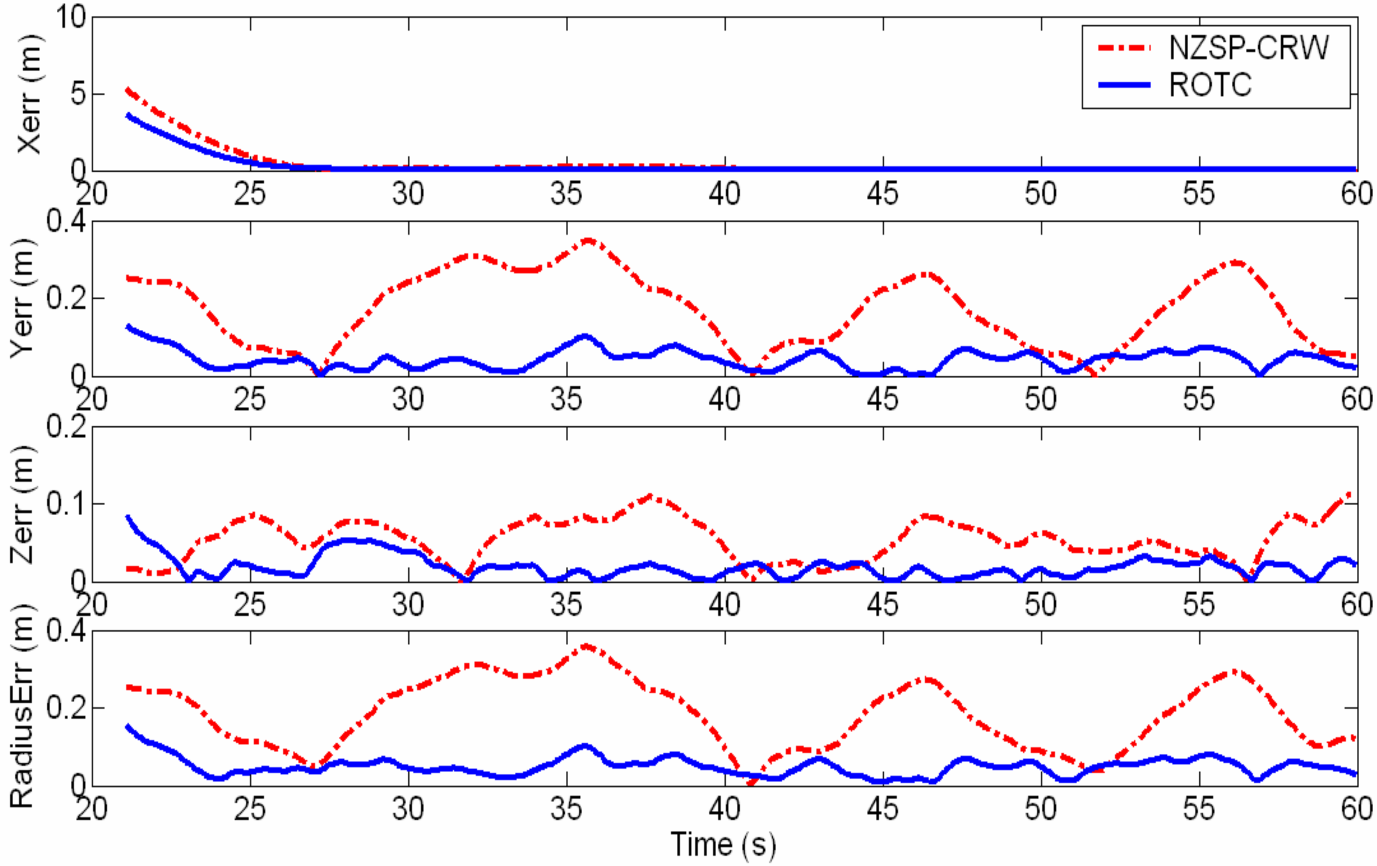
Discontinuities in VisNav solution in high turbulence due to beacon dropouts



Comparison : Tracking NZSP v/s ROTC



Comparison : Tracking Error
NZSP v/s ROTC



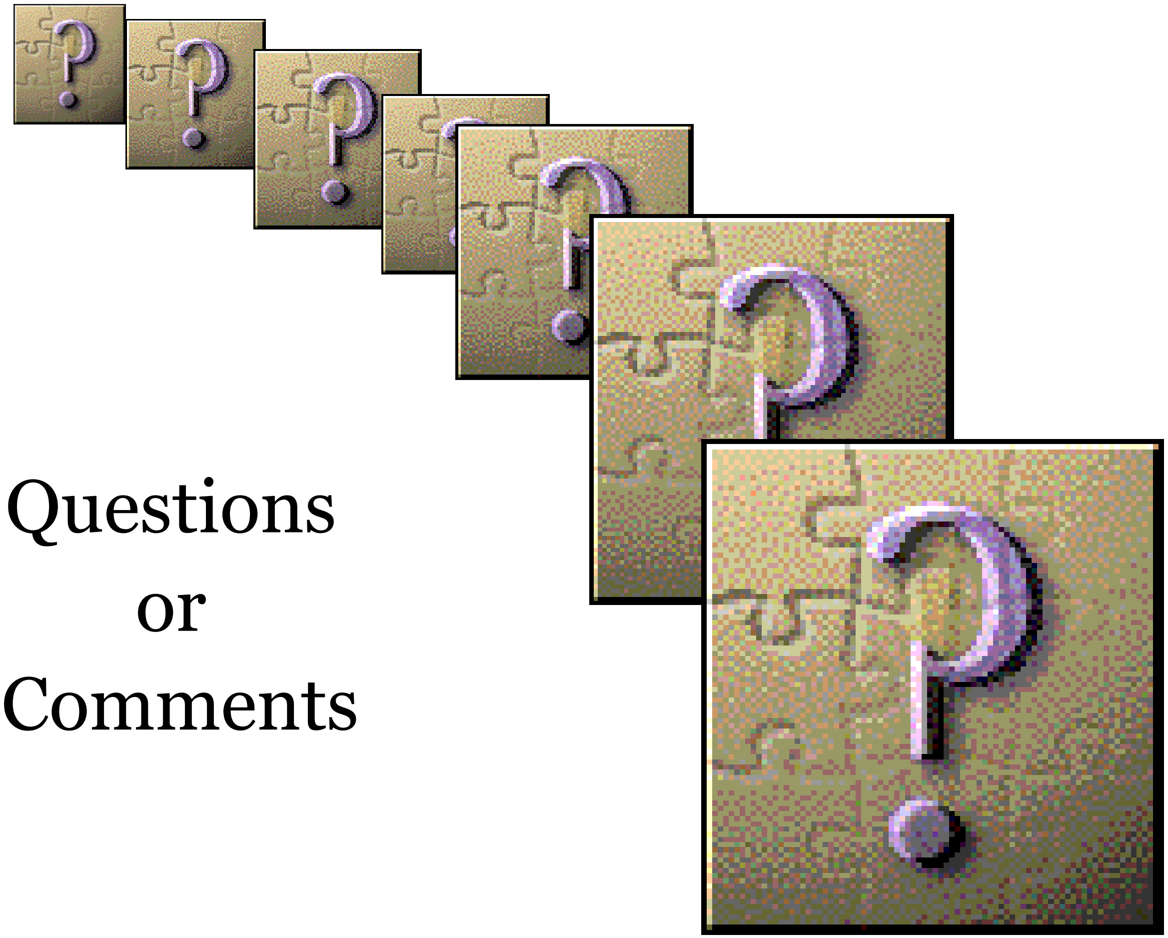
Conclusions

- 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