



# Active-Vision Control Systems for Aircraft

SAE Aerospace Control & Guidance Systems Committee #97

March 1-3, 2006

AFOSR, AFRL

Georgia Tech, MIT, UCLA, Virginia Tech

[controls.ae.gatech.edu/avcs](http://controls.ae.gatech.edu/avcs)



Active-Vision Control Systems  
for Complex Adversarial 3-D Environments



# Active-Vision Control Systems MURI

- Development of sound methods that utilize 2-D and 3-D imagery to
  - Enable aerial vehicles to autonomously detect and prosecute targets in uncertain complex 3-D adversarial environments
  - Include capabilities and approaches inspired by those found in nature
  - Do these things without relying upon highly accurate 3-D models of the environment
- New strategies of
  - Target recognition/tracking
  - Obstacle/hazard avoidance
  - Navigation, guidance, and control



# The Team

- Anthony J. Calise, Georgia Tech
- Eric N. Johnson, Georgia Tech
- Allen Tannenbaum, Georgia Tech
- Patricio Vela, Georgia Tech
- Anthony J. Yezzi, Jr., Georgia Tech
- George Barbastathis, MIT
- Naira Hovakimyan, Virginia Tech
- Stefano Soatto, UCLA

*...and many others*



# Focus Areas

- Air/ground target location in congested environment, including the notion of tracking/pursuing things that move, that are occasionally occluded
  - Pursuit/evasion, “See and avoid”
  - Formation or coordinated flight
- UAV/munition operating in an environment including obstacle/terrain/hazard avoidance
- The use of visual information as replacement for traditional flight control sensors



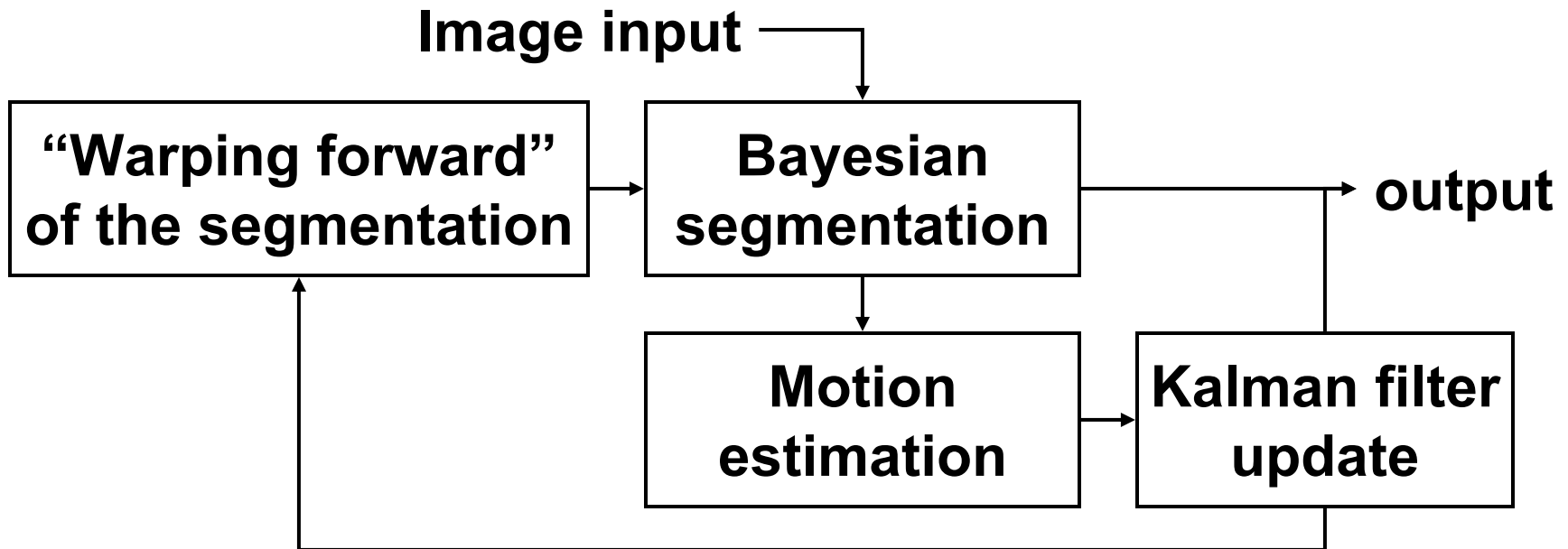
# Tracking with Region-Based Deformation

- Simultaneous segmentation, registration flow
- Registration using energy minimization with gradient descent
- Handle occlusions



# Dynamic Bayesian Segmentation

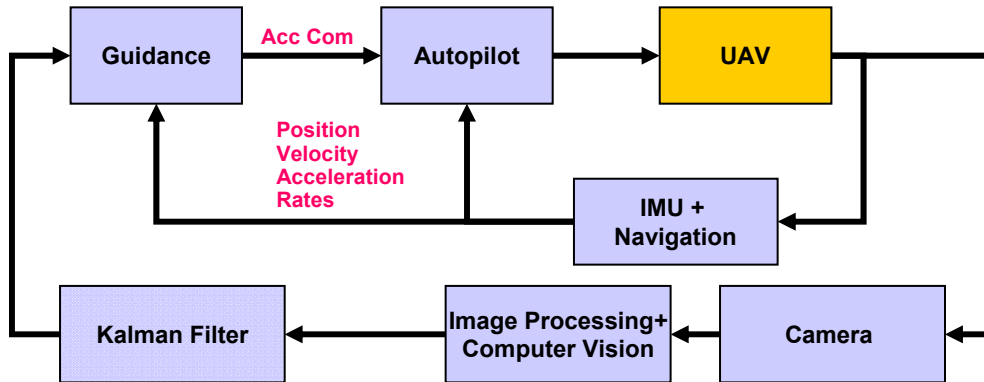
- Combines Kalman filtering, dynamic Bayesian estimation, and uses dynamically adapted priors
- Takes advantage of mutually beneficial interaction of components



# Tracking in Clutter

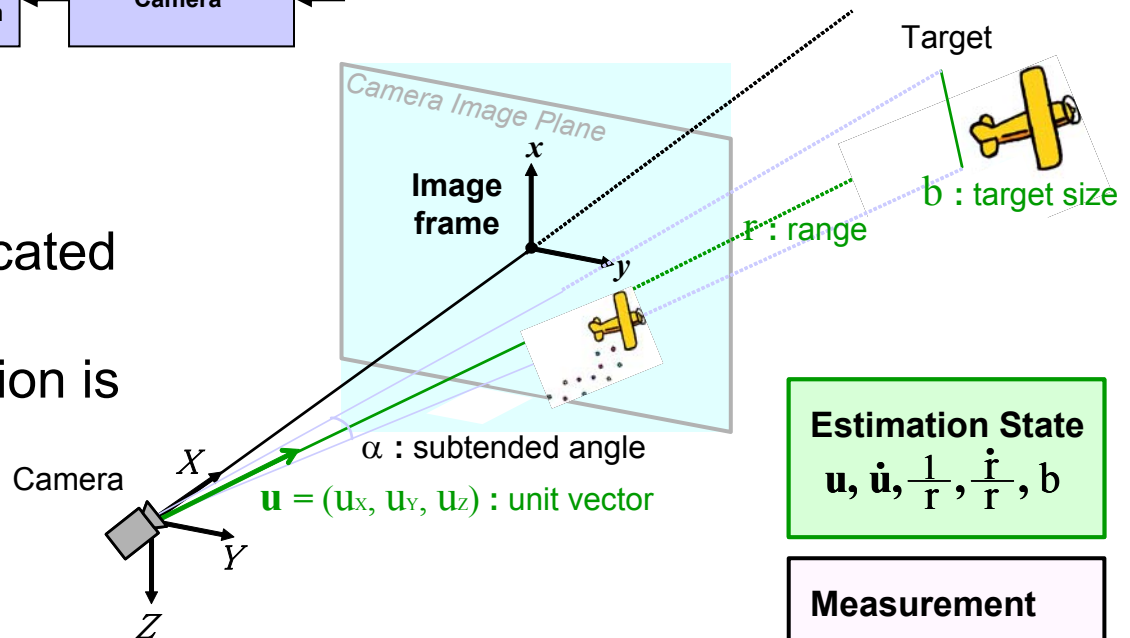


# Air-to-Air Vision-Based Tracking



Estimated:  
LOS Rate  
Range  
Object Size

No information is communicated between aircraft, and only passive 2-D vision information is available to maintain formation



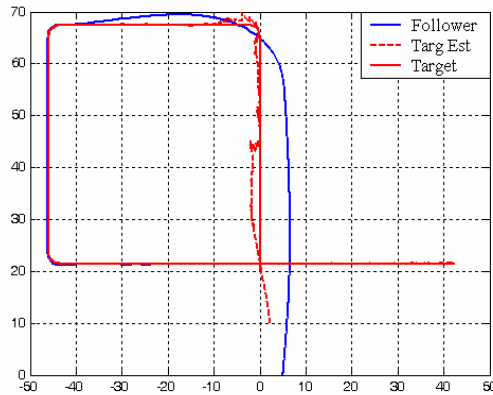
**Estimation State**  
 $\mathbf{u}, \dot{\mathbf{u}}, \frac{1}{r}, \dot{\frac{1}{r}}, b$

**Measurement**  
 $\mathbf{u}, \alpha$

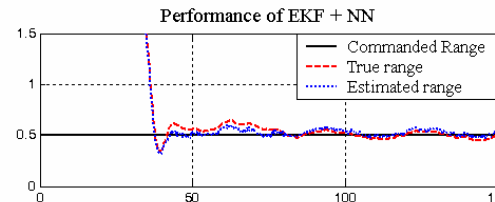
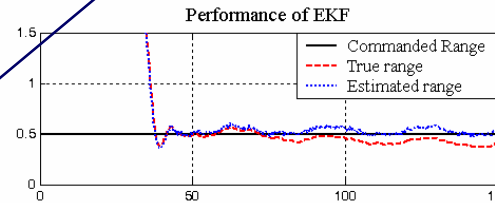
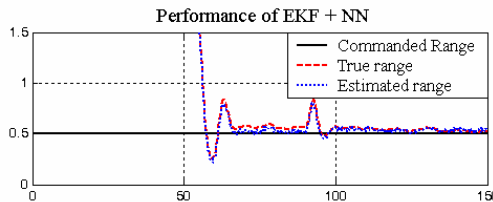
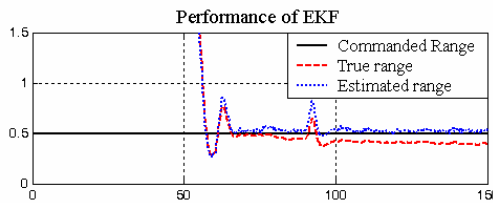
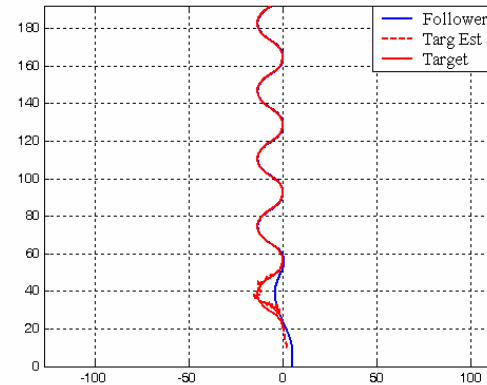


# Estimating Dynamics of Maneuvering Target

## Box Target Maneuver



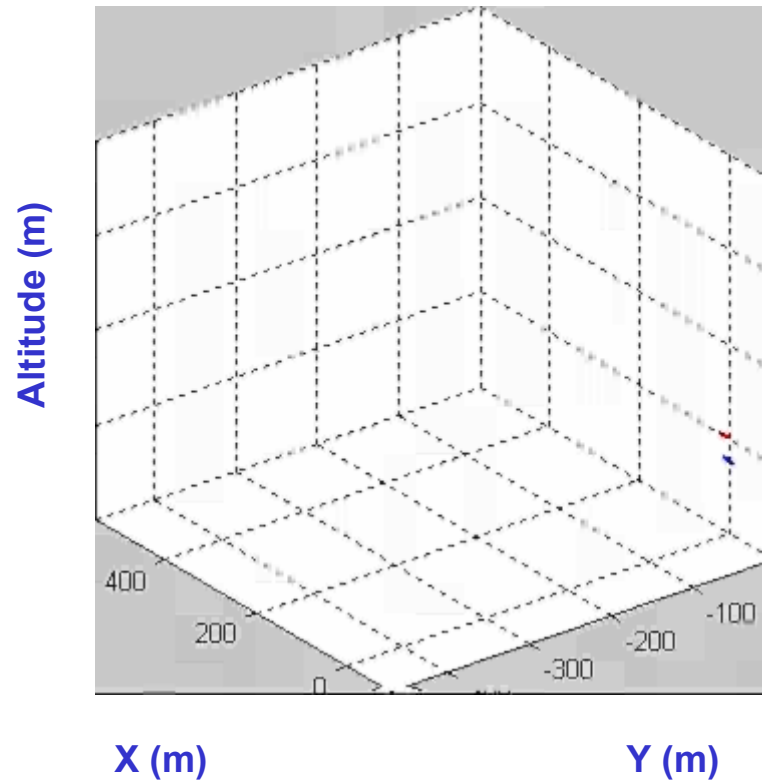
## Sinusoidal Target Maneuver



Neural Network corrects estimation *bias*



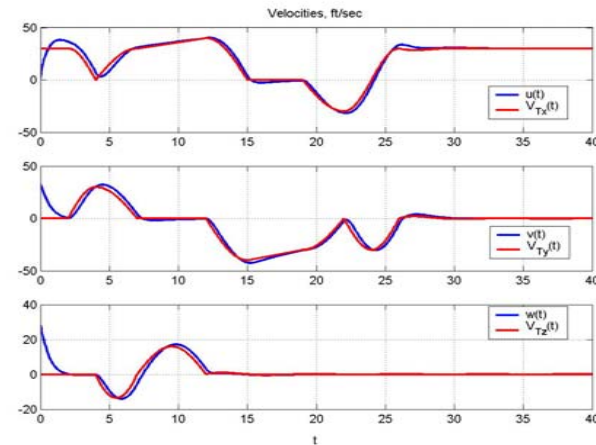
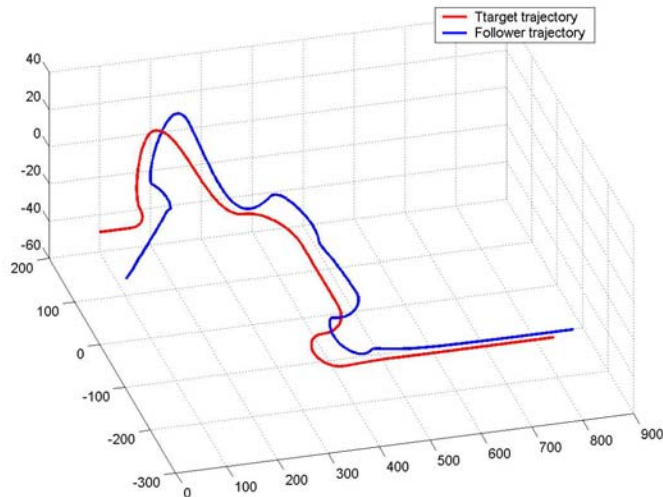
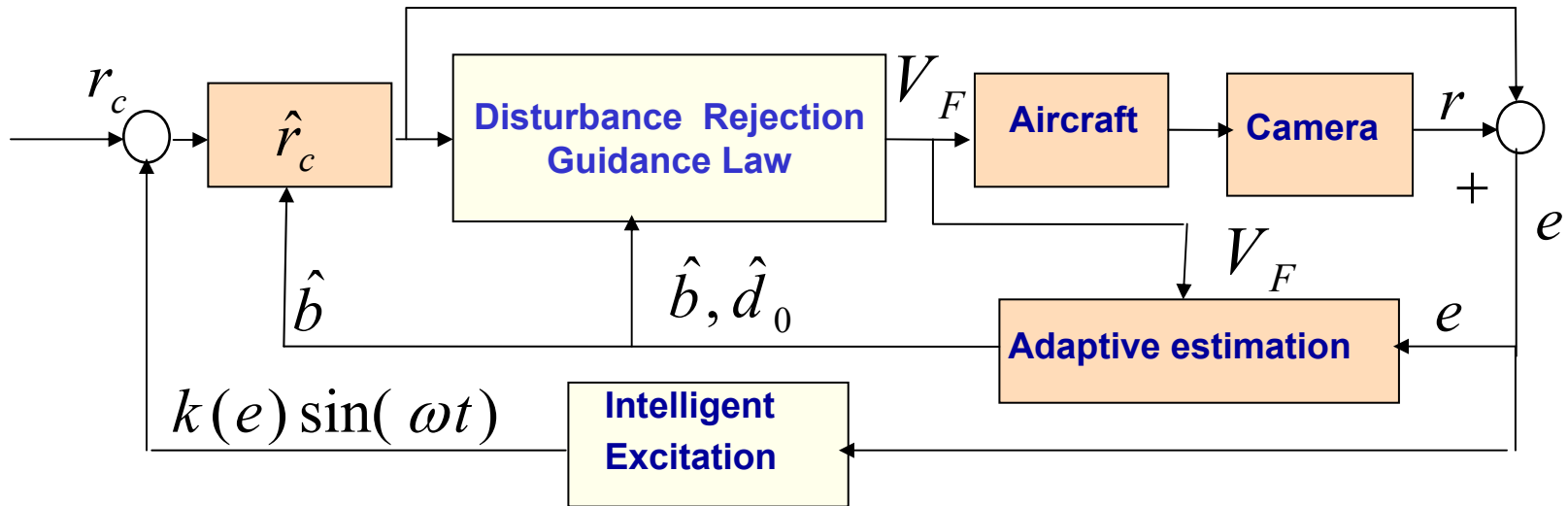
# Formation Flight Movie (adaptation on)



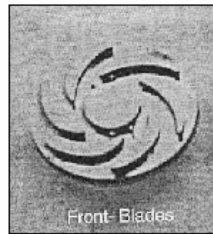
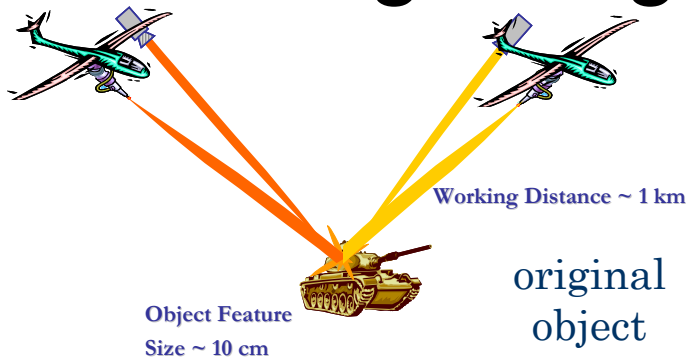
- Leader
- Follower



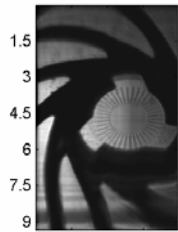
# Intelligent Excitation Improves Estimator Performance



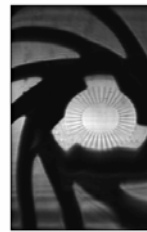
# Long Range Surface Profilometry



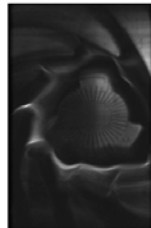
Object Distance = 46 cm  
Object depth features  $\approx 225 \mu\text{m}$



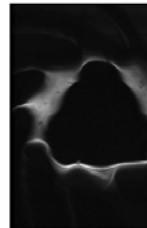
$z=0 \mu\text{m}$



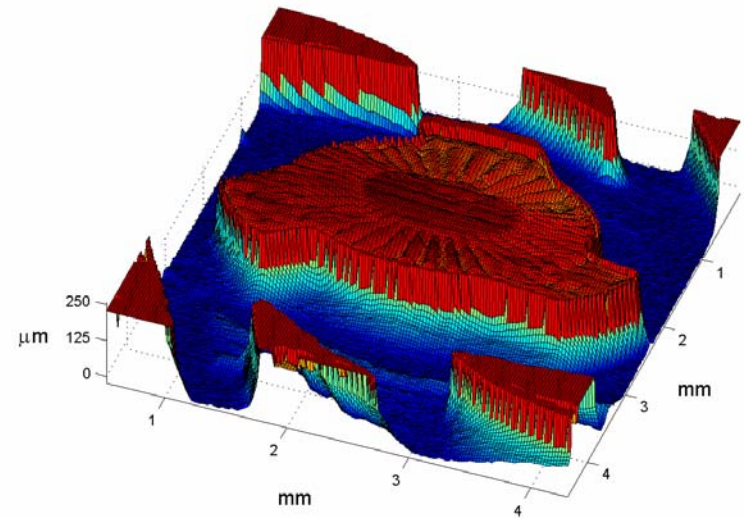
$z=50 \mu\text{m}$



$z=200 \mu\text{m}$



$z=250 \mu\text{m}$



Thanks to Prof. Chee Wei Wong for the micro-turbine



Active-Vision Control Systems  
for Complex Adversarial 3-D Environments

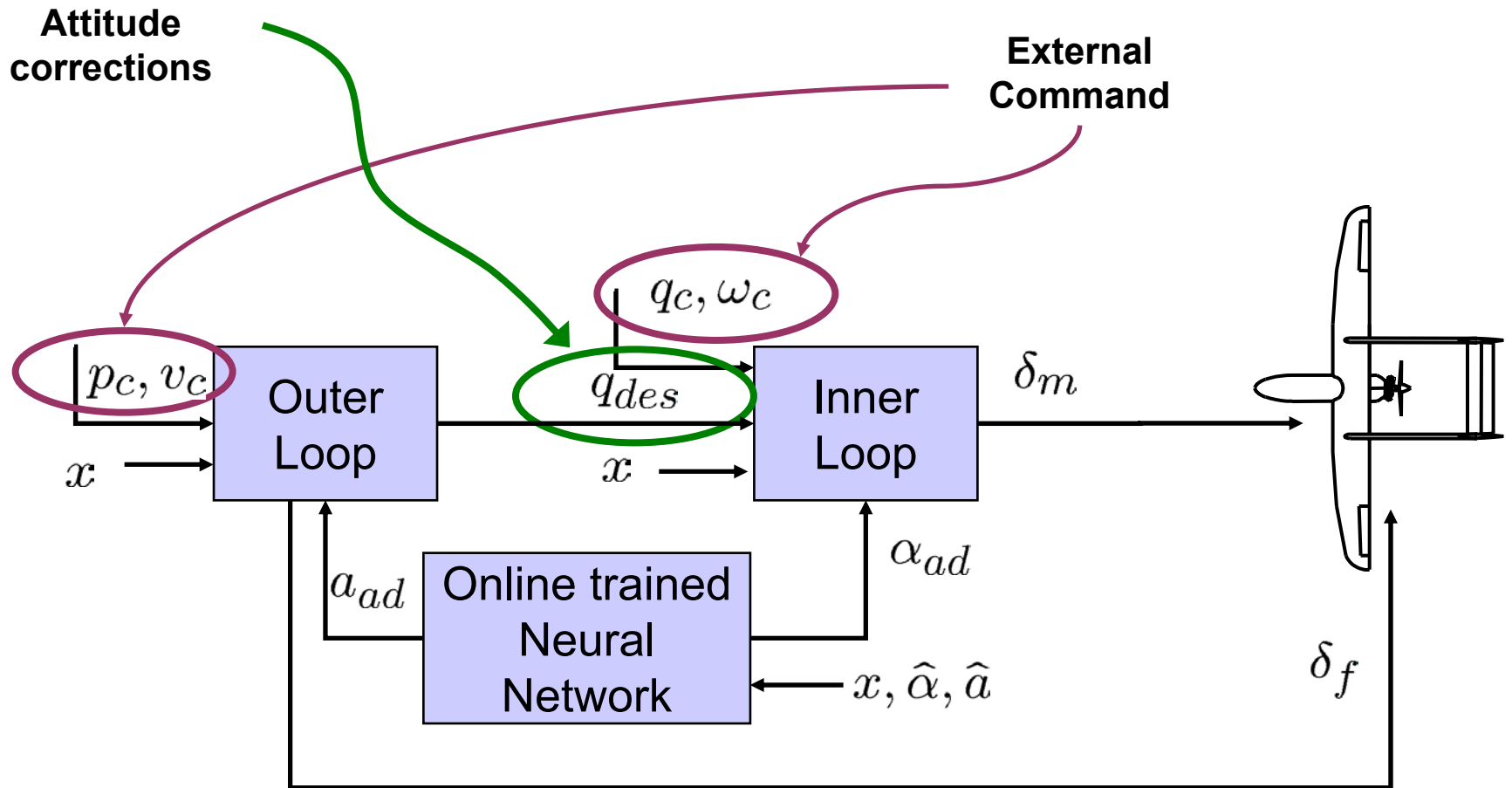


# Laboratory/Flight Testing Tools

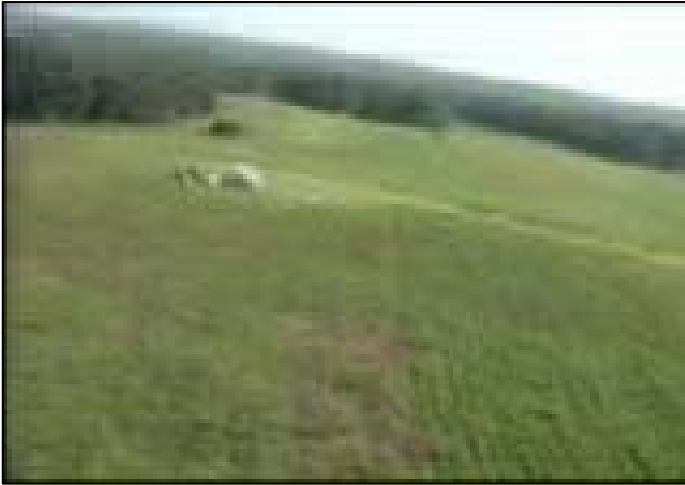
- Simulation process
  - Algorithms tested in software, real-time hardware, and then flight tested
- Flight tests on proven platforms, instrumented to provide precise “truth” data to maximize research productivity
  - GTMax research UAV
  - GTEdge agile maneuvering test aircraft
  - New larger airplane
  - Other Aircraft



# Neural Network Adaptive Flight Control



# Georgia Tech's Yamaha RMAX: GTMax



More than 280 research test flights since March 2002



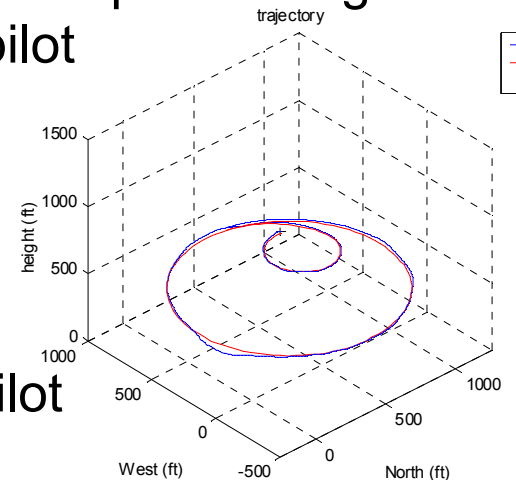
# Agile Maneuvering Test Aircraft: GTEdge

- 33% scale Edge 540T



Transition to zero speed using adaptive autopilot

95 knot using autopilot



# Autopilot Tests on GTSpy

- MASS Helispy
- Custom Small autopilot
- Weight - 5.5 lbs
- Duct Diameter - 11 in



# AVCS Test Aircraft 4.8m Fixed-wing



Wing Span: 4.8m  
Aircraft Length: 3.3m  
Large payload comp.  
Removable nose-cone



First flight Feb 2006  
Second aircraft  
partially complete

# AVCS Test Aircraft 4.8m Fixed-wing



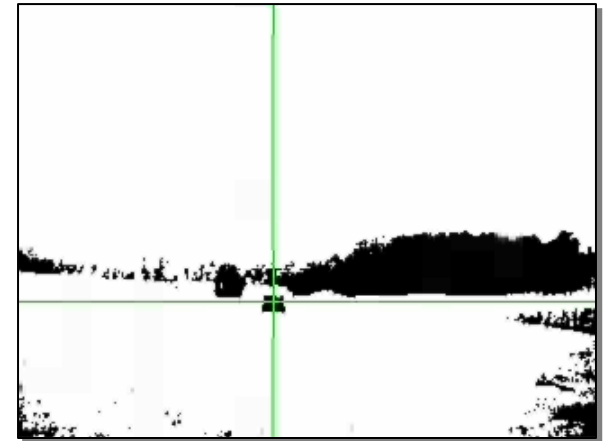
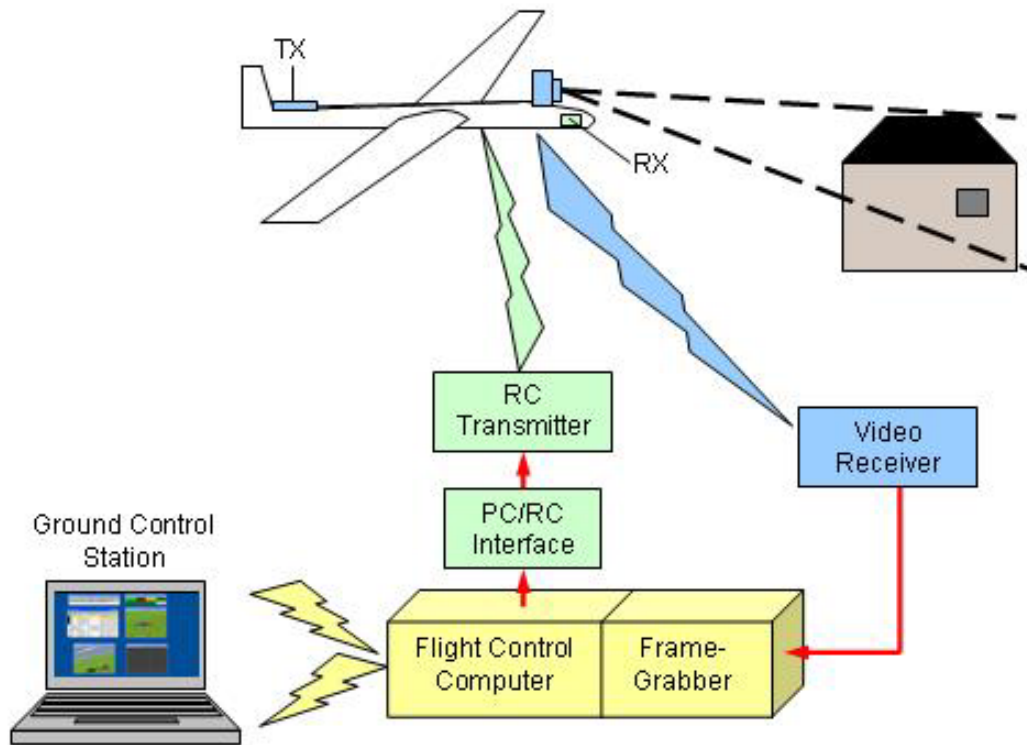
First Flight February 17, 2006



**Active-Vision Control Systems**  
for Complex Adversarial 3-D Environments



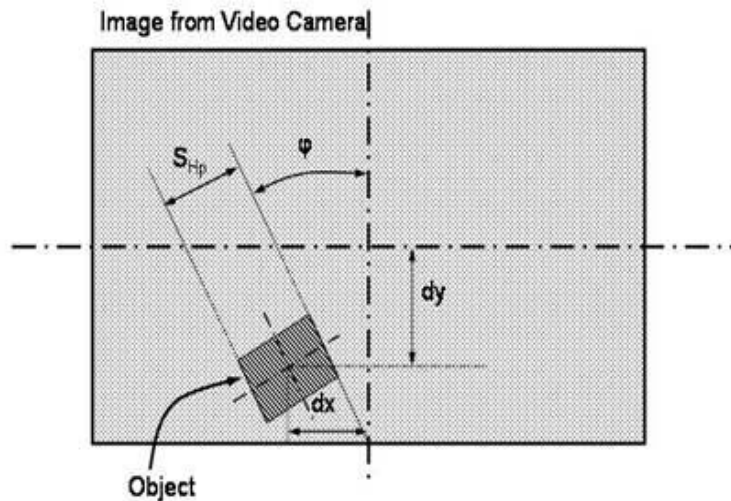
# Vision-Only Guidance, Navigation, and Control



# The Measurements

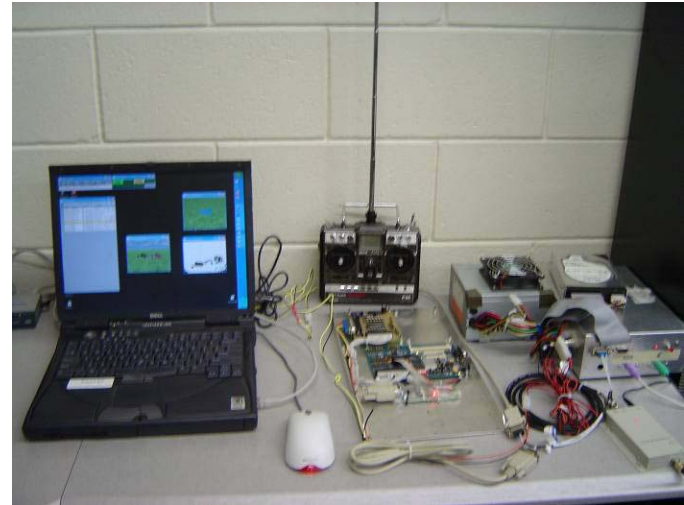
Available measurements from a candidate window

- Size
- Rotation
- Horizontal pos. in camera
- Vertical pos. in camera

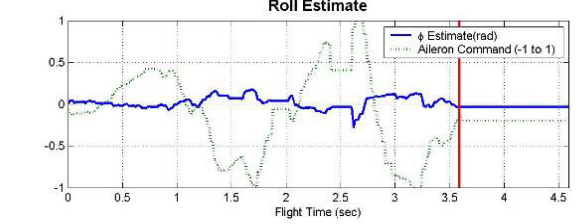
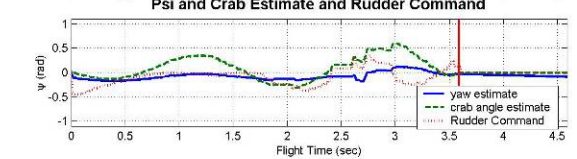
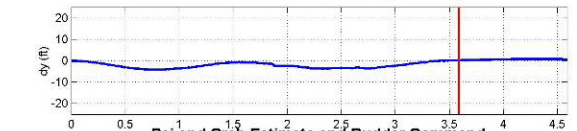
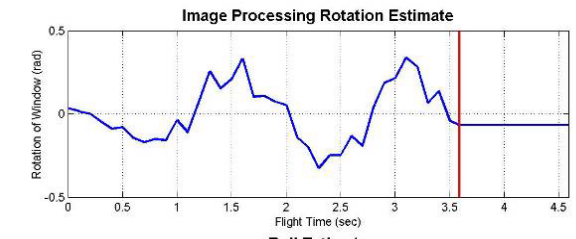
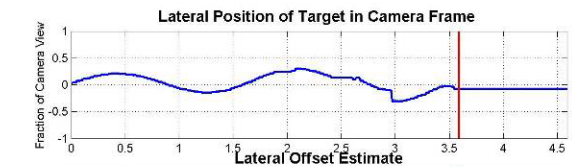
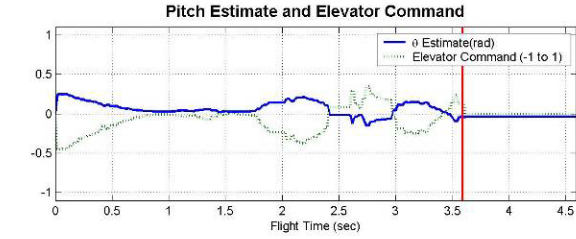
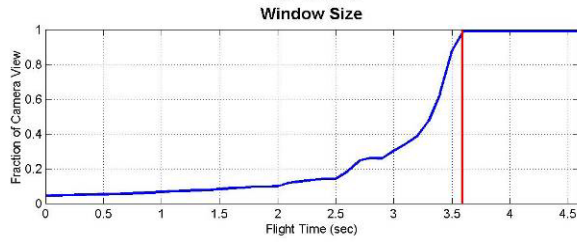
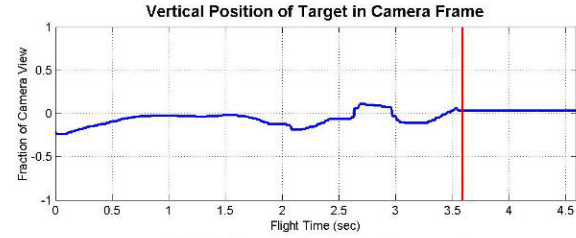
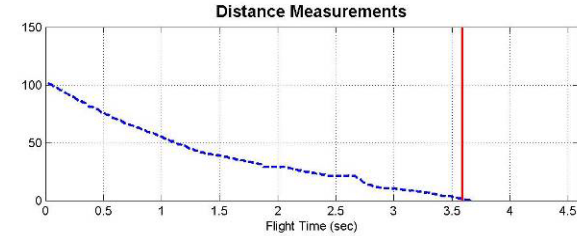


# Hardware in the Loop for Vision Systems

- Actual glider with video camera and transmitter looking at the simulated camera output
- Playback of recorded video



# Flight Test Results



# Vision-Based Approach and Landing

- Autonomous landing at a landing zone, when the exact location, orientation, and elevation of the landing zone is unknown



# Vision-Based Approach and Landing

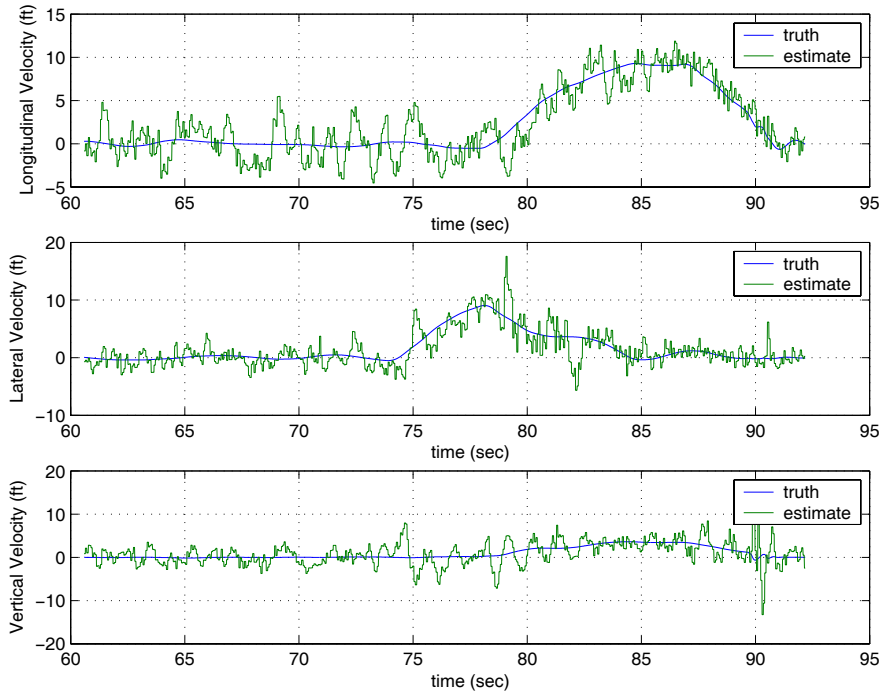
## Approach:

- Landing “beacons” (optical targets) are placed at known relative position and elevation
- Vehicle flies an approach towards the beacons
- Vehicle relative position and attitude is estimated, with sufficient accuracy for touchdown
  - Image processor determines beacon locations in image
  - State of vehicle with respect to the beacons estimated

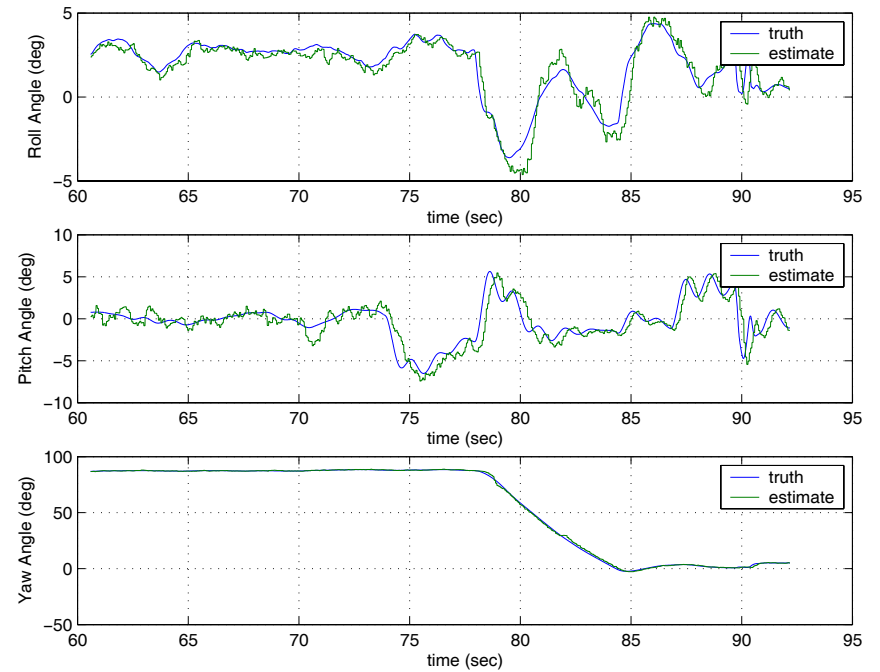


# Simulation Results

## Position Estimate

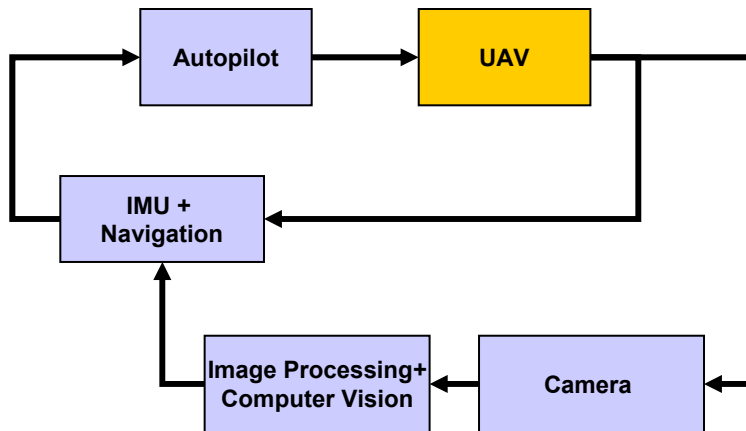


## Attitude Estimate



# Vision-Aided Inertial Navigation

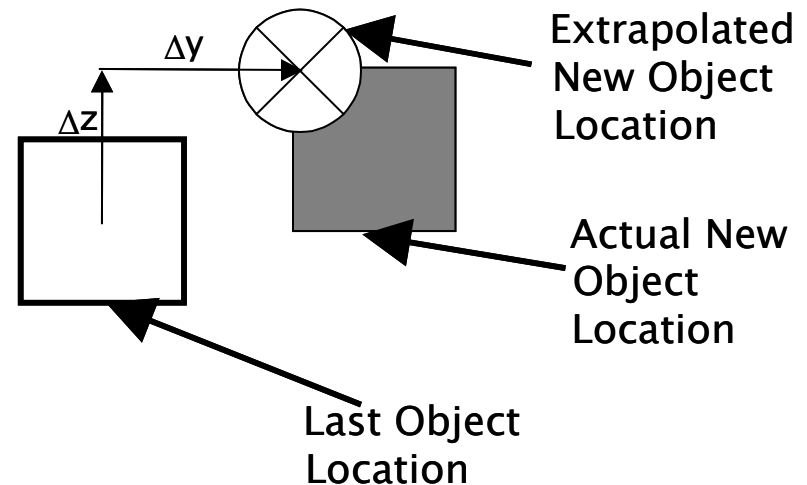
- Inertial Navigation System (INS) aided by 2-D vision sensor looking at a selected image target



# Vision-Aided Inertial Navigation

- Approach

- Use assumed range (altitude), position in image, size of object in image, and aircraft state to estimate object position, size, and orientation
- Use subsequent measurement of object image position and size in image to update INS
- Utilize inertial data to maintain lock on target
- Operate without GPS (or any other position aiding)



# Vision-Aided INS Trials



Using Existing Features  
(in this case a window)



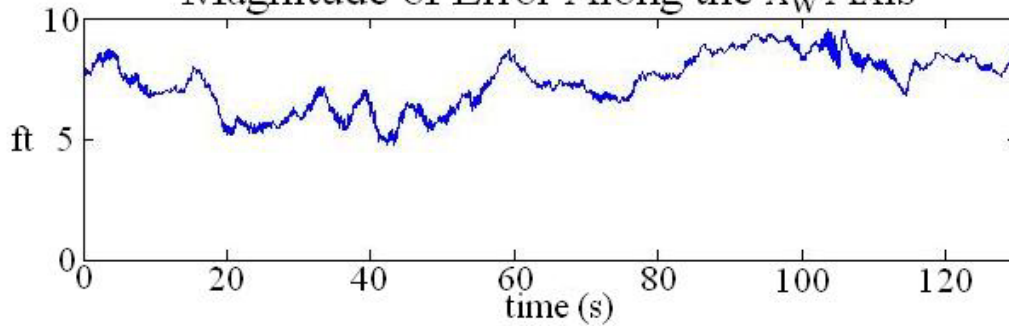
Special Purpose Optical Target

# Close Approach to Building, no GPS

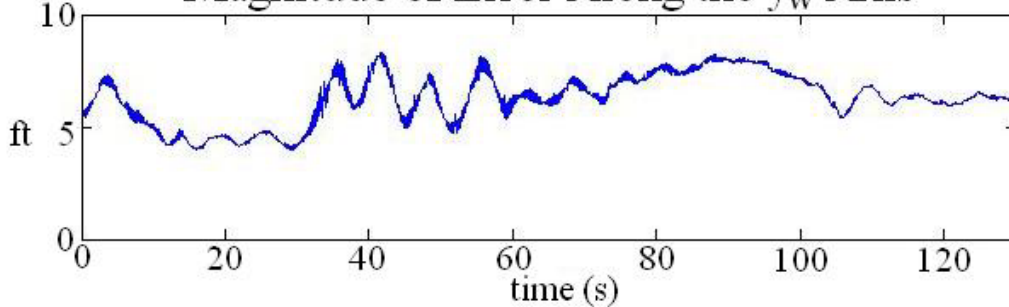


# Flight Test Results: Error Plots

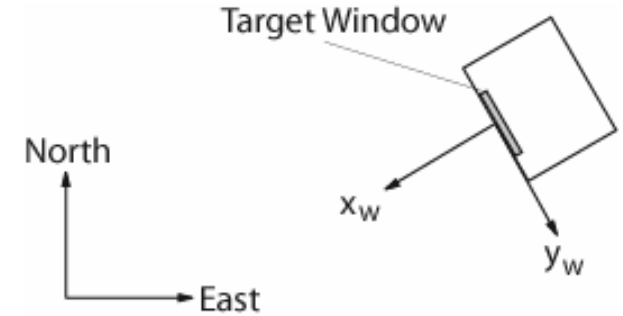
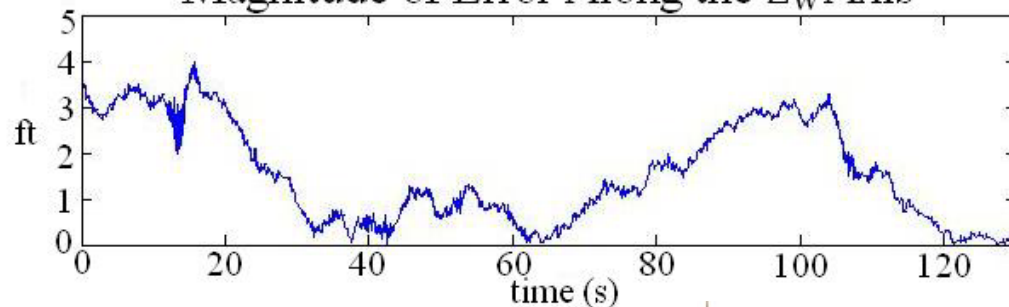
Magnitude of Error Along the  $x_w$  Axis



Magnitude of Error Along the  $y_w$  Axis



Magnitude of Error Along the  $z_w$  Axis



$$\text{error} = |\text{estimate} - \text{GPS}|$$

Max Errors:

9.6 ft (x)

8.3 ft (y)

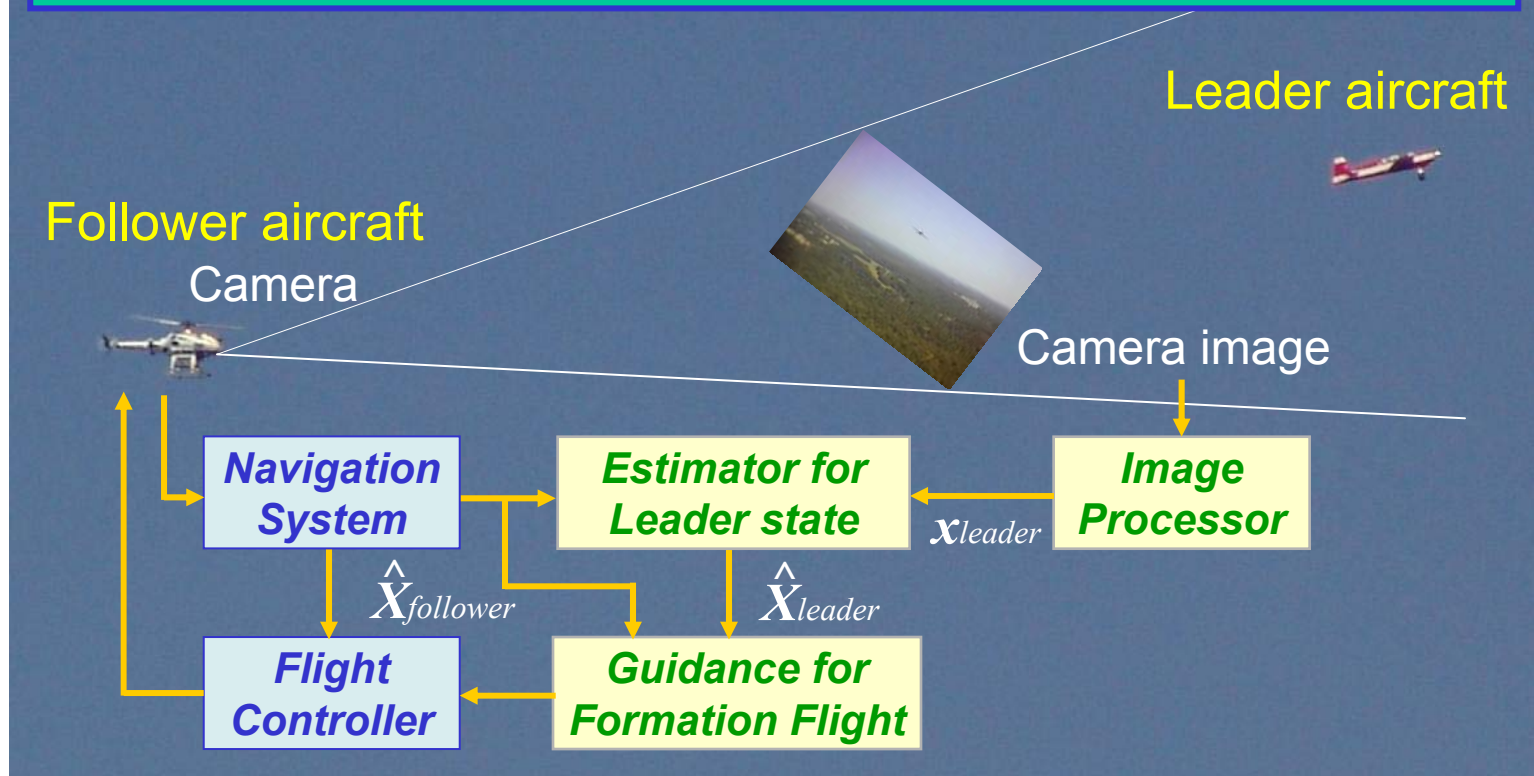
4.0 ft (z)



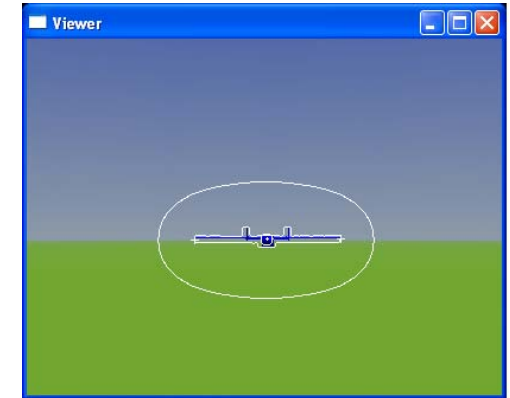
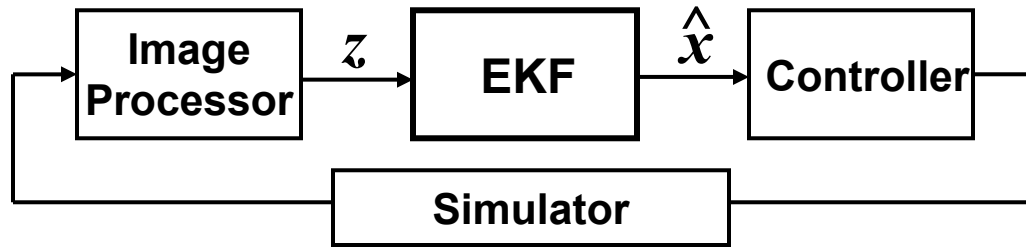
# Vision-Based Formation Flight

Vision-based guidance and navigation for formation flight

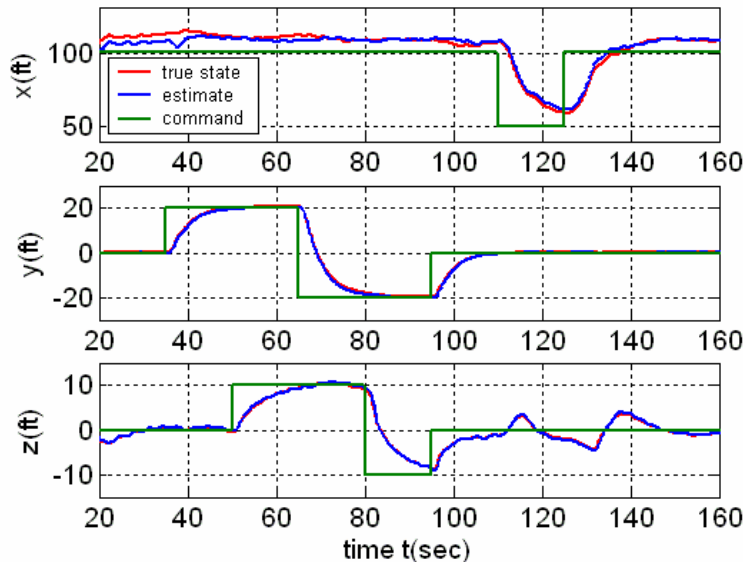
- using a single 2D passive vision sensor
- without communication
- assuming known follower's state



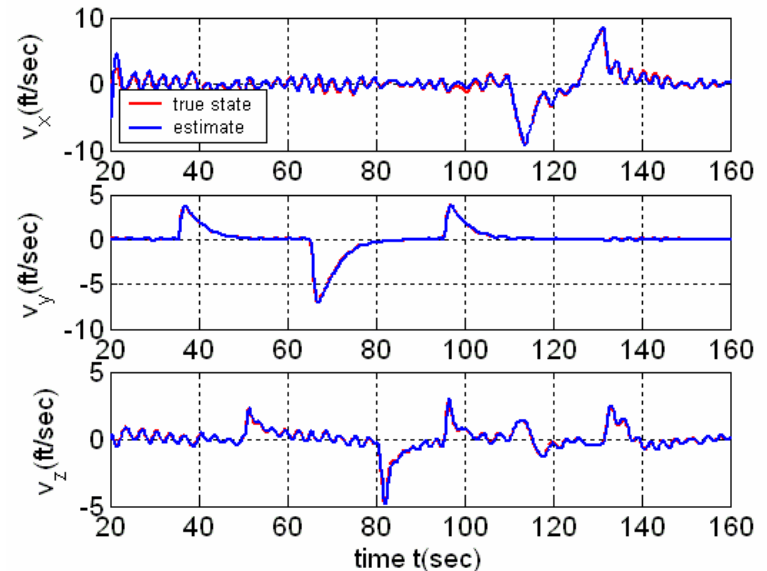
# 6-DOF Image-in-the-Loop Sim Results



- Relative position



- Relative velocity



# Tests on Recorded Videos

- Fast marching methods + target acquisition process  
= 10 frames/sec



Video 1



Video 2



# Estimator Design

Apply Extended Kalman Filter (EKF) to

- **Measurement**

$$z = \begin{bmatrix} u^c \\ \alpha \end{bmatrix} \leftarrow \text{Unit vector expressed in a camera frame}$$

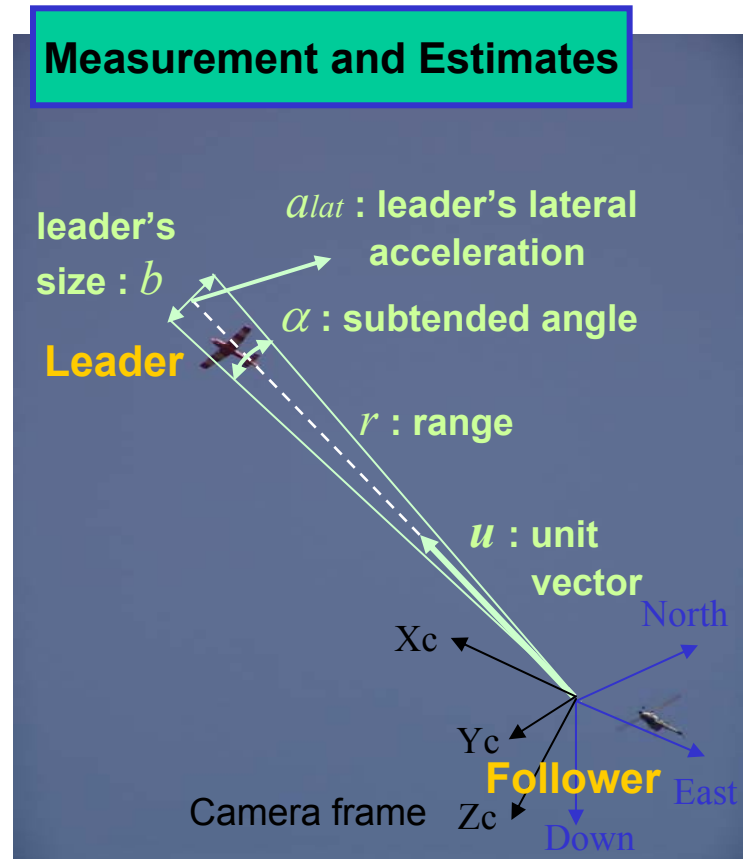
calculated by using image processor outputs

- **Estimation state**

$$X = \begin{bmatrix} u^{NED} \\ \dot{u}^{NED} \\ 1/r \\ \dot{r}/r \\ b \\ a_{lat} \end{bmatrix} \leftarrow \text{Unit vector expressed in a NED frame}$$

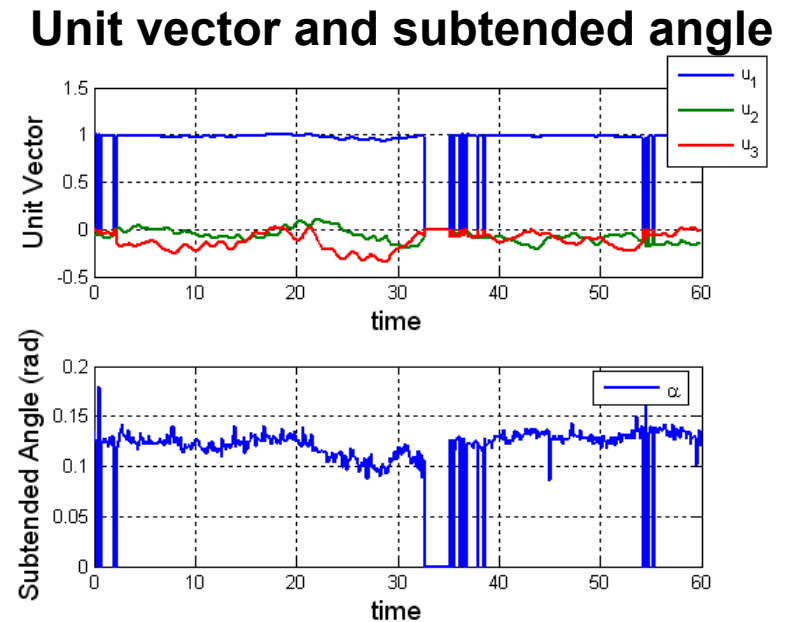
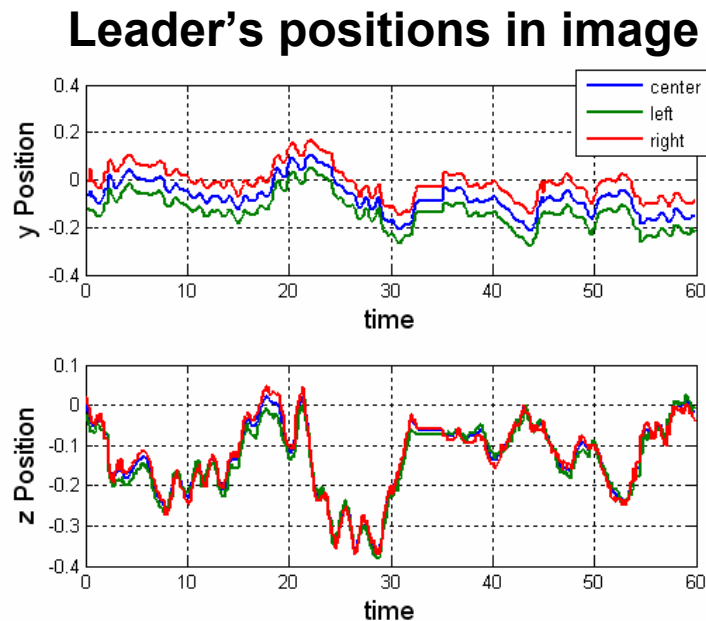
$$u^c = L_{CL} u^{NED}$$

$a_{lat}$  ← Leader's lateral acceleration  
In the leader's wind frame  
( perpendicular to leader's velocity vector )



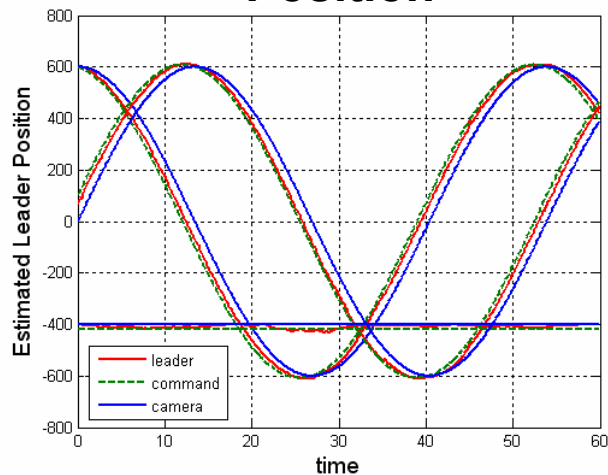
# Simulation Results

- Image source : recorded video in flight test
- Simulated camera motion : circling with a constant speed
- Commanded camera position : *100ft behind, 20ft below* the leader
- **Image processor outputs and EKF measurement**

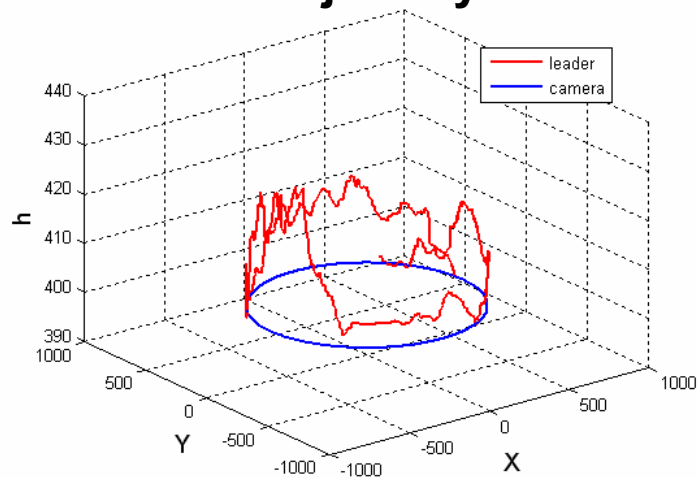


# Simulation Results (cont'd)

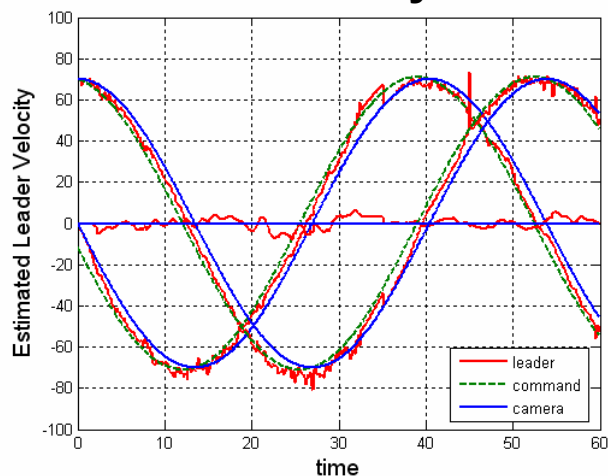
## Position



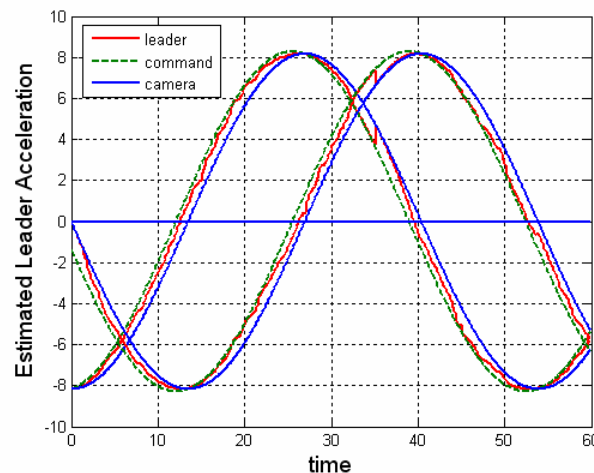
## Trajectory



## Velocity



## Acceleration



# Flight Test

- **Leader Aircraft : GTEdge**
- **Follower Aircraft : GTMax**
  - Body-Fixed Camera
- **Formation Flight Configuration**
  - GTEdge : circling with a constant speed  
( *~600ft radius, 400ft altitude, 70ft/sec speed* )
  - GTMax : maintain a relative distance  
( *100ft behind, 20ft below* )
  - Guidance for formation flight initially is using GTEdge navigation outputs (GPS/INS)
  - All processing onboard



# Formation Flight Tests (GTMax/GTEdge)



# Formation Flight Tests (GTMax/GTEdge)



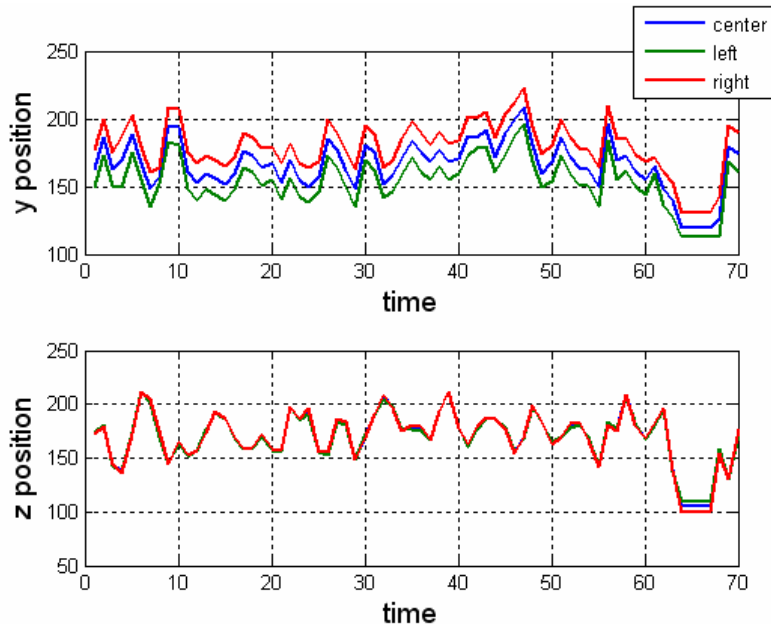
# Formation Flight Tests (GTMax/GTEdge)



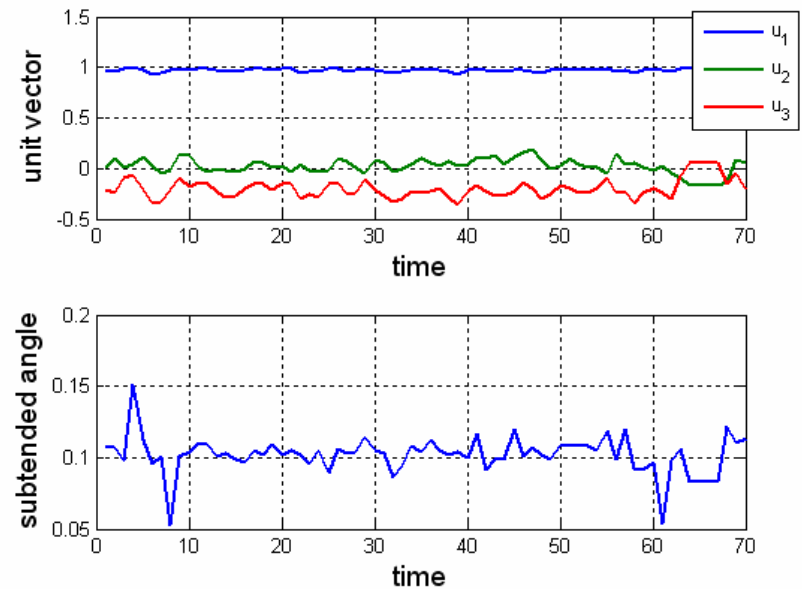
# Flight Test Results

- Data recorded for 70sec at 1Hz
- Image processor outputs and EKF measurement

## Leader's positions in image



## Unit vector and subtended angle

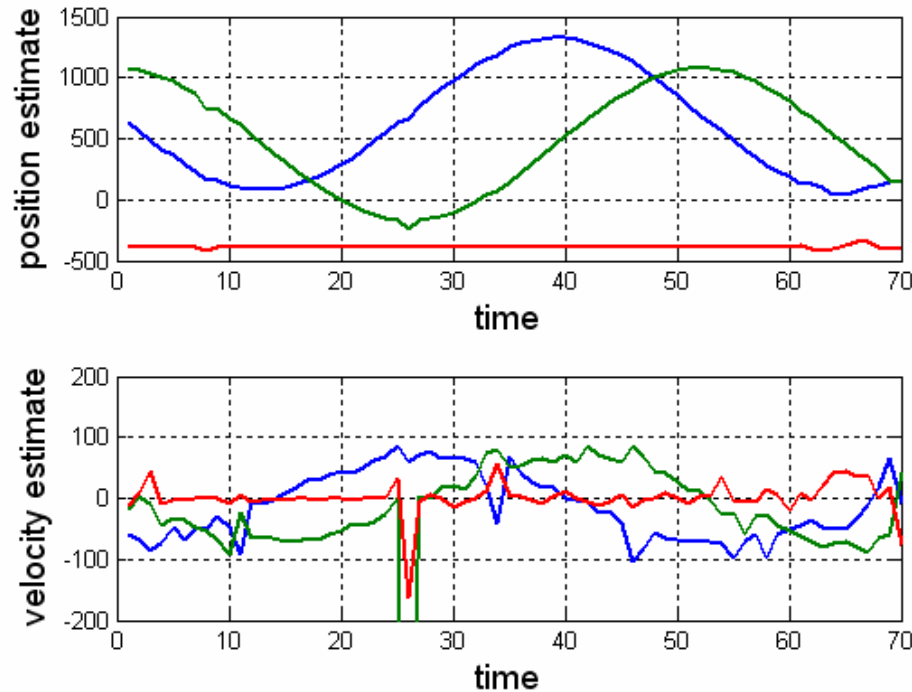


# Flight Test Results (cont'd)

# 16

- **Estimation Results**

## Position and Velocity Estimates



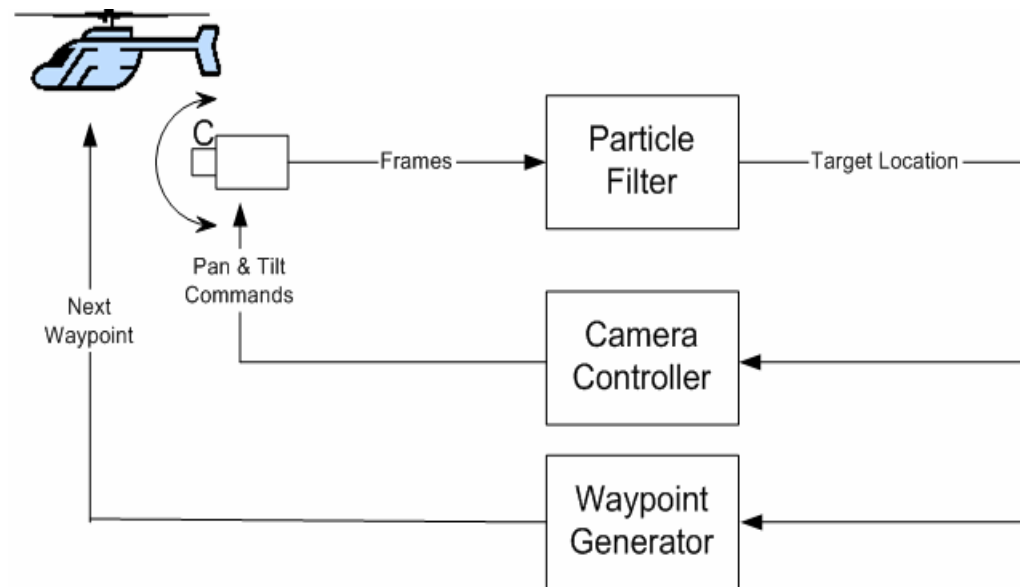
# Status

- Currently going to “close the loop” on guidance
- Added air data system to GTEdge to allow constant airspeed flight
- Current efforts include more advanced vision processing, estimation, and guidance
- Leads into other intended scenarios: see/avoid, pursuit

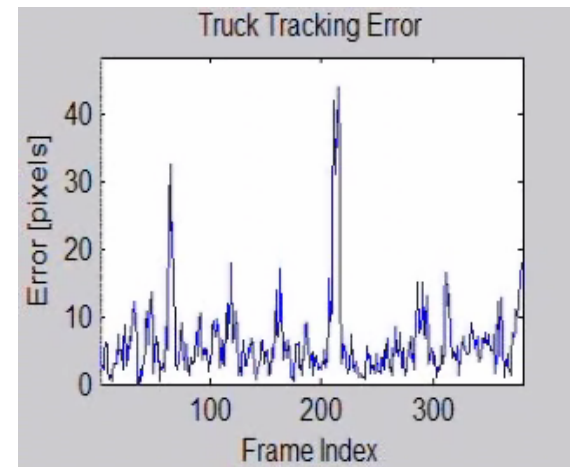
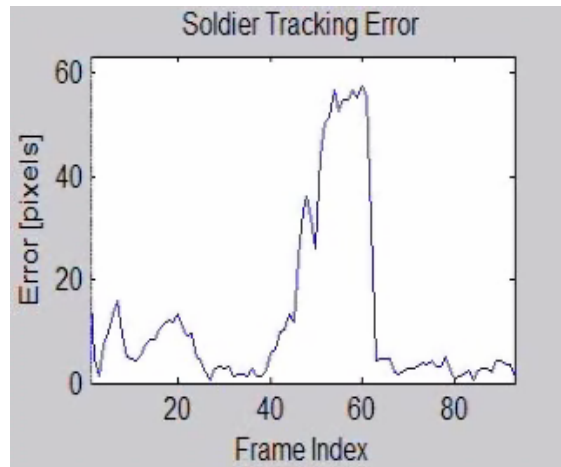
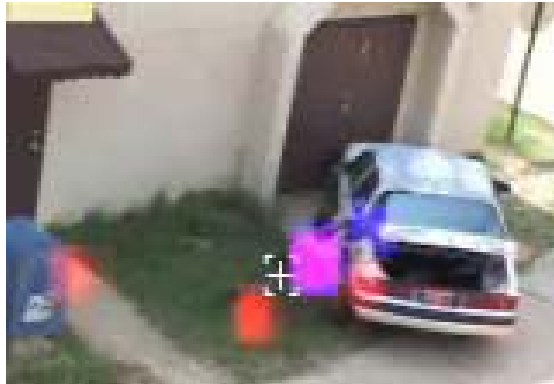


# Moving Ground Target Tracking

- Goal - keep target in camera field of view
  - Interpret image
  - Orient camera
  - Generate trajectory
- Camera commanded to point at target's ground position
- Trajectory is generated to follow target with small attitude changes



# Open-Loop Tracking Results



# Closed Loop Tracking Result

- DARPA Heterogeneous Urban RSTA Teams (HURT) Program
- Victorville, CA in September 2005
- GTMax automatically chasing a van through suburban neighborhood



# Obstacle Avoidance

- **Assumptions**

- Known Camera State: Position and Attitude
  - Stationary Obstacles
  - Straight Obstacle Edges
- } e.g. Buildings

- **Image Processor**

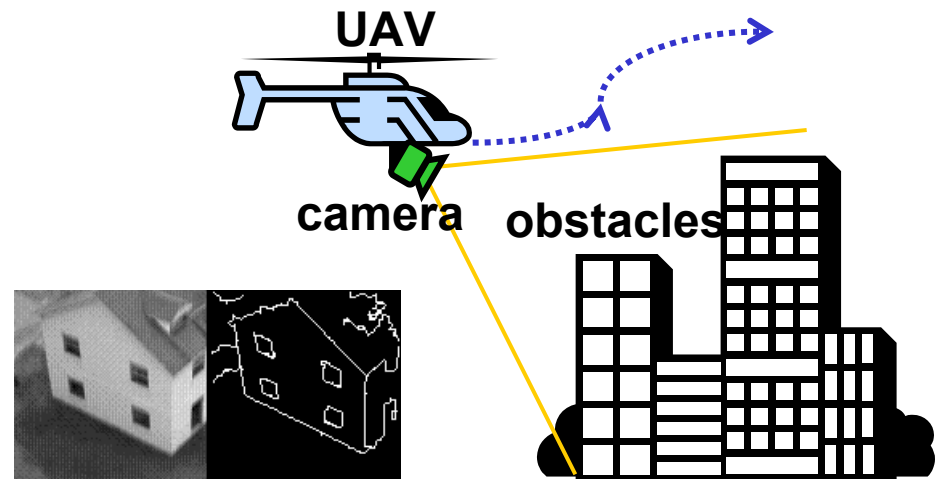
- Outputs Line Segments on a 2D Image Plane

*corresponding to Obstacle Edges*

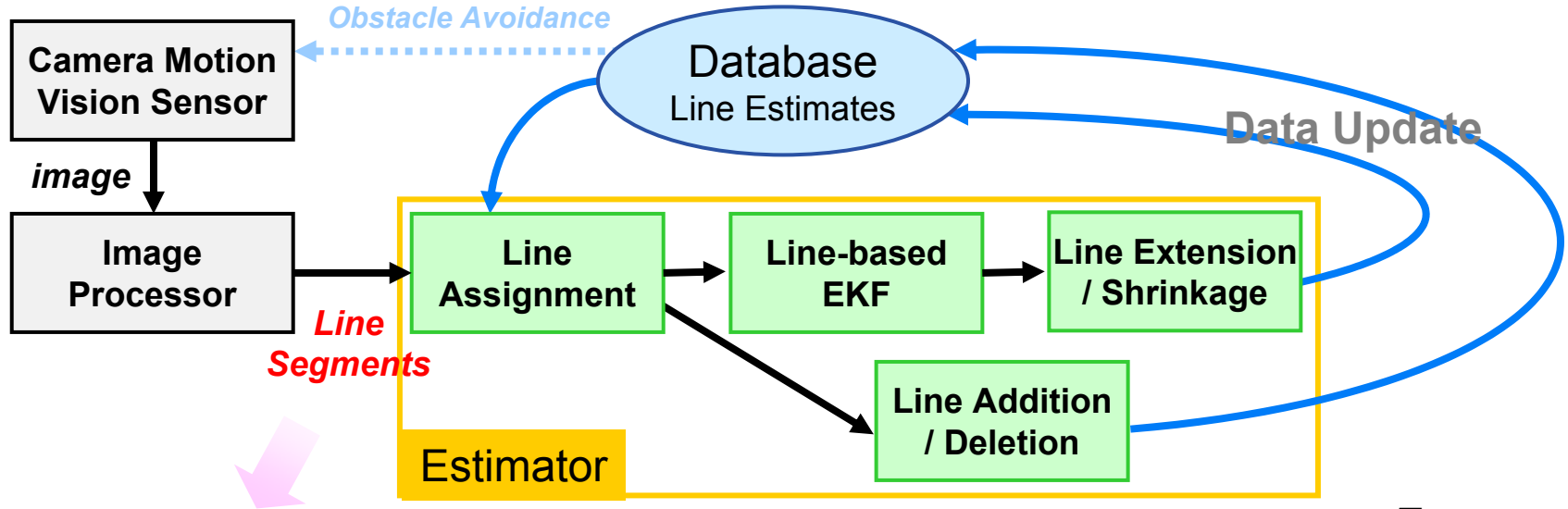


- **Estimator**

- Outputs **Obstacle Edge Estimates** in a 3D Space



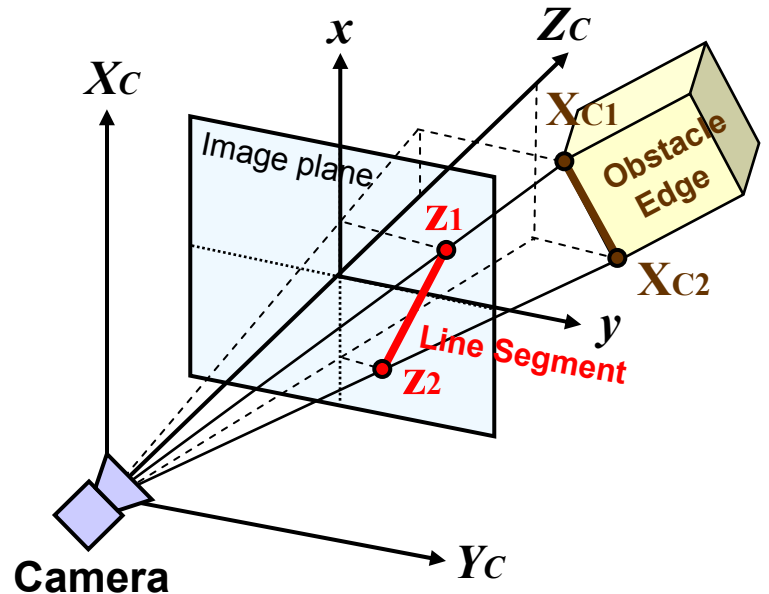
# Estimator Design



## • Measurement

- Line Segment  $\leftrightarrow$  Obstacle Edge  
 $(z_1, z_2)$   $(X_{C1}, X_{C2})$   
 expressed by two endpoint positions

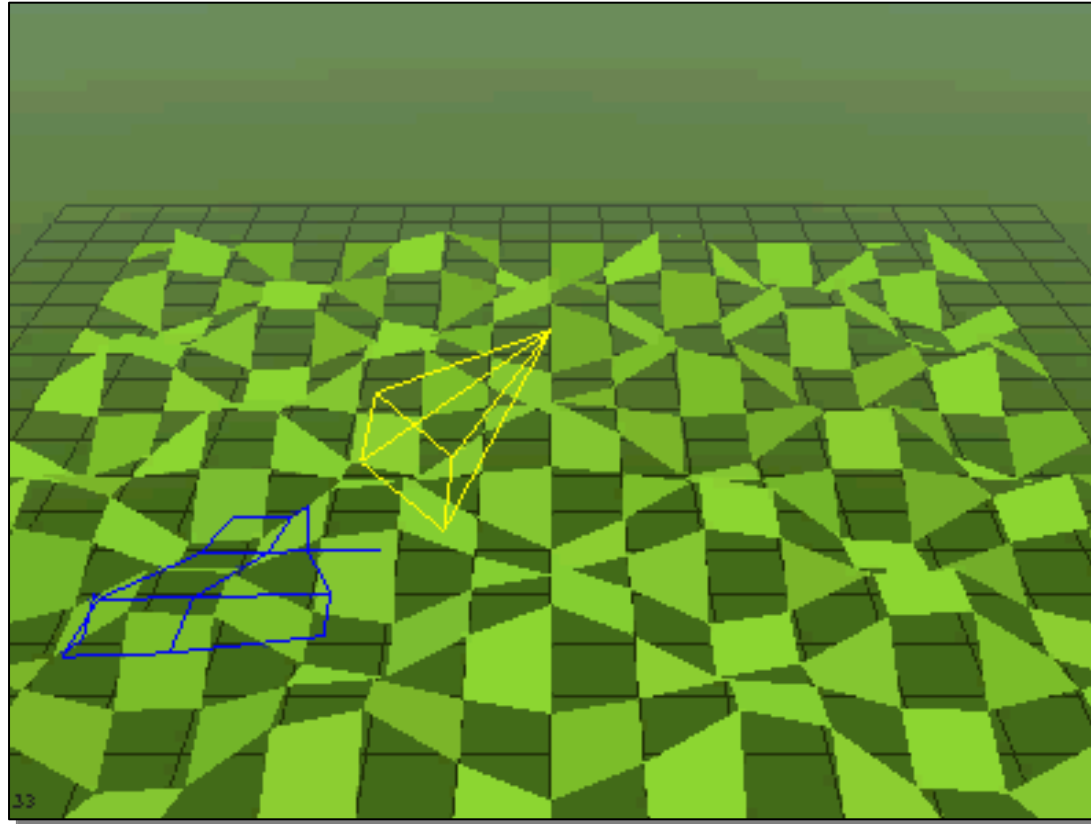
$$z_i = \begin{bmatrix} x_i \\ y_i \end{bmatrix} = \frac{1}{Z_{Ci}} \begin{bmatrix} X_{Ci} \\ Y_{Ci} \end{bmatrix}, \quad X_{Ci} = \begin{bmatrix} X_{Ci} \\ Y_{Ci} \\ Z_{Ci} \end{bmatrix}$$



# Vision-Based Obstacle Detection: 3-D Obstacle Database Construction

Current View  
(yellow)

Terrain 3-D  
Estimate  
(blue)



True Terrain  
(green)

# Future Plans

- Continue to expand on air-to-air tracking
  - Cluttered background
  - Flight testing and facilitate technology transition
- Air-to-ground tracking (by airplanes)
  - Leverage air-to-air work (particularly cluttered background and guidance work)
- Obstacle avoidance
  - Initial emphasis on unknown fixed obstacles, ownship state known
  - Using passive monocular 2-D sensor
    - Requires considerable work in image processing, 3-D estimation, and guidance
  - Using new sensor design (profilometry)



# Expected Outcomes and Transitions

- New capabilities of autonomous sensing and control, enabling operations:
  - In a clandestine/covert manner
  - In close proximity to hazards, structures, and/or terrain
  - In uncertain and adversarial 3-D environments
- Relevant flight test validation
- Enable more capable/reliable existing air vehicles and guided munitions
- Enable entirely new systems to be developed (for example, capable of operating in urban environments)

