Collaborative Control of Unmanned Air Vehicles Concentration

Stochastic Dynamic Programming and Operator Models for UAV Operations

Anouck Girard

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Overview of C^2UAV Concentration

- Team:

- Phil Chandler (AFRL), Emilio Frazzoli (MIT), Anouck Girard (UM), Raymond Holsapple (AFRL), Corey Schumacher (AFRL), Mark Mears (AFRL), Meir Pachter (AFIT), Steve Rasmussen (AFRL)

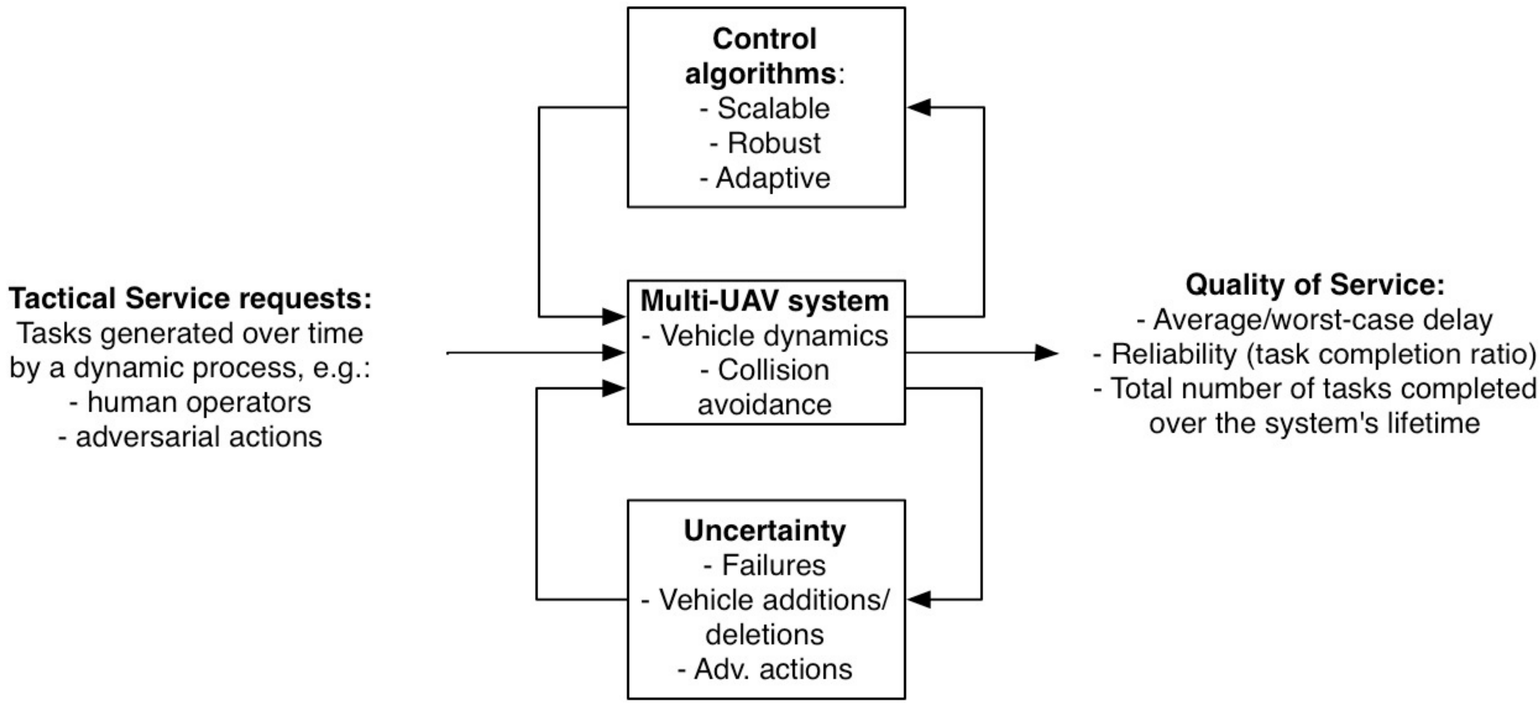
- Current students: John Baker (PhD), Amir Matlock (PhD), Chris Oravetz (MS), Ricardo Sanfelice (Post-doc), Sertac Karaman (PhD)

- Post-doctoral fellow (TBD)

Cooperative Control of Unmanned Air Vehicles (C^2UAV) Concentration

- Challenge:
  - Complex, (task couplings, unreliable communications, partial information…)
  - dynamic,
  - uncertain environments,
  - scalability
- Focus in two main areas:
  - Supervision and control for collaborative heterogeneous systems
    - Mixed-initiative operations
  - Dynamic mission planning
    - Provably efficient, scalable and robust
- All done in close collaboration with AFRL/VACA researchers as part of the Collaborative Center.

Input/output view of heterogeneous multi-UAV systems



Research area:

"Higher-level" coordination and control algorithms

Supervision and Control for Collaborative Heterogeneous Systems

- “Persistent” ISR scenarios (“helicopter down”)
- Supervision
  - Interconnected decision and control
  - Prioritizing / scheduling the operator’s time and attention on dynamic, dangerous situations
- (Possibly multiple) operator modeling
- Information de-confliction and combination

Dynamic Mission Planning

- "Hard" problems:
  - Complex tasks/user models (combinatorial, stochastic)
  - Vehicle dynamics (differential constraints)

- Causal dynamic re-planning,
  - Optimal solutions practically impossible to obtain $\Rightarrow$ Approximation methods

- Formal correctness, performance and robustness guarantees in uncertain, time-varying environments

- Scalable, robust, adaptive algorithms for high quality of service

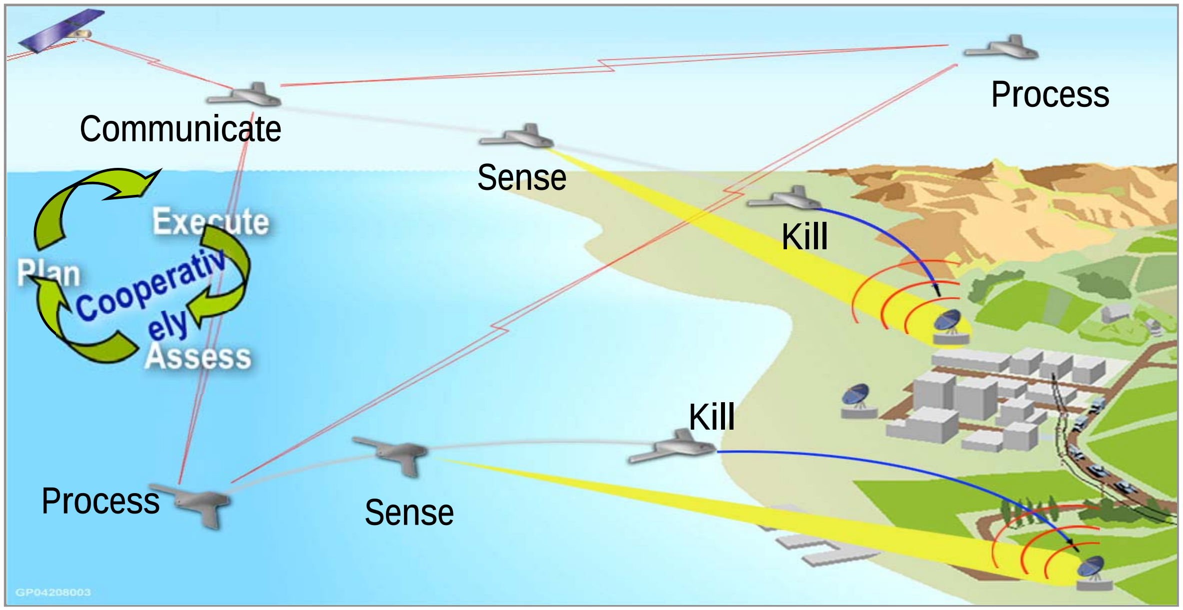
C^2UAV Collaboration Plans

- Co-advising of PhD students
- Yearly MAX student conference
  - Open, especially to AFRL and advisory board
- Seminars
- Common "Cooperative UAV" class/material
- Conference session / journal special issue organization
- Post-doctoral researcher assures UM/MIT/AFRL collaboration

- IFAC Tutorial: Cooperative Multi-Agent Systems: Distributed Control and Estimation
- Submitting 2 papers in Cooperative UAV session at ACC 2008
- Emilio Frazzoli at UM for controls seminar and MAX meeting in November 2007

Supervision and Control for Collaborative Heterogeneous Systems

Supervision and Control for Collaborative Heterogeneous Systems

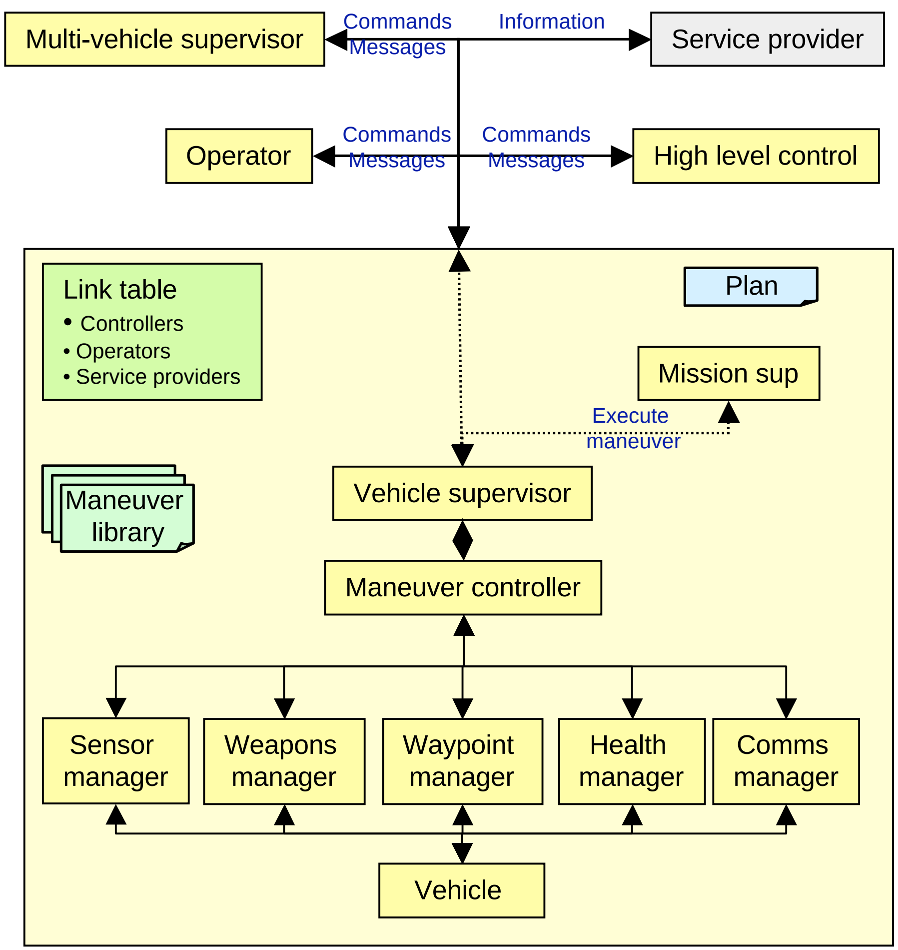


In a mixed initiative environment planning procedures and execution control must allow intervention by experienced human operators

Experience and operational insight of human operators cannot be reflected in math models, so the operators must approve or modify the plan and the execution

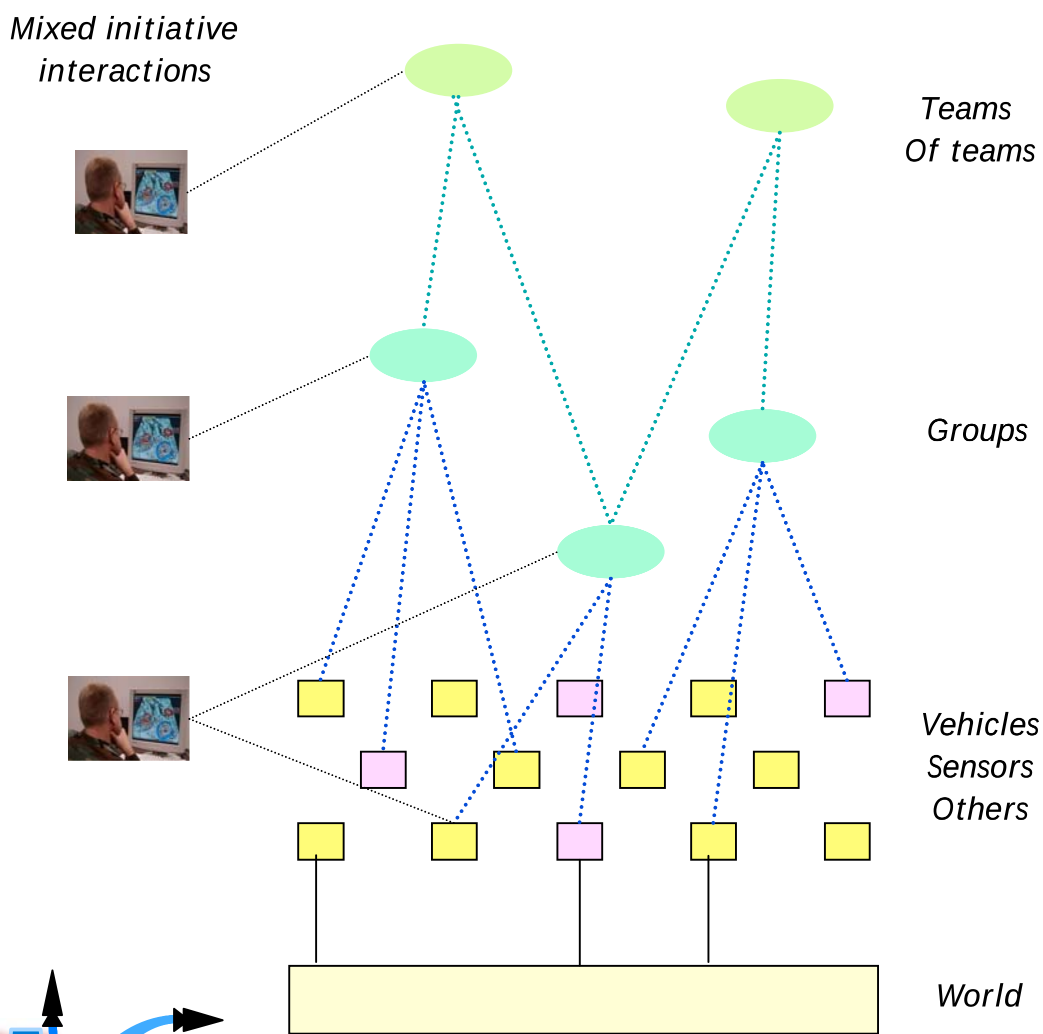
Impossible to design controllers that respond satisfactorily to every possible contingency. In unforeseen situations, the controllers ask the human operators for direction.

Mixed Initiative Control



- Layering
  - Levels of abstraction
  - Operator interactions (levels)
- Operator
  - Plan/Command
    - Load plan
    - Execute plan
    - Abort plan execution
    - Modify plan
    - Interact with maneuvers
  - …
  - Create/pass link
  - Configure

Tools and Technologies



Mixed initiative interactions

Embedded systems design

Control and dynamic optimization

Interoperated networks

Middleware frameworks

Command and control frameworks

Interoperable vehicles/sensors

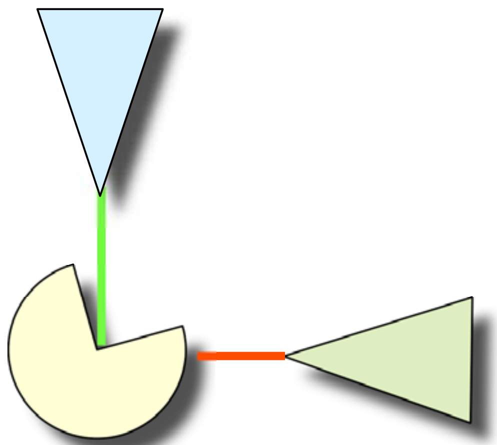
Supervision and Control for Collaborative Heterogeneous Systems

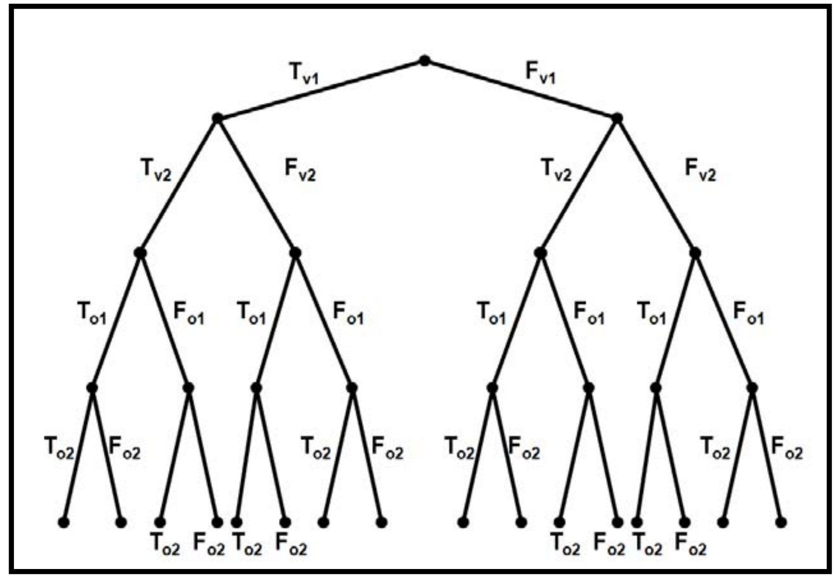
- Scenario definition and/or refinement, together with AFRL VACA
- Common software interface definition, together with AFRL VACA
- Supporting Stochastic Dynamic Programming (SDP) controller design, evaluation and testing for COUNTER program
- Improvements to SDP controller, operator assistance and modeling, collaborative UAV control for heterogeneous teams, information theoretic exploration
- Related ongoing work: adversary modeling as hybrid system configurations with switching, wind estimation, experimental testbed

COUNTER Decision Making and Operator Modeling

J. Baker, R. Holsapple, A. Girard

Possible Outcomes

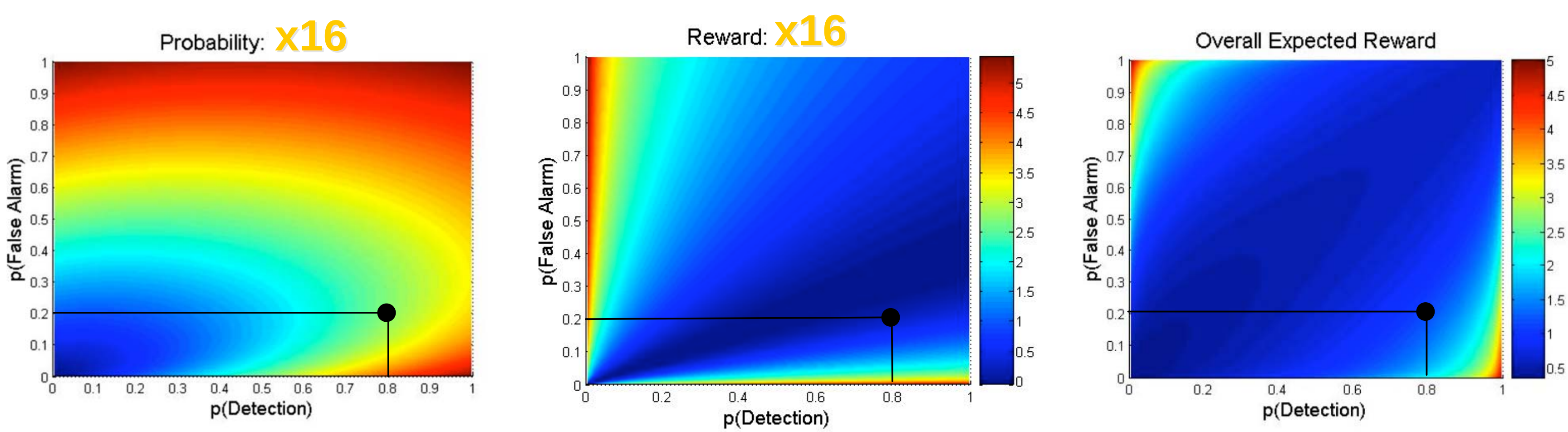




- Will the feature be visible?
- Will the operator claim to see a feature?
- What are the probabilities for two visits?
- How does the revisit approach affect this?
- What are the rewards for the outcomes?

Rewards and Revisits

- Each outcome has an associated probability and reward
- An overall expected reward for a second visit is determined
- Given the expected reward and other criterion, a revisit may occur



- Is the system optimal?
- How does it compare to other methods?

Extensions

- Different revisit strategies
- Adversarial actions
- Improved operator models (flight tests this fall)

- Optimal stopping for inspection in dynamic environments

- Decision support for coordinated vehicle operations

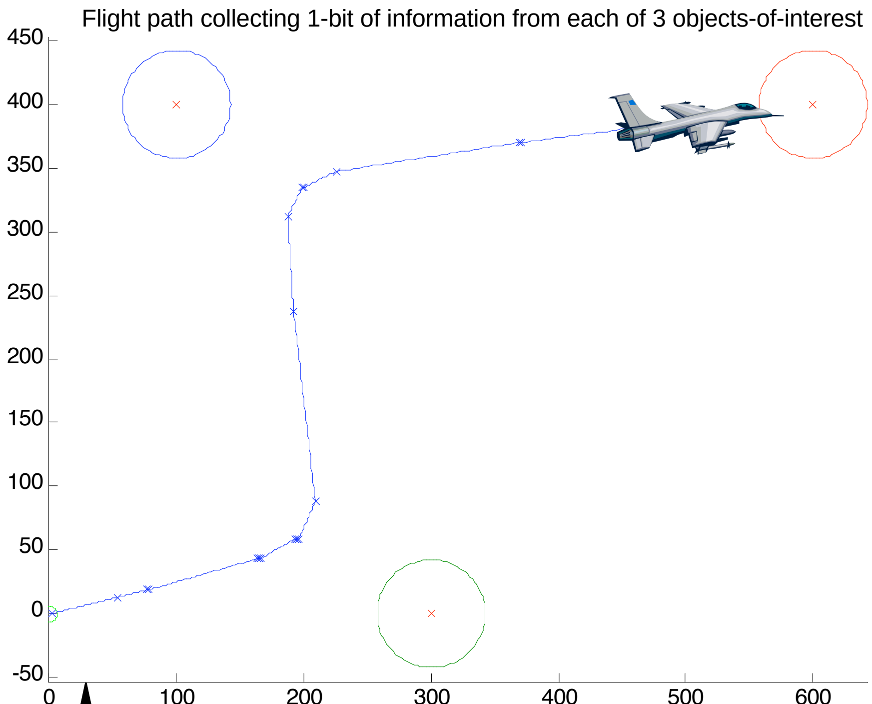
- Load balancing across multiple operators

Information Theoretic Exploration

A. Klesh, P. Kabamba, A. Girard

Information Optimal Search for UAVs with Applications in Exploration

- Optimal search method to collect information about a set of objects of interest
- Objects of interest are determined before flight
- Information model from Shannon's Theory of Communication
- Signal-to-Noise Ratio from Radar Equation



- Objective:
  - Find an optimal path that collects at least a minimum amount of information in the quickest amount of time while traveling at a constant speed
  - Identify an accurate heuristic that can be used to quickly generate paths for an area with many objects and multiple UAVs

Wind-field Reconstruction Using Flight Data

H. Palanthandalam-Madapusi, A. Girard,
and D. S. Bernstein

Motivation

- Motivation: Wind effects on UAVs
- Problem: Estimate unknown wind velocity field
- Flight equations

$$\dot{x} = V_{\mathrm{AC/W}} \cos\psi + V_{\mathrm{W/E}} \cos\phi$$
$$\dot{y} = V_{\mathrm{AC/W}} \sin\psi + V_{\mathrm{W/E}} \sin\phi$$
$$\dot{\psi} = \omega$$

  - x, y position coordinates of the aircraft
  - ψ aircraft heading angle
  - $V_{\mathrm{AC/W}}$ airspeed of the aircraft
  - $V_{\mathrm{W/E}}$ wind velocity magnitude
  - ϕ wind direction

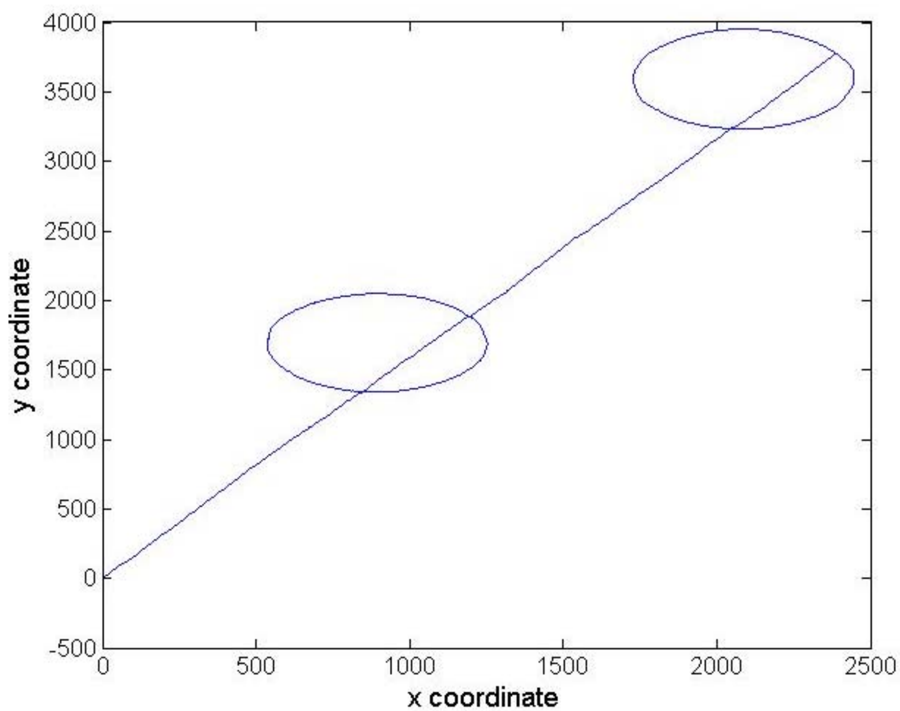
Wind-field Reconstruction

- Unknowns: Wind velocity $V_{\mathrm{W/E}}$ and wind direction ϕ
- GPS measurements of x, y and airspeed $V_{\mathrm{AC/W}}$ are available
  - Case 1: Aircraft heading angle ψ known
    - Linear estimation problem
  - Case 2: Aircraft heading angle ψ unknown
    - Nonlinear estimation problem

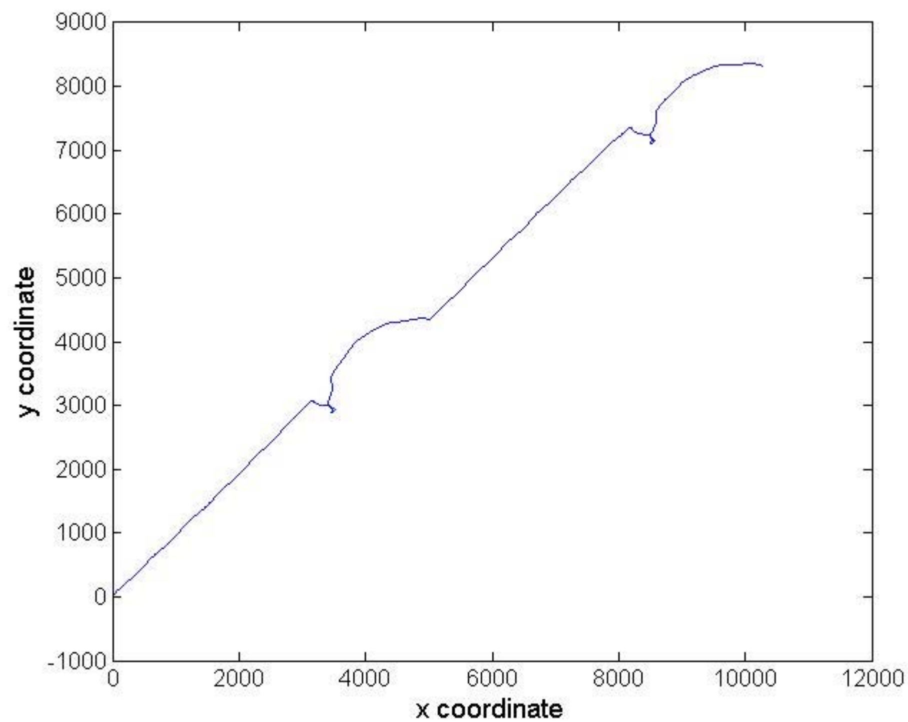
Approach

- Unbiased Minimum-Variance (UMV) Filter
  - Generalization of the Kalman Filter
  - Estimates unmeasured states *and* unknown inputs
  - Requires number of measurements to be greater than or equal to number of unknown inputs
  - For linear dynamics, extends classical Kalman filter
  - For nonlinear dynamics, extends unscented Kalman filter

Flight Path Perturbation Due to Wind



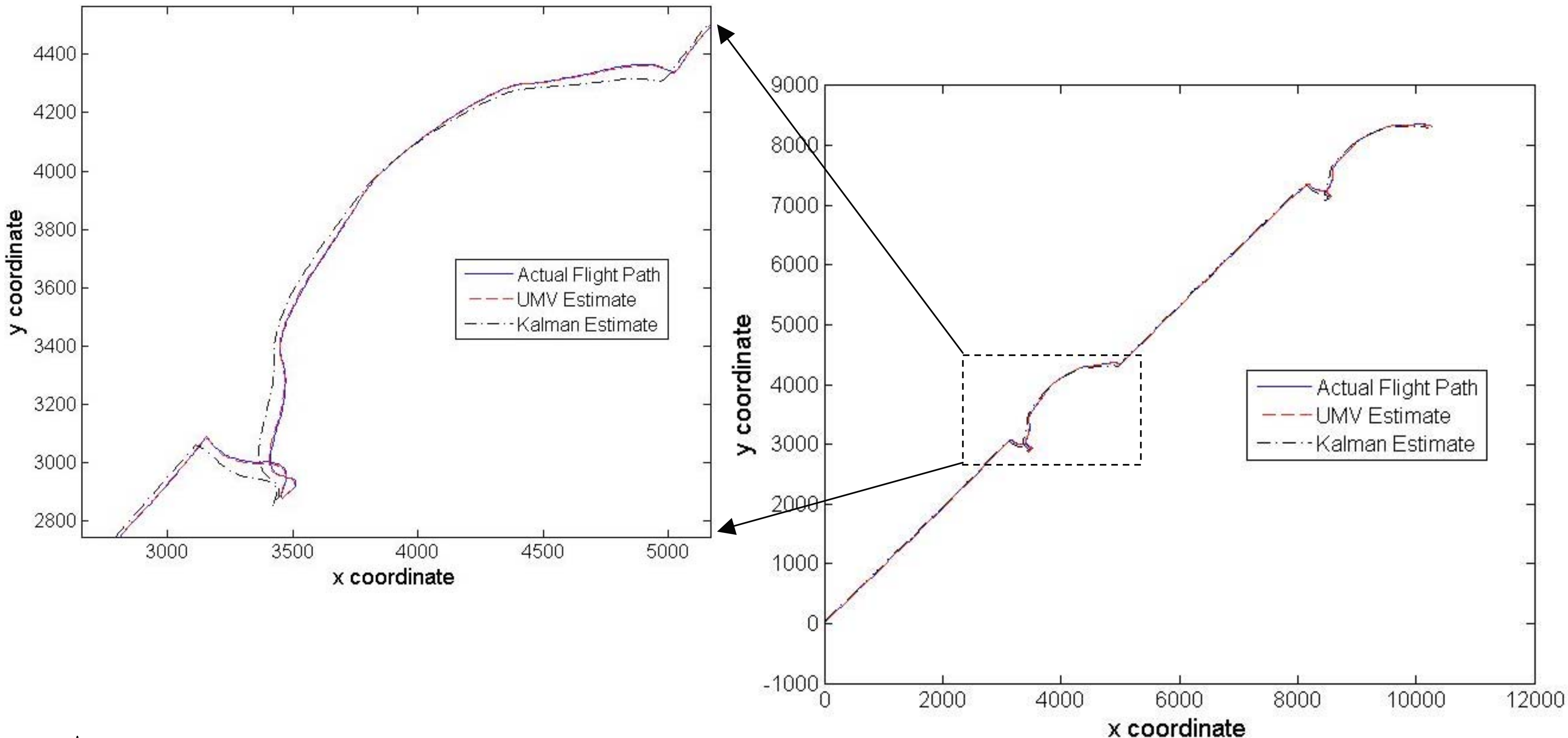
No wind disturbance



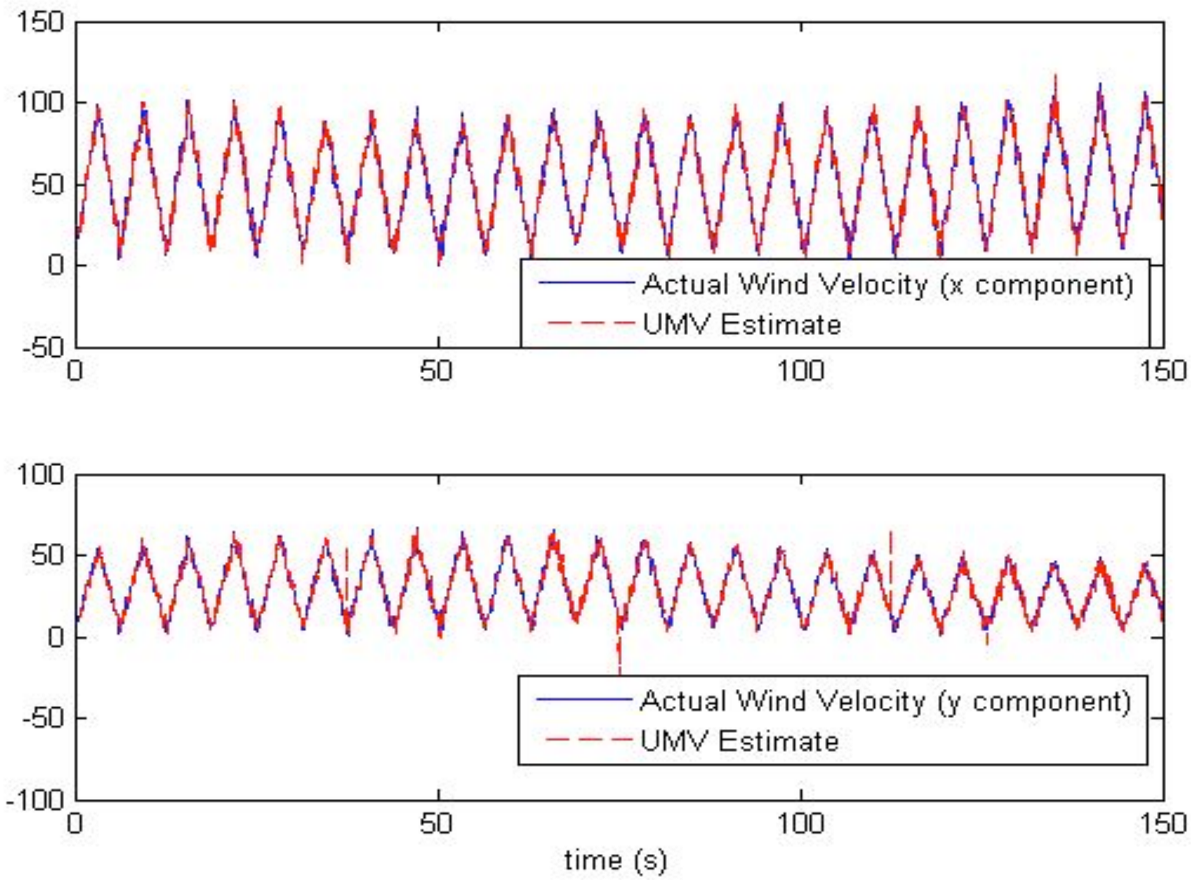
With sawtooth wind disturbance

Flight Path Estimates

Case 1: Known Heading



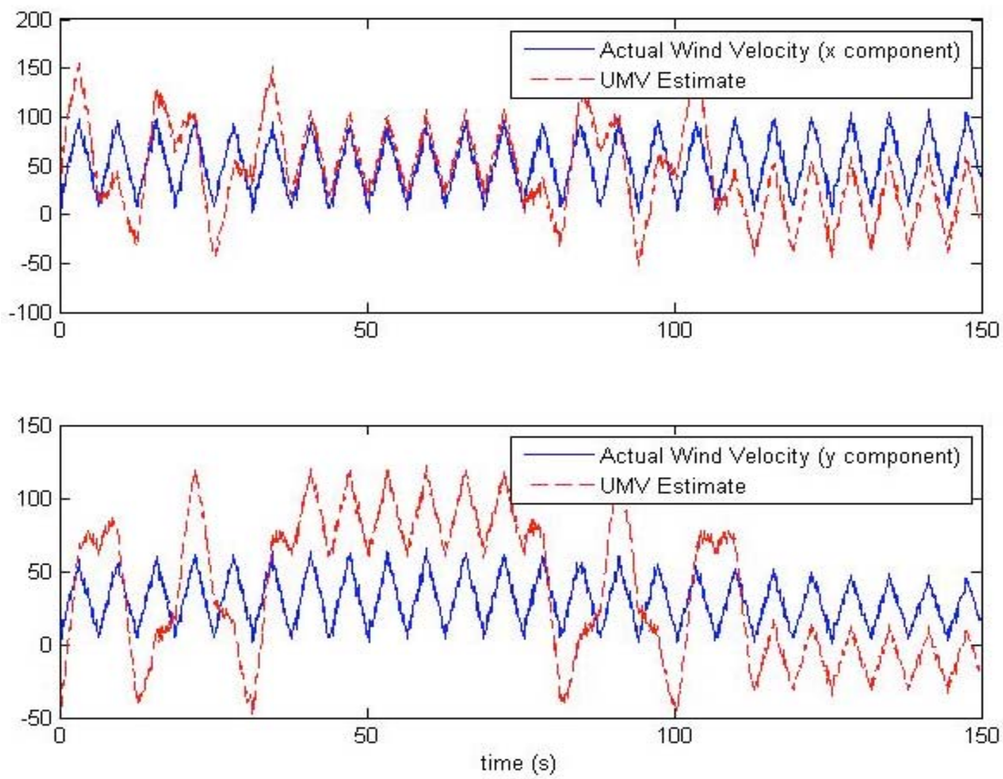
Wind Estimation
Case 1: Known Heading



Linear UMV filter

Wind Estimation

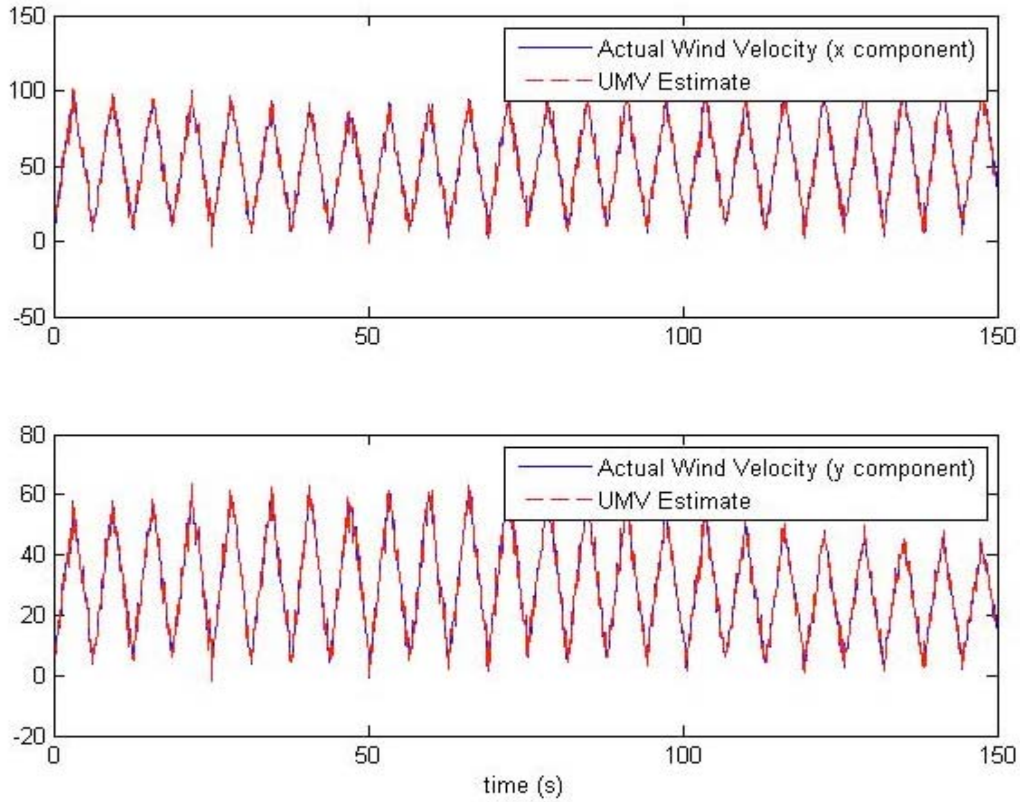
Case 2: Unknown Heading Angle



- Nonlinear UMV filter
- Kinematic ambiguity prevents wind field estimation

Wind Estimation

Case 2: Unknown Heading Angle



- Nonlinear UMV filter
- Known <u>initial</u> heading removes kinematic ambiguity

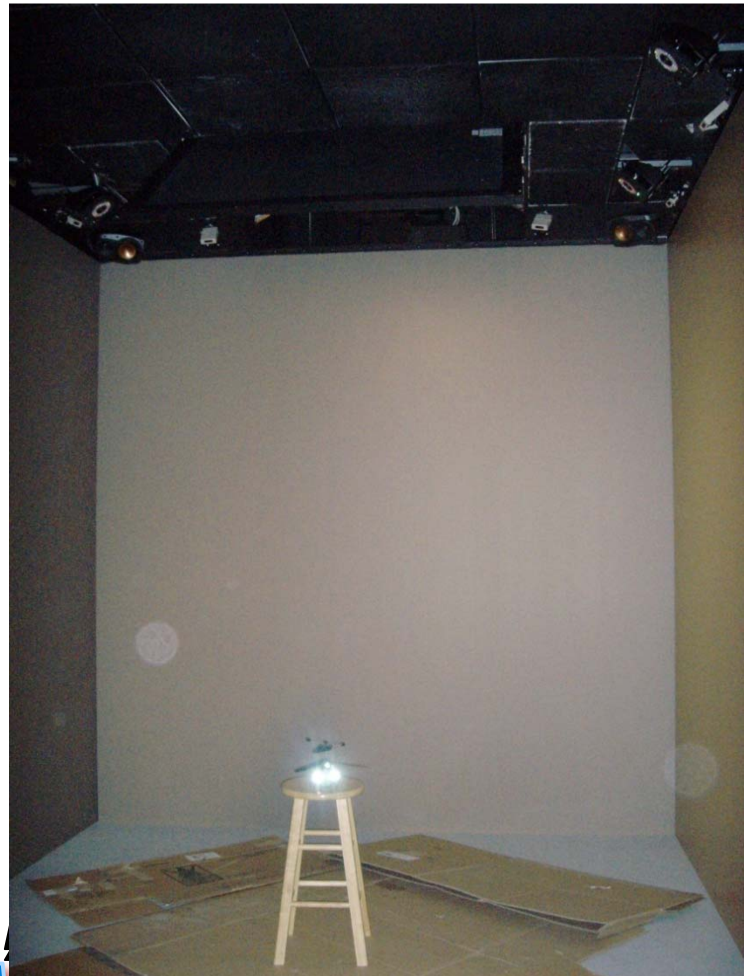
Experimental Setup

A. Girard, D.K. Lee, Z. Hasan

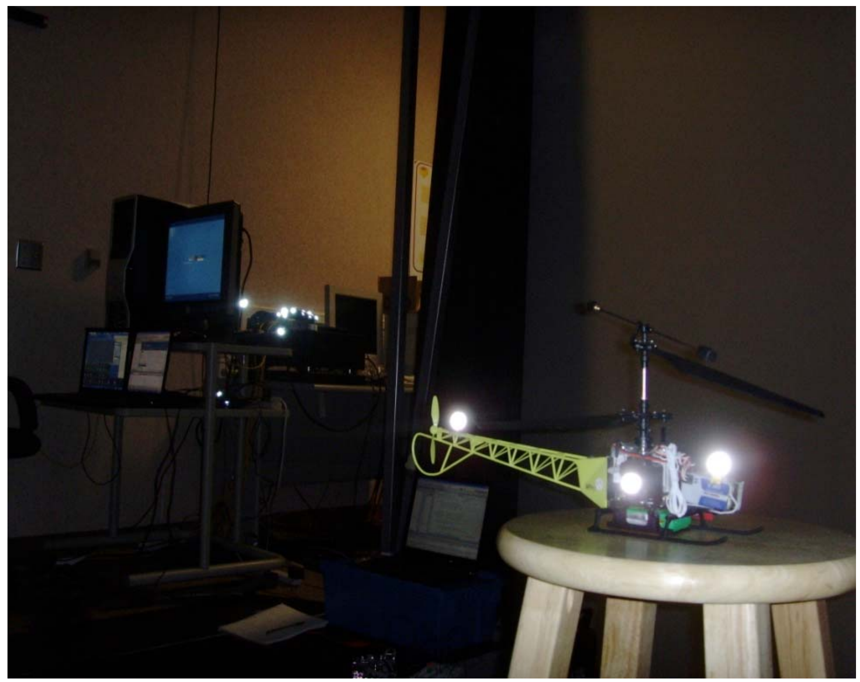
Aerospace Robotics and Controls Lab

- 2 Micro Air Vehicles
  - 2ft wingspan
  - Re ≈127,000
  - 2 video cameras
  - Integrated autopilot
- 5 ground robots
- 2 autonomous underwater vehicles
- Micro helicopters

Vicon Camera System



Digital Media Tools Lab
at Duderstadt center



OpenCV

Left Camera

Right Camera

Research Objectives