Collaborative Control of Unmanned Air Vehicles Concentration

Stochastic Dynamic Programming and Operator Models for UAV Operations

Anouck Girard
August 29, 2007
Overview of C²UAV 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 (C²UAV) 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

Control algorithms:
- Scalable
- Robust
- Adaptive

Multi-UAV system
- Vehicle dynamics
- Collision avoidance

Uncertainty
- Failures
- Vehicle additions/deletions
- Adv. actions

Tactical Service requests:
Tasks generated over time by a dynamic process, e.g.:
- human operators
- adversarial actions

Quality of Service:
- Average/worst-case delay
- Reliability (task completion ratio)
- Total number of tasks completed over the system’s lifetime

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 ⇒ Approximation methods

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

• Scalable, robust, adaptive algorithms for high quality of service
C²UAV 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
  - Teams
    - Of teams
  - Groups
  - Vehicles
    - Sensors
    - Others
  - World

- Interoperable vehicles/sensors

- Control and dynamic optimization

- Command and control frameworks
  - Middleware frameworks
  - Interoperated networks
  - Embedded systems design
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
  \[ \dot{x} = V_{AC/W} \cos \psi + V_{W/E} \cos \phi \]
  \[ \dot{y} = V_{AC/W} \sin \psi + V_{W/E} \sin \phi \]
  \[ \dot{\psi} = \omega \]
  - \( x, y \) position coordinates of the aircraft
  - \( \psi \) aircraft heading angle
  - \( V_{AC/W} \) airspeed of the aircraft
  - \( V_{W/E} \) wind velocity magnitude
  - \( \phi \) wind direction
Wind-field Reconstruction

• Unknowns: Wind velocity $V_{W/E}$ and wind direction $\phi$.
• GPS measurements of $x, y$ andairspeed $V_{AC/W}$ are available.
  – Case 1: Aircraft heading angle $\psi$ known
    • Linear estimation problem
  – Case 2: Aircraft heading angle $\psi$ 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

![Flight Path Estimates for Case 1: Known Heading](image)
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 initial heading removes kinematic ambiguity
Experimental Setup

A. Girard, D.K. Lee, Z. Hasan
Aerospace Robotics and Controls Lab

- **2 Micro Air Vehicles**
  - 2ft wingspan
  - $Re \approx 127,000$
  - 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

- Stochastic, Uncertain Environments
- Persistent Services, Limited Resources
- Collaborative Heterogeneous Systems
- Human Operators
- Supervision and Control Algorithms
- Demonstration/Validation (with AFRL)