Introduction

• We are developing methods to control mobile sensor systems to seek information quickly, safely, and reliably.
• The methods use a model of how the vehicles view the world, through sensors, and how they process information, through filters, to maximize the rate at which they acquire information.
• Approximations to the information-maximizing objective function enable the network size to be scalable, yet globally cooperative.
• A particle filter method was formulated to allow use of general sensor models, that are nonlinear and non-Gaussian.
• Distributed optimization methods were developed with real-time performance, and guaranteed collision avoidance.
• These methods were tested in simulation, and are being implemented on our multi-agent quadrotor testbed, STARMAC.

Control Objectives:
• Automatic information gathering
• Safe interaction

Constraints:
• Power budget
• Communication bandwidth
• Computational resources

Variables:
• Vehicle States: x
• Control Actions: u
• Target State: y
• Observations: z

Multi-Agent Testbed

The Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control (STARMAC)

System Components
• Quadrotor Helicopters (6) – Vertical Takeoff and Landing (VTOL)
• Safe to fly indoors and outdoors
• Low maintenance requirements
• Onboard Computation – Embedded controller
  • Real-time high rate control
  • PC104 (Pentium-M Computer)
• Real-time optimization
• Onboard Sensing – GPS, Inertial and Ultrasonic
• Additional Sensing Payloads – Beacon receiver
  • LASER range finder (LIDAR)
  • Cameras (monocular, stereo)

Dynamics
Angular and vertical accelerations are controlled by differential speed control of electric motors.

Methods to Compute Mutual Information
The mutual information, is computed directly from the particle filter using Monte Carlo Integration. This is computationally expensive, as the network size increases, so two approximations were developed:

Simple-Node Approximation
This decomposition is computationally simple to evaluate. The vehicles cooperate due to emergent behavior--all vehicles have a common view of the world through shared observations. They pursue information considering their own sensors alone.

Pairwise-Node Approximation
This decomposition is more computationally intensive, but is provably more accurate than the single-node. The vehicles take into account the effect of each other vehicle, pair-wise. This enables direct cooperation.

Quantifying Information

Coupled Estimation and Control Model

Sensor
Filter
Dynamics
Controller

Unlike a standard control system, the information-seeking controller causes 3 vehicles to approach the target, reducing the effect of noise, and 2 vehicles to approach it for sensing it.

Information-Seeking Cost Function
• Observations are processed by a sensor filter, to update the target state probability distribution.
• The sensor model used by the filter is a function of the vehicle states, which we control.
• To optimize the control inputs to “seek information”, minimize the expected uncertainty of the target state.
• The expected uncertainty is the negative expected log-likelihood. It can be split into two terms:
  \[ H(y|x_k+1) = H(y|x_k) - I(x_k+1|y) \]

Effect of Maximizing Mutual Information

1. Maximize Observation Uncertainty
   Manager to make observations for which the measurement can’t easily be guessed. Think of making an observation as “asking a question”. The question is useless if we know the answer.

2. Minimize Expected Sensor Model Uncertainty
   Manager to make observations for which the sensor model is more certain than the true state. The more certain the sensor model, the more certain the updated target state model.

Methods to Compute Mutual Information

Processing Sensor Information

Sensor Models
The probability of making an observation, given the system state, is modeled for each type of sensor as a probability distribution:

\[ p(x|\theta, y) \]

Sensor Filter
The filter processes observations from the sensors to update the target state model, a probability distribution:

\[ p(y|x, p(y|x_k)) \]

In this work, Bayesian updates are done using particle filters, due to their advantages for nonlinear problems with high initial uncertainty, multimodal probability distributions, and non-Gaussian noise.

Effect of Maximizing Mutual Information

Distributed Optimization
As the number of vehicles increases, the computational resources they introduce can be used with a distributed optimization program. Two methods were developed:

1. Iterative Distributed Optimization
   Agents agree on control actions to take through an iterative algorithm. Their agreement, and collision avoidance, is enforced using penalty functions.

2. Decoupled Optimization
   Agents independently determine their best control actions with respect to the group. The resulting optimization problem is simpler, and requires no iteration. However, it does not enforce agreement on avoiding collision. When augmented with cooperative collision avoidance, shown below, this method has low computational complexity.

Cooperative Collision Avoidance
• Maintains minimum vehicle separation distance
• Method for Acceleration Constrained Vehicles
  • Agents compute pairwise “keep-out” regions
    • Collision avoidance control inputs are required when one or more vehicles are at their “keep-out” boundaries

Range-Only Sensor Simulation
This sensor measures the distance to the target, with additive noise. The information-seeking controller causes 3 vehicles to approach the target, reducing the effect of noise, and 2 vehicles to provide supporting observations from afar.

Results

Bearsers-Only Sensor Simulation
This sensor measures the direction to the target, with additive noise. Using the information-seeking controller, the vehicles fan out to gain unique perspectives, and approach the expected target’s location, only to reduce the effect of the additive noise.

Optimization
The plot shows an example of a bearings-only mobile sensor’s possible mutual information gain from moving to any point, with tighter contours having more information. The contours change as observations are made.

Distributed Optimization
The initial probability distribution was uniform over the square search region. The cone shaped distribution results from noisy range measurements.

Decision-Making
The plot represents the full target state, with a position and an orientation. The curved distribution results from many noisy magnetic field line measurements.

Rescue Beacon Receiver Simulation
This sensor measures the magnetic field line orientation, with additive noise. The information-seeking controller causes 3 vehicles to approach the target, reducing the effect of noise, and 2 vehicles to provide supporting observations from afar.

Research Directions
• Experiments with STARMAC
  • Search with a rescue beacon
  • Monitoring with a camera
  • Multiple target search
• Further develop the collision avoidance technique
  • Develop additional applications
  • Beacon tracking scenarios
  • RFID tracking
  • Unexploded ordnance detection
  • Survey of disaster areas
  • Biological studies (animal tracking)
  • Spacecraft Rendezvous & Docking

Decentralized Information-Seeking Control for Mobile Sensor Networks
Gabriel M. Hoffmann, Claire J. Tomlin