Cooperative Control and Consensus Building for Autonomous Vehicle Swarms

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Vehicle Systems

- unmanned ground vehicle (UGV)
- unmanned underwater vehicle (UUV)
- unmanned air vehicle (UAV)
- vehicles in outer space & other worlds

In this talk, robot == vehicle == system
Cooperative / Coordinated Control

• Motivation:
  While single vehicles performing solo missions can yield some benefits, greater benefits will come from the cooperation of teams of vehicles.

• Common Theme:
  coordinate the movement of multiple vehicles in a certain way to accomplish an objective.

  e.g. many small, inexpensive vehicles acting together can achieve more than one monolithic vehicle.
  • e.g., networked computers
  • Shifts cost and complexity from hardware platform to software and algorithms.

• Multi-vehicle Applications:
  Autonomous household appliances, enhanced surveillance systems, hazardous material handling systems, active reconfigurable sensing systems, space-based interferometry, future autonomous combat systems, etc.
Cooperative Control Applications

• **Formation Control**
  Mobile robots, unmanned air vehicles, autonomous underwater vehicles, satellites, spacecraft, Automated highways

• **Non-formation Control**
  Task Assignment, cooperative transport, cooperative role assignment, air traffic control, cooperative timing
  • Cooperative search, reconnaissance, surveillance (military, homeland security, border patrol, etc.)
  • Cooperative monitoring of forest fires, oil spills, wildlife, etc.
  • Rural search and rescue.
Typical Approaches to Formation Control

- Leader-following
- Behavioral
- Virtual Leader / Virtual Structure
Leader-follower Approach

• Basic Idea:
  Motion prescribed by the leader: the rest simply follow.

• Advantages:
  Simple to understand and implement; mathematically analyzable.

• Disadvantage:
  Leader does not know about followers: no formation feedback; the followers are unaware of the goal; leader is a single point of failure.
Behavioral Approach

- Basic Idea: Several competing behaviors.

- Advantages: Decentralized; Robust: Every vehicle knows about its goal; local information exchange.

- Disadvantage: Precision is compromised; difficult to analyze mathematically.
Formation Control
Virtual Leader / Virtual Structure Approach

- Basic Idea:
  Desired formation treated as rigid body; Vehicles track assigned locations on structure.

- Advantages:
  High precision; mathematically analyzable; Simple to implement.

- Disadvantage:
  Centralized; Acting as a virtual structure limits some potential applications.
Cooperative Control: Inherent Challenges

- Complexity:
  - Systems of systems.
- Communication:
  - Limited bandwidth and connectivity.
  - What? When? To whom?
- Arbitration:
  - Team vs. Individual goals.
- Computational resources:
  - Will always be limited
Consensus Seeking in Multi-vehicle Systems

Meet for lunch problem
- Agree to meet for lunch but forget to decide on a time
- Each person may only get hold of some people
- Some people’s opinion may be valued more than others
- What algorithm to use to reach consensus on a time
- Convergence speed

Consensus seeking facilitates
- Distributed decision making
- Multi-robot coordination using local interactions
- Multiple UAV cooperative timing mission
- Formation keeping mission
Consensus Algorithms

• Basic Idea
  Each vehicle updates its information state based on the information states of its local (possibly time-varying) neighbors in such a way that the final information state of each vehicle converges to a common value.

• Extensions
  Relative state deviations, incorporation of other group behaviors

• Feature
  Only local neighbor-to-neighbor information exchange required

Vicsek’s Model

http://www.red3d.com/cwr/boids/
Rendezvous

Vehicle dynamics: $\ddot{r}_i = u_i$.

Control Law: $u_i = -\alpha \dot{r}_i - \sum_{j \in N_i} k_{ij}(r_i - r_j) + \gamma (\dot{r}_i - \dot{r}_j)$. 
Decentralized Cooperative Timing Example

- Consensus strategy similar to Kalman filter
- Initially, each UAV determines its own ETA
- Team ETA is updated using discrete-time consensus strategy
- Every two seconds, each UAV communicates its ETA to another UAV (randomly chosen)
- Wind prevents UAVs from achieving timing exactly
Experimental Results

Experiment was performed on a mobile actuator and sensor network platform at Utah State University.

Team:
Graduate Students: Haiyang Chao, Bill Bourgeois, and Nathan Sorensen
Faculty: YangQuan Chen and Wei Ren
Experimental Results

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Rendezvous

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Formation Control

Consensus reached on deviation vectors

Consensus reached on a possibly time-varying formation center
Experimental Results

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Formation Stabilization

Team:
Graduate Students: Haiyang Chao, Bill Bourgeois, and Nathan Sorensen
Faculty: YangQuan Chen and Wei Ren
AmigoBot Platform
Formation Control Strategy

<table>
<thead>
<tr>
<th>Communication Network</th>
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<tbody>
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<td>( x_{i}^{vc} )</td>
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<td>( {j \in N(t) \mid x_{j}^{vc} } )</td>
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<tr>
<td>Consensus-based Formation</td>
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<td>State Estimator ( \text{#i} )</td>
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<td>Group Leader</td>
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<td>Follower</td>
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<td>Consensus-based Formation</td>
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<td>Control Module ( \text{#i} )</td>
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<td>( {j \in J(t) \mid y_{j} - y_{j}^d } )</td>
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<td>( r_{i} )</td>
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<td>( u_{j} )</td>
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<tr>
<td>Vehicle ( \text{#i} )</td>
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<td>( r_{i} - r_{i}^d )</td>
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AmigoBot Formation Control Experiment
Synchronized Spacecraft Rotations

Spacecraft attitude dynamics:

\[ \dot{q}_i = -\frac{1}{2} \omega_i \times \dot{q}_i + \frac{1}{2} \dot{q}_i \omega_i, \quad \ddot{q}_i = -\frac{1}{2} \omega_i \cdot \dot{q}_i \]

\[ J_i \dot{\omega}_i = -\omega_i \times (J_i \omega_i) + \tau_i. \]

Control torque:

\[ \tau_i = -k_G q^d_i \dot{q}_i - d_G \omega_i - \sum_{j \in N_i} [a_{ij} \dot{q}_j q_i + b_{ij} (\omega_i - \omega_j)], \]

where \( k_G, d_G, a_{ij}, \) and \( b_{ij} \) are positive scalars, and \( q^d_i \) denotes the desired attitude for each spacecraft.
Synchronized Spacecraft Rotations

Distributed attitude alignment among six spacecraft. The above figure shows the quaternion attitudes of spacecraft \#1, \#3, and \#5, where \( q^d = [0, 0, 0, 1]^T \) and \( q_i^{(j)} \) denotes the \( j^{th} \) component of quaternion \( q_i \).
Thank you!

Questions?