Cooperative UAVs for Remote Data Collection and Relay

Kevin L. Moore Michael J. White, Robert J. Bamberger, and David P. Watson

Systems and Information Science Group
Research and Technology Development Center
Johns Hopkins University Applied Physics Laboratory

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Outline

- Dynamic Surveillance Networks
- DSNs for Data Exfiltration
  - Project Concept
  - Hardware
  - Architecture
- DSN Algorithmic Approach
  - Consensus Variables
  - Global Optimization via Coordination
- Preliminary Results
- Conclusions
Dynamic Surveillance Networks

- Network of “entities”
  - Communication infrastructure
  - Entity-level functionality
  - Implied global functionality
  - Not necessarily homogeneous

- Surveillance:
  - Primarily considering entities that are sensors
  - “Bigger picture” includes actors as well

- Dynamic
  - Entities may be mobile
  - Communication topology might be time-varying
  - Data actively and deliberately shared among entities
  - Decision-making and learning
Motivating Example 1

- Autonomous swarm for plume tracking

Sensor-carrying UAVs and UGVs assess and track the development of a hazardous plume resulting from a CBR terrorism act.
Motivating Example 2

- Autonomous confederation building, adaptive to changes in battlefield conditions
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DSN Data Exfiltration Project

- Demonstrate UAVs data collection from unattended ground sensors
  - Clusters of low-power, unattended sensors
  - Cluttered urban environment
  - Cooperating UAVs for fly-by data collection
    - Payload limits restrict range
    - Run-time issues dictate need for “smart” operation
**DSN Data Exfiltration Project**

- **Data exfiltration application**
  - Sensor clusters are deployed “by hand”
  - Not all clusters can communicate with each other
  - Exact cluster locations are not known

- **UAVs execute a cooperative search to find the clusters**
  - Search begins with a pre-planned raster scan
  - Search is refined based on cluster discovery results

- **After discovery, UAVs cooperate to collect data from all the clusters in some optimal way**
  - UAVs configure to provide maximum coverage of clusters or
  - An optimal path is planned to travel between clusters
Adaptation occurs in response to changes in the UAV resources or the sensor clusters:

- Periodically, one of the UAVs returns to the base station to relay data from the sensor clusters; when this happens the remaining UAV automatically re-plans its operations.
- If a sensor cluster is lost the UAVs cooperatively reconfigure.
DSN Data Exfiltration Project

- Leverages Several Previous APL Efforts
  - UAV for fly-by data collection
  - UAV for data-hopping between ground nodes
  - Coordinated (central control) of multiple UGVs
  - Cooperative control of UGVs for search applications
  - Communication framework for cooperative autonomy networks (802.11-based)
  - Distributed (swarm-like) UGVs and UAVs demonstrating emergent behavior:
    - Heterogeneous Mix of Small Ground & Air Vehicles
    - Co-Fields Behavior Algorithms
    - Common Supervisory Control Architecture
    - Collaborative Field Testing with Army Research Lab, Aberdeen.
    - Initial Focus on Distributed ISR Application
DSN Hardware

- Simulated sensor – laptop with directional antenna

- Payload – Autoplot and single board computer with 802.11b device

- Vehicles – TransAtlantic Model (TAM) and MIG27
DSN Hardware/Communications Architecture

COTS UAV Setup

- **GPS**
- **Piccolo Autopilot**
- **900 MHz Wireless Data Transceiver**
- **72 MHz Futaba Receiver**
- **900 MHz Piccolo Telemetry Link**
- **72 MHz R/C**
- **Antenna**
- **Wireless communications**
- **RS232 cable**
- **Ethernet cable**
- **Piccolo Ground Station**

**Normal Setup**
- Applied Data Systems Bitsy Plus Single Board Computer
- UAV Fuselage
- 2.4 GHz 802.11b Cisco PCMCIA Client Adapter
- 2.4 GHz 802.11b Network Communications
- Second UAV Cisco Access Point
- Laptop

**COTS UAV Setup**
- Piccolo Ground Station
- 900 MHz Piccolo Telemetry Link
DSN Architecture Concept

Future work

Advanced Autopilot

Reactive Control

Waypoints

Supervisory Control

Data

Autonomy Board

Local Decision Logic

Cooperative Decision Logic

Mission Payload (Sensor)

Communication System

Users, Other Vehicles

Reactive Sensors

Vehicle Sensors

GPS\IMU

Airframe

Servos

External Environment

Future work

Advanced Autopilot

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Autonomy Board

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Communication System

Users, Other Vehicles

Reactive Sensors

Vehicle Sensors

GPS\IMU

Airframe

Servos

External Environment
Each state has its own sub-state machine

DSN Supervisor

Input/Output1, Output2, …

Inputs:
- A: Automatic
- M: Manual
- ND: Negotiation Done
- CR: Change Request
- T: Transfer
- TP: Transfer Complete
- E: Error

Outputs:
- FP: Flight Plan
- DCV: Data Collection Variable

States and Transitions:
- **Loiter w/Negotiate**: Transition to Manual, Loiter w/Exfilt, Loiter w/Data Transfer.
- **Loiter w/Exfilt**: Transition to Manual, Loiter w/Exfilt & Negotiate.
- **Loiter w/Data Transfer**: Transition to Manual, Loiter w/Exfilt, Loiter w/Negotiate.
- **Manual**: Transition to Loiter w/Negotiate, Loiter w/Exfilt, Loiter w/Data Transfer.

Transitions:
- A/FP, DCV
- M
- M
- E/FP, DCV
- ND/FP, DCV
- T/FP, DCV
- E/FP, DCV
- CR/FP, DCV
- E/FP, DCV
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BN Algorithmic Approach

- Bigger picture is coordination and control of multiple, cooperating, heterogeneous entities:

- Our technical approach, a generalization of potential field approaches, is based on so-called consensus variables and has connections to problems in:
  - Coupled-oscillator synchronization
  - Neural networks
Consensus Variable Perspective

- Assertion:
  - Multi-agent coordination requires that *some* information must be shared

- The idea:
  - Identify the essential information, call it the *coordination or consensus variable*.
  - Encode this variable in a distributed dynamical system and come to consensus about its value

- Examples:
  - Heading angles
  - Phase of a periodic signal
  - Mission timings

- In the following we build on work by Randy Beard, *et al.* at BYU, to use consensus variables to solve global problems in a distributed fashion
Consensus Variables

- Suppose we have $N$ agents with a shared *global* consensus variable $\xi$
- Each agent has a *local* value of the variable given as $\xi_i$
- Each agent updates their local value based on the values of the agents that they can communicate with

$$\dot{\xi}_i(t) = - \sum_{j=1}^{N} k_{ij}(t) G_{ij}(t)(\xi_i(t) - \xi_j(t))$$

where $k_{ij}$ are gains and $G_{ij}$ defines the communication topology graph of the system of agents
- Key result from literature: If the graph has a spanning tree then for all $i$ $\xi_i \rightarrow \xi^*$
Example: Single Consensus Variable

\[
\begin{pmatrix}
\xi_1 \\
\xi_2 \\
\xi_3 \\
\xi_4 \\
\xi_5 \\
\xi_6 \\
\xi_7 \\
\xi_8 \\
\xi_9
\end{pmatrix}
= 
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\kappa_21 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\kappa_32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\kappa_43 & -\kappa_45 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\kappa_56 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\kappa_67 & -\kappa_68 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\kappa_71 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\kappa_87 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\kappa_91 & -\kappa_98 & 0
\end{pmatrix}
\begin{pmatrix}
\xi_1 \\
\xi_2 \\
\xi_3 \\
\xi_4 \\
\xi_5 \\
\xi_6 \\
\xi_7 \\
\xi_8 \\
\xi_9
\end{pmatrix}
\]
Example 2: Spatially locate group of resources (green) to optimally cover a group of targets (targets).

Targets and resources have some assumed strength and capability, respectively.
• Corresponding node equations become:

\[
\gamma \frac{dq_i^R(t)}{dt} = - \sum_{j=1}^{N_T} (q_i^R - q_j^T)
\]

\[
- \sum_{j=1}^{N_R} g(\|q_i^R - q_j^R\| - (p_i + p_j))(q_i^R - q_j^R)
\]

\[
- \sum_{j=1}^{N_T} h(\|q_i^R - q_j^T\| - (p_i + s_j))
\]

• where \( h(v, k) = \begin{cases} 
  v & \|v\| - k > 0 \\
  0 & \|v\| - k \leq 0 
\end{cases} \)
DSN Application

4 targets, 2 resources

4 targets, 1 resource

6 targets, 2 resources

5 targets, 6 resources
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Preliminary Test Flights at ARL-Aberdeen
Waypoint Tracking and “Pinging”
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Concluding Comments

- We have presented the idea of dynamic surveillance networks
  - Special case of a more general notion of resource networks
- We discussed a specific DSN concept: data exfiltration from UGS using UAVs and presented our hardware and architecture
- We presented an algorithmic approach to coordination for the data exfiltration problem
  - Based on the idea of consensus variables
  - We have discussed extensions of these ideas to the problem of global optimization via cooperating distributed entities
- These ideas are being applied to our dynamic surveillance network project
  - Preliminary results showed the ability to fly autonomously using our autonomy flight board and to successfully communicate between UAVs and ground nodes