Cooperative UAVs for Remote Data Collection and Relay

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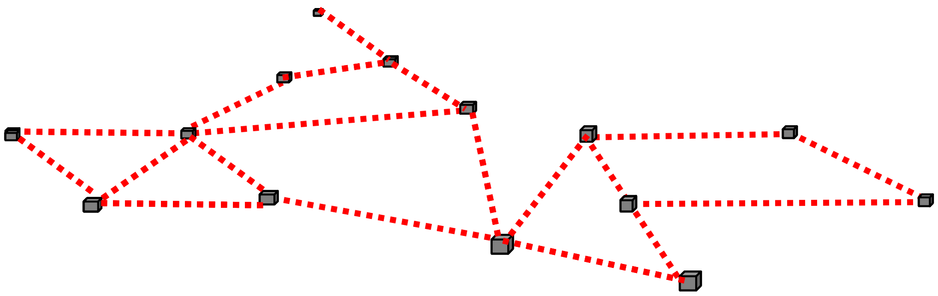
Outline

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

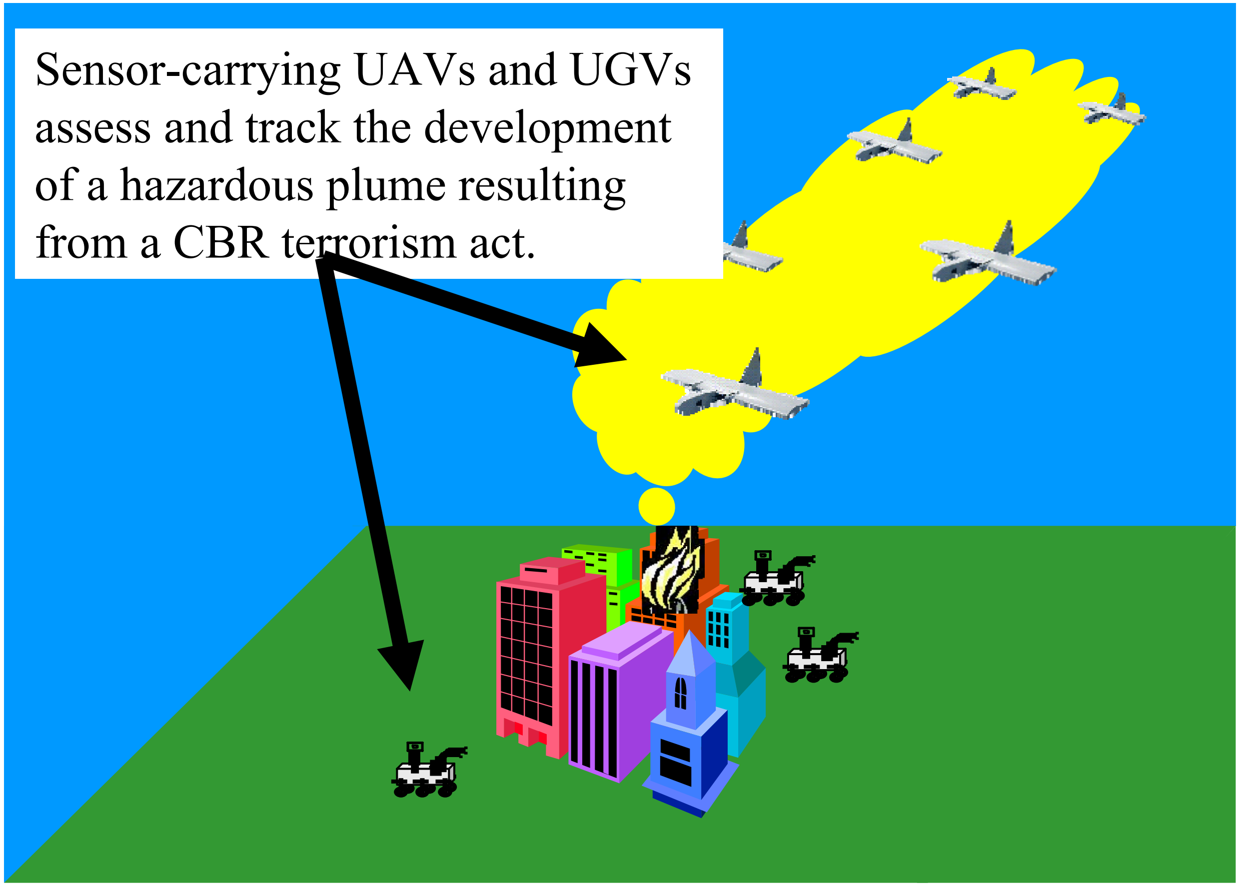
Dynamic Surveillance Networks

- 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



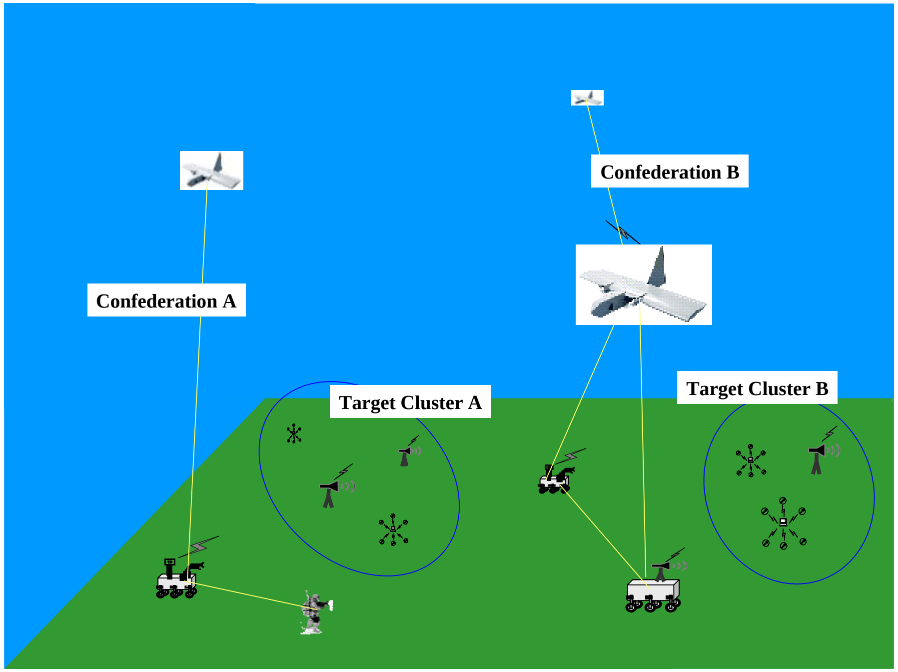
Motivating Example 1

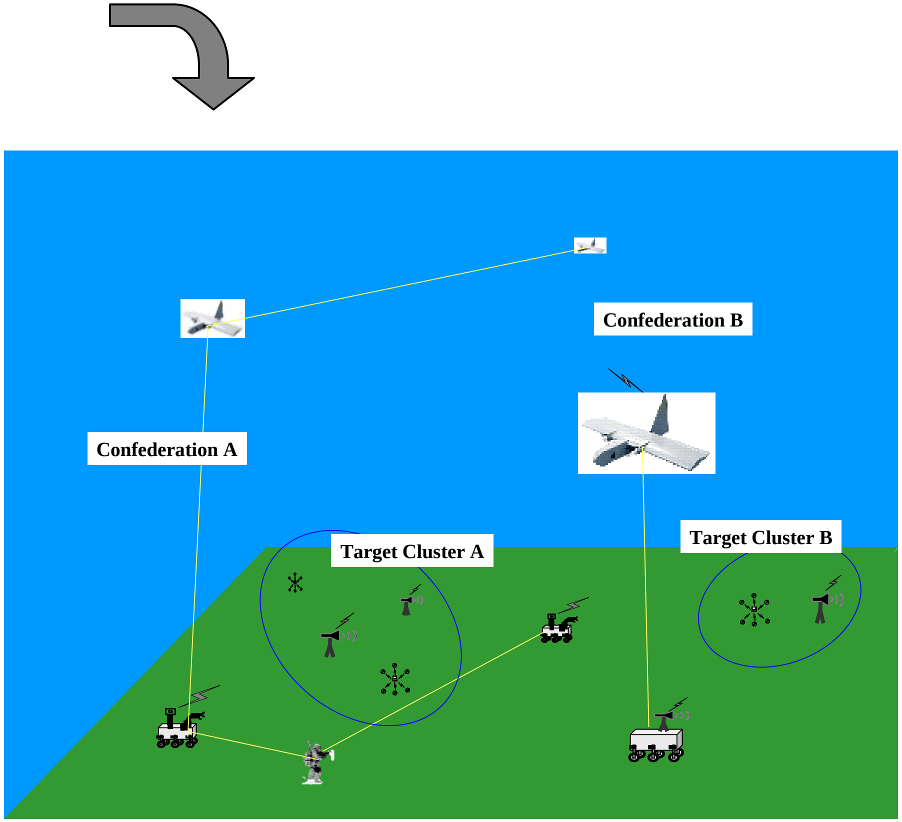
- Autonomous swarm for plume tracking



Motivating Example 2

- Autonomous confederation building, adaptive to changes in battlefield conditions





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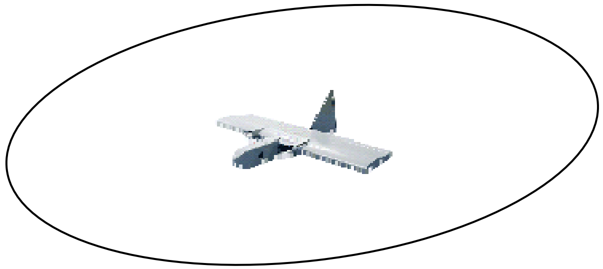
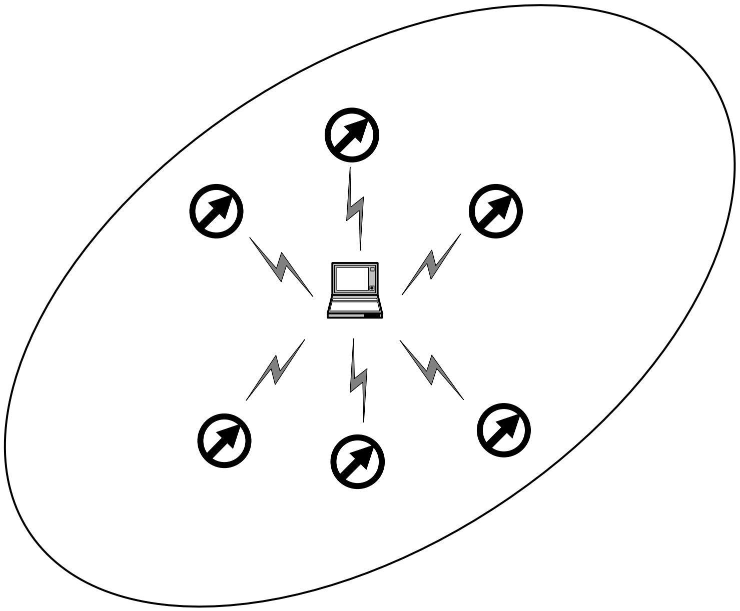
DSN Data Exfiltration Project

- **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

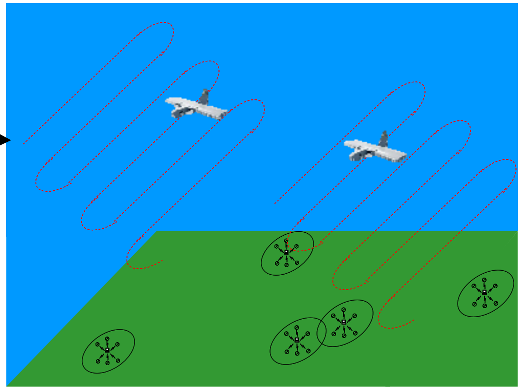




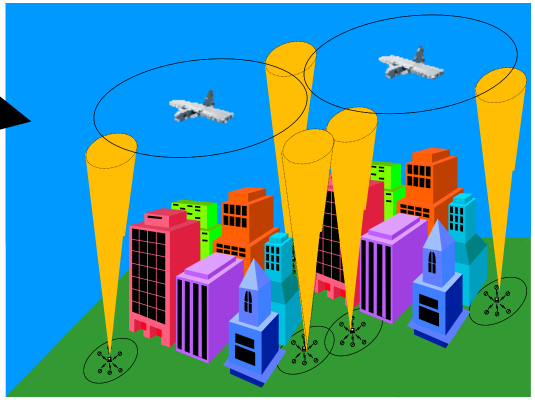
DSN Data Exfiltration Project

- **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



DSN Data Exfiltration Project

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- **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 senor clusters; when this happens the remaining UAV automatically re-plans its operations
  - If a sensor cluster is lost the UAVs cooperatively reconfigure

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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

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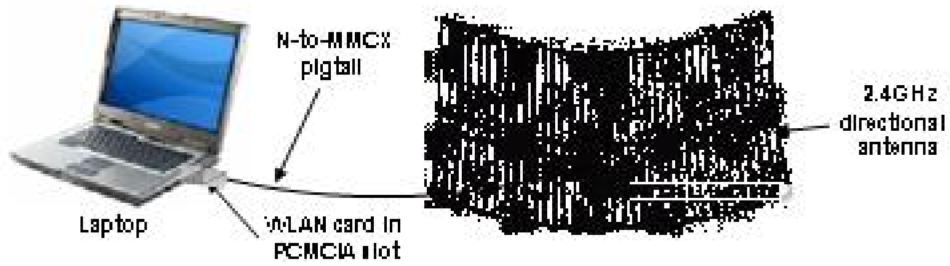
- Simulated sensor – laptop with directional antenna



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

- Vehicles – TransAtlantic Model (TAM) and MIG27

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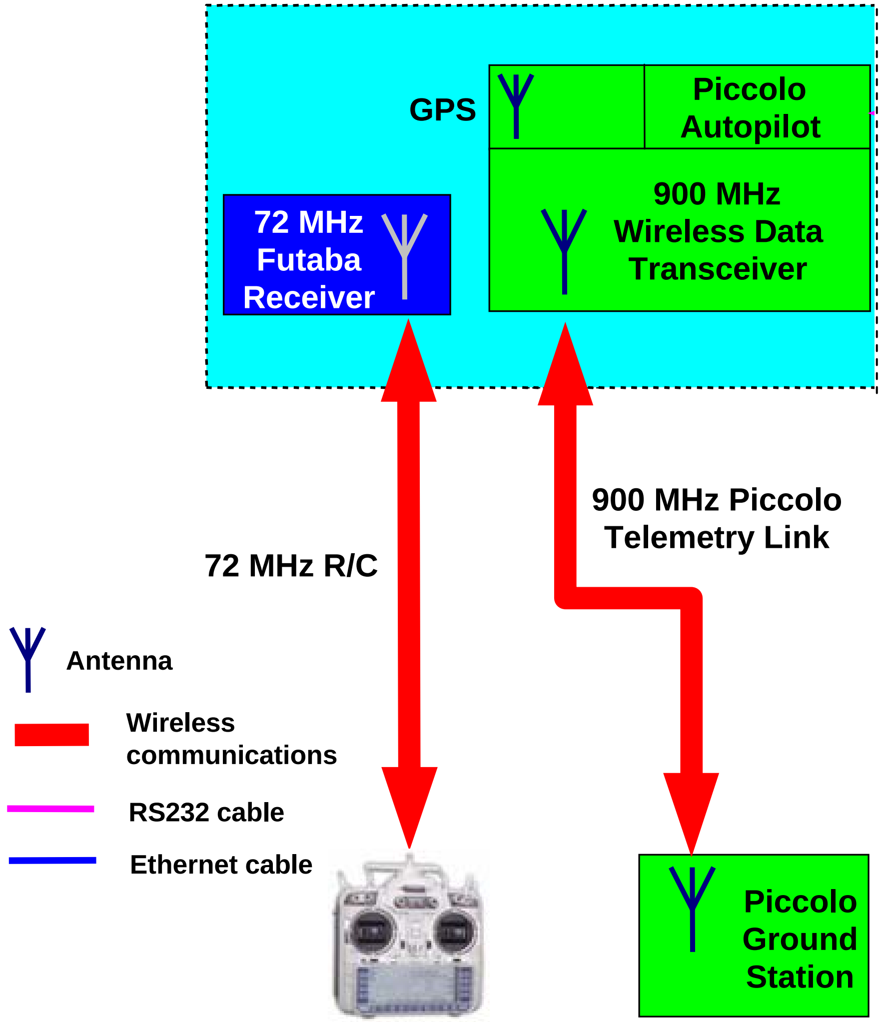
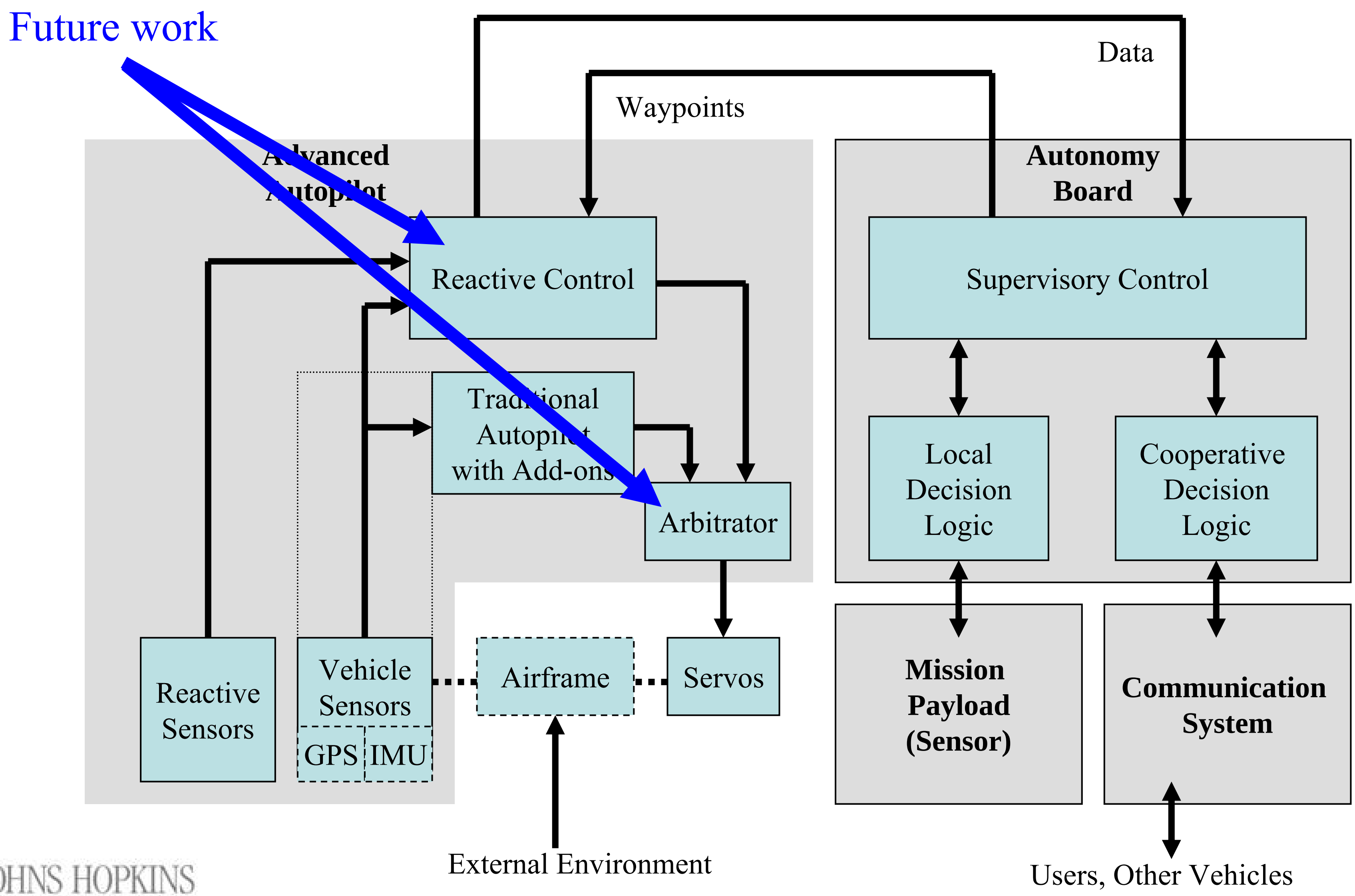
DSN Hardware/Communications Architecture



COTS UAV Setup

DSN Architecture Concept

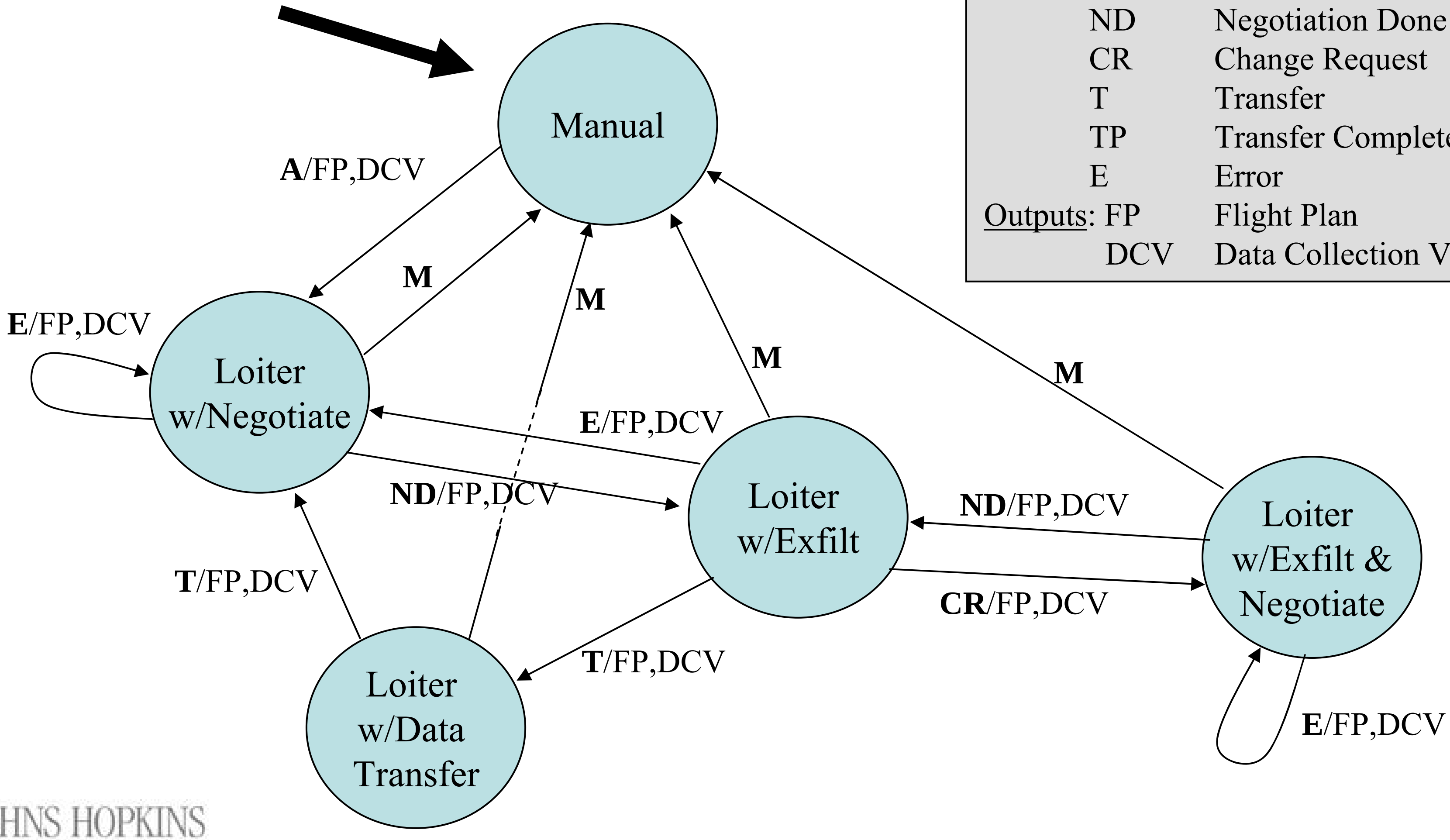


DSN Supervisor

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

Each state has its own sub-state machine



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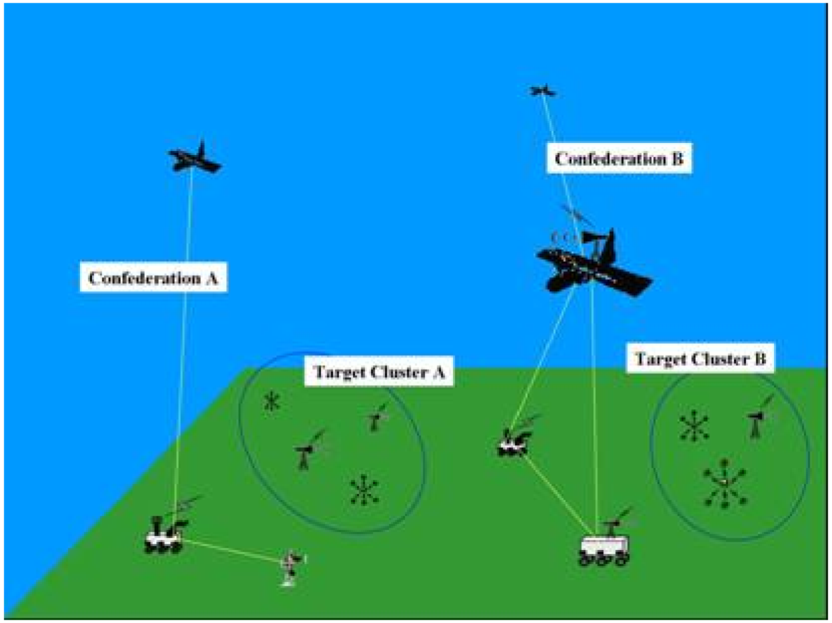
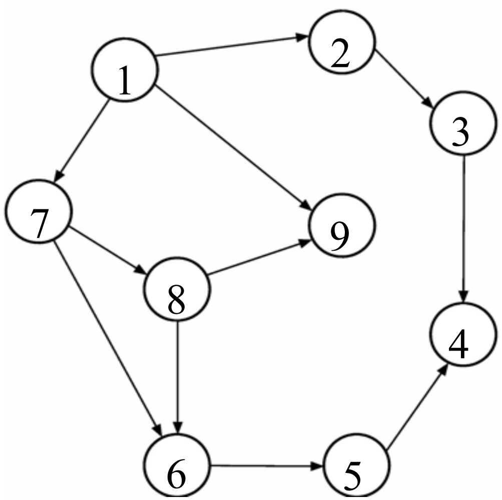
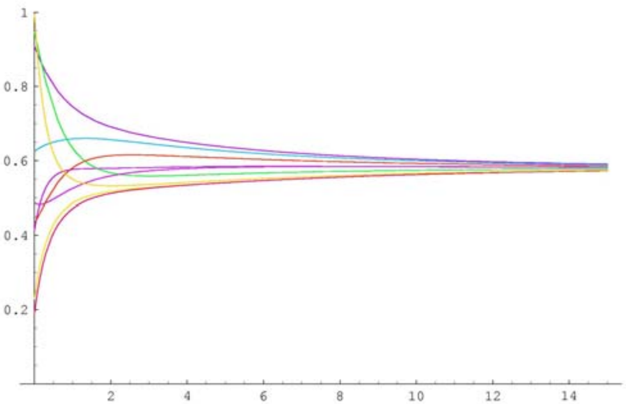
DSN Algorithmic Approach

- 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

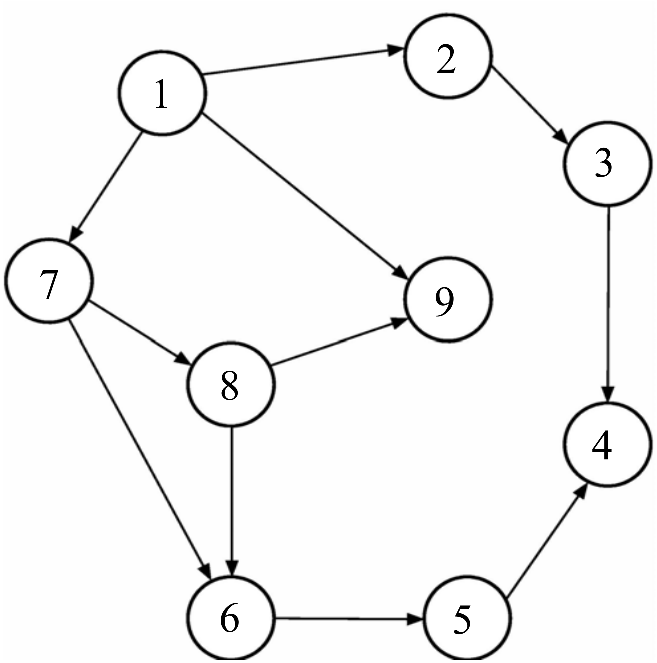
- Suppose we have *N* agents with a shared *global* consensus variable ξ
- Each agent has a *local* value of the variable given as ξ_i
- Each agent updates their local value based on the values of the agents that they can communicate with

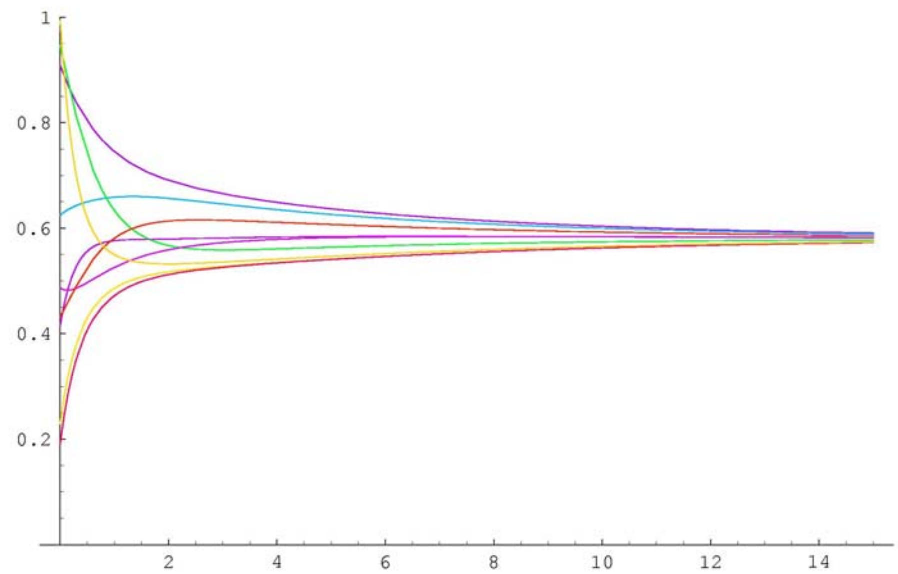
$$\dot{\xi}_i(t) = -\sum_{j=1}^{N} k_{ij}(t) G_{ij}(t)(\xi_i(t) - \xi_j(t))$$

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* $\xi_i \longrightarrow \xi^*$

Example: Single Consensus Variable

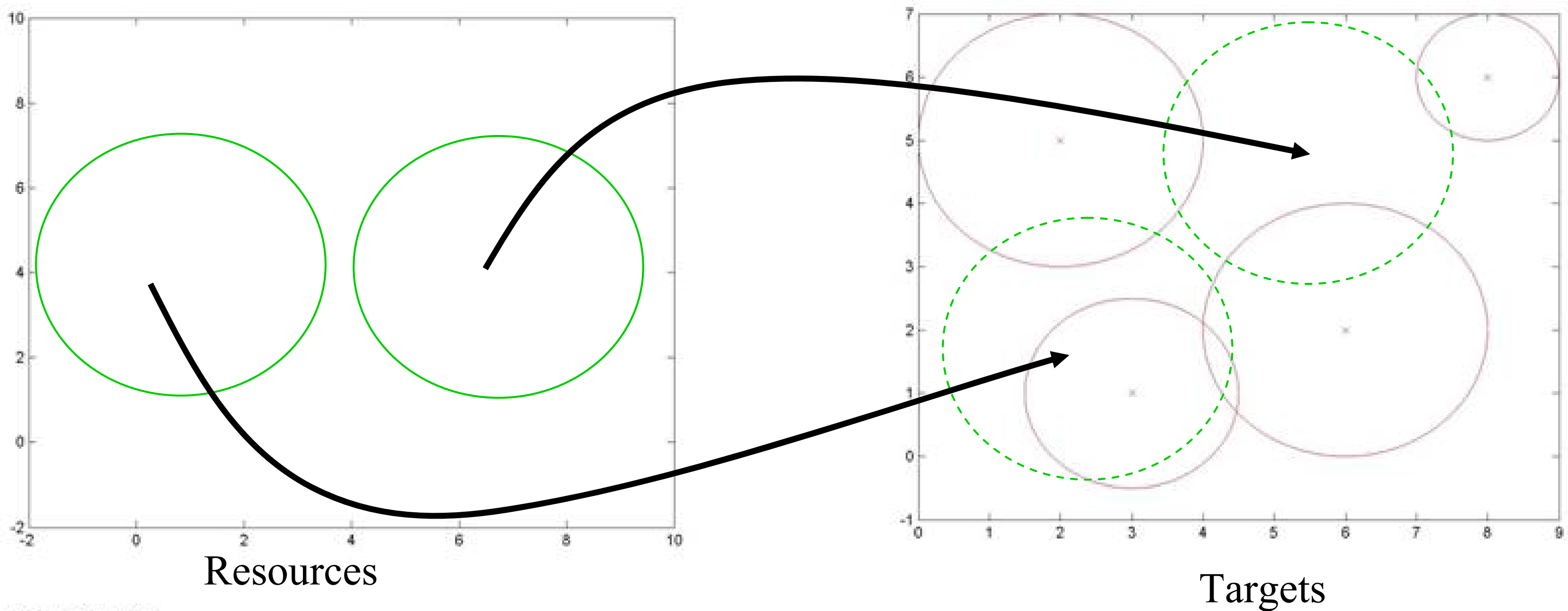




$$
\begin{pmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{\xi}_3 \\ \dot{\xi}_4 \\ \dot{\xi}_5 \\ \dot{\xi}_6 \\ \dot{\xi}_7 \\ \dot{\xi}_8 \\ \dot{\xi}_9 \end{pmatrix}
=
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
k_{21} & -k_{21} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & k_{32} & -k_{32} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & k_{43} & -k_{43}-k_{45} & k_{54} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -k_{56} & k_{56} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -k_{67}-k_{68} & k_{67} & k_{68} & 0 \\
k_{71} & 0 & 0 & 0 & 0 & 0 & -k_{71} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & k_{87} & -k_{87} & 0 \\
k_{91} & 0 & 0 & 0 & 0 & 0 & 0 & k_{98} & -k_{91}-k_{98}
\end{bmatrix}
\begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \\ \xi_5 \\ \xi_6 \\ \xi_7 \\ \xi_8 \\ \xi_9 \end{pmatrix}
$$

DSN Application

- **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



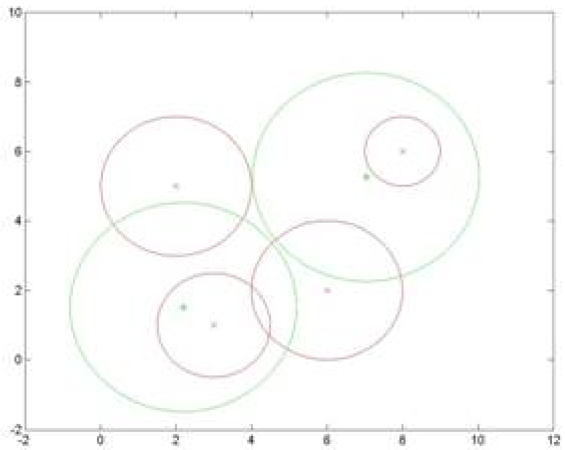
DSN Application

- Corresponding node equations become:

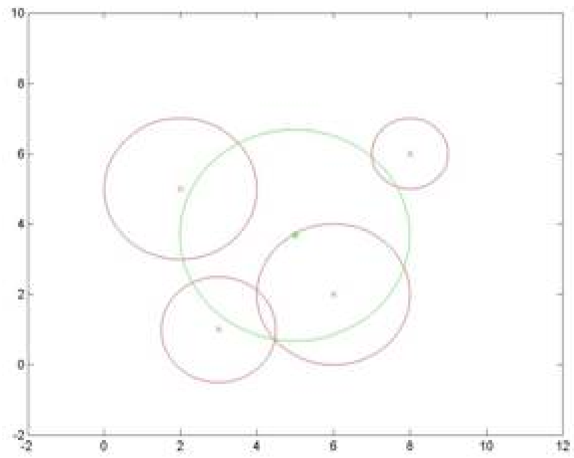
$$\gamma \frac{dq_i^R(t)}{dt} = -\sum_{j=1}^{N_T} (q_i^R - q_j^T) - \sum_{j=1}^{N_R} g(\|q_i^R - q_j^R\| - (p_i + p_j))(q_i^R - q_j^R) - \sum_{j=1}^{N_T} h(\|q_i^R - q_j^T\| - (p_i + s_j))$$

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

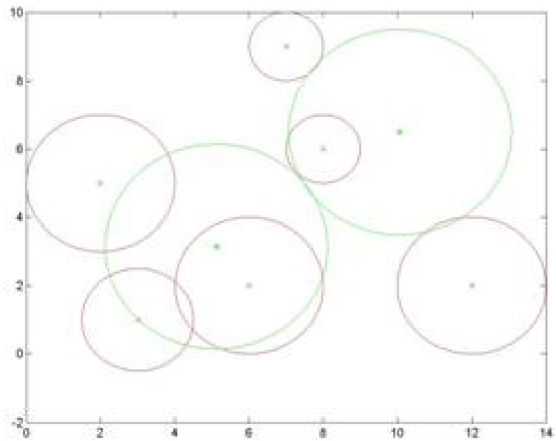
DSN Application



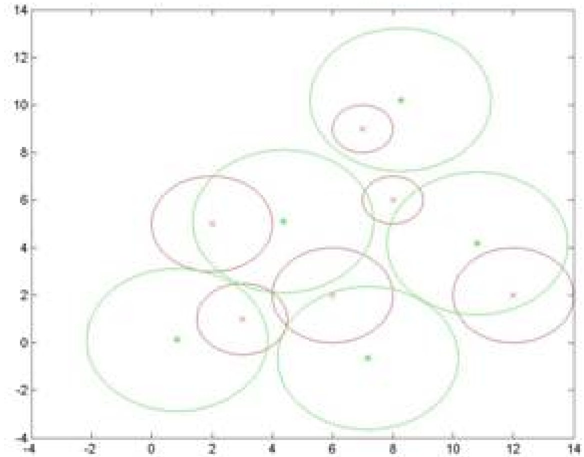
4 targets, 2 resources



4 targets, 1 resource



6 targets, 2 resources



5 targets, 6 resources

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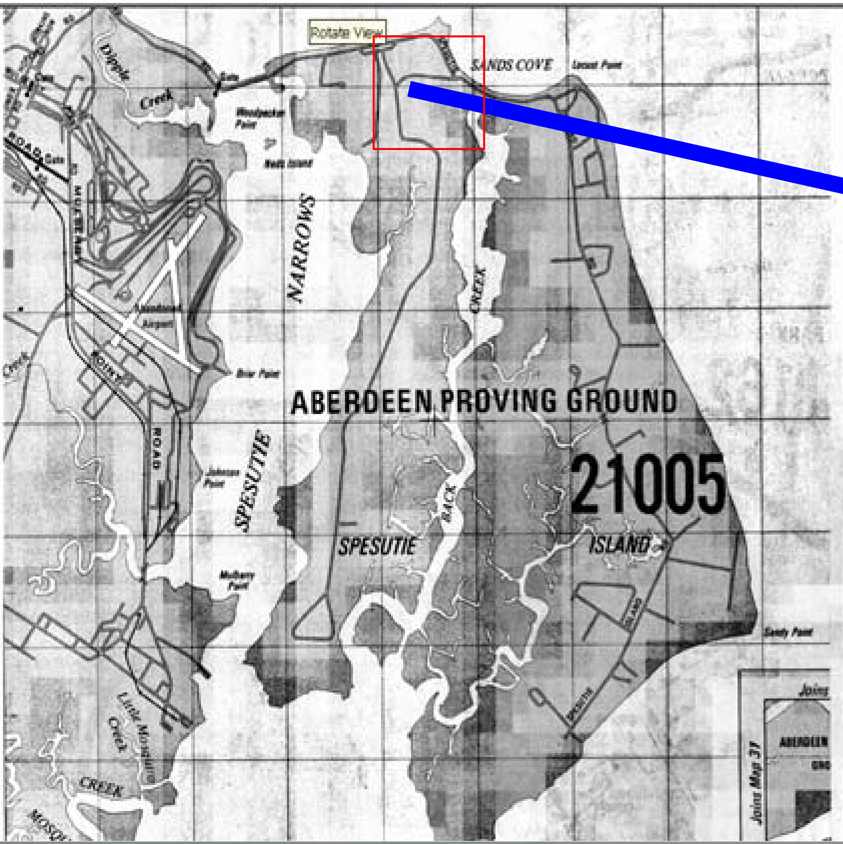
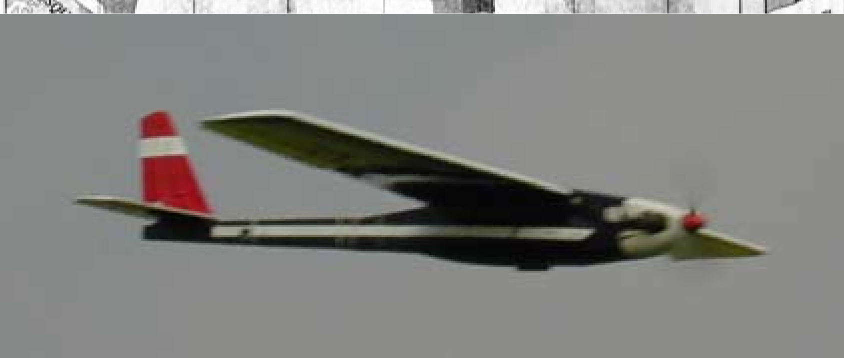
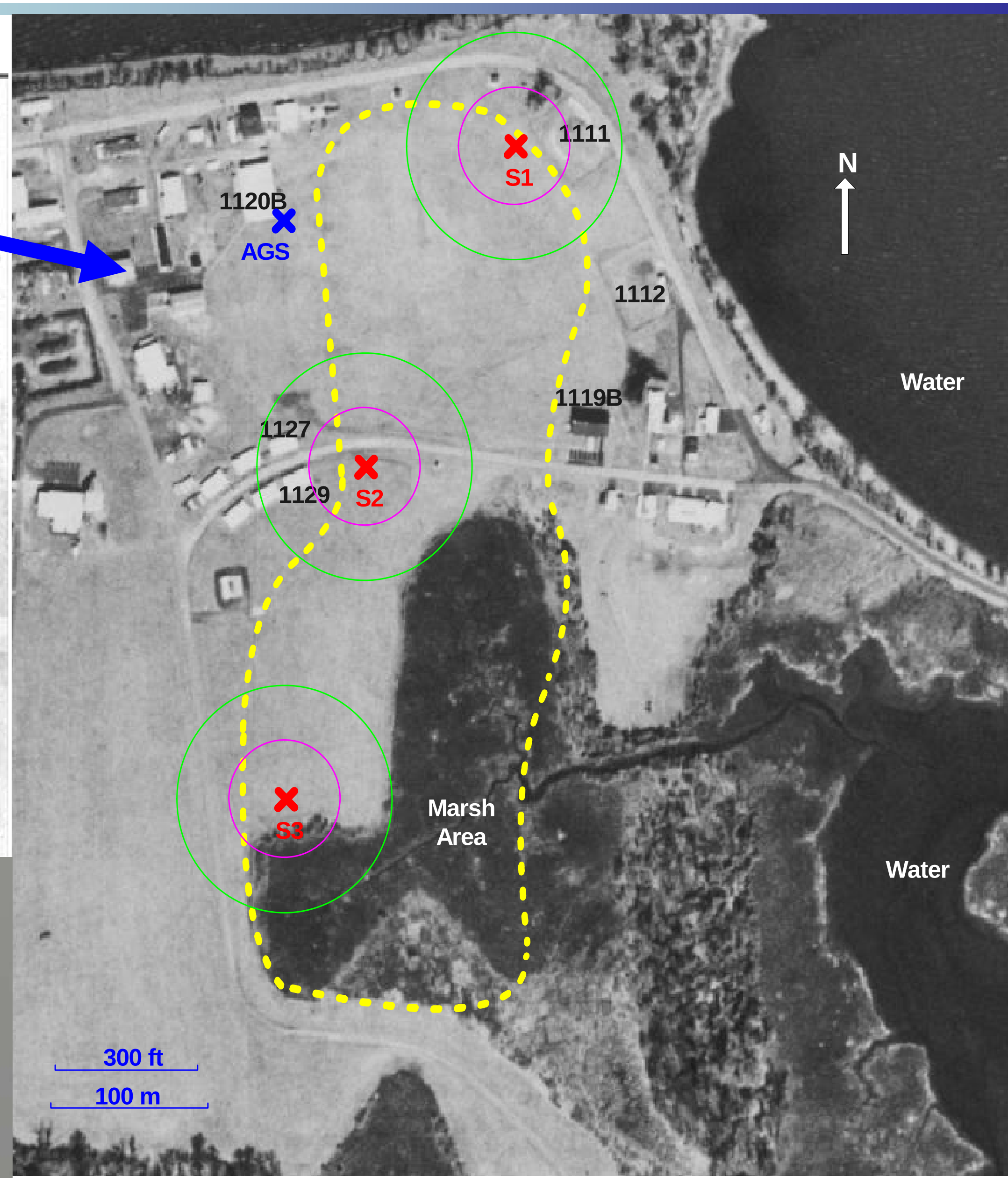
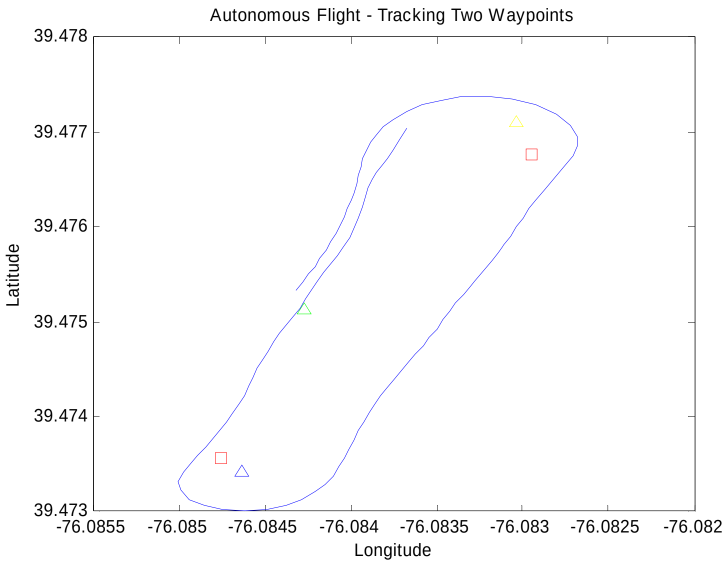
Preliminary Test Flights at ARL-Aberdeen

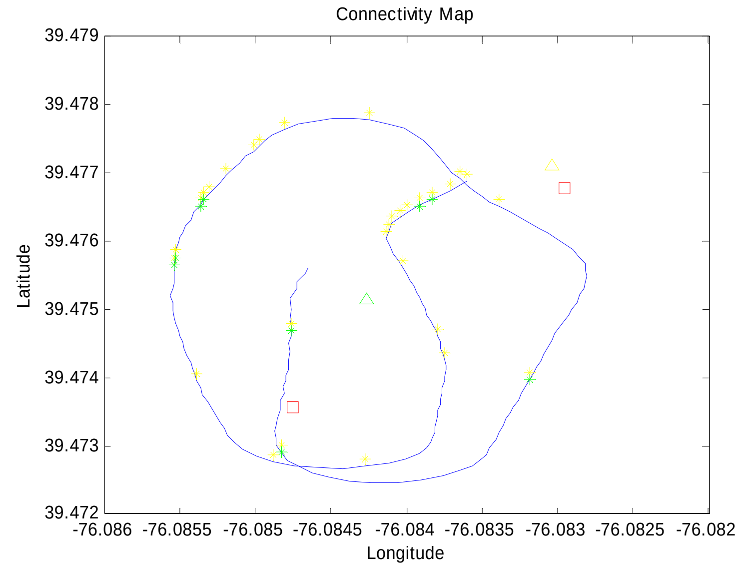


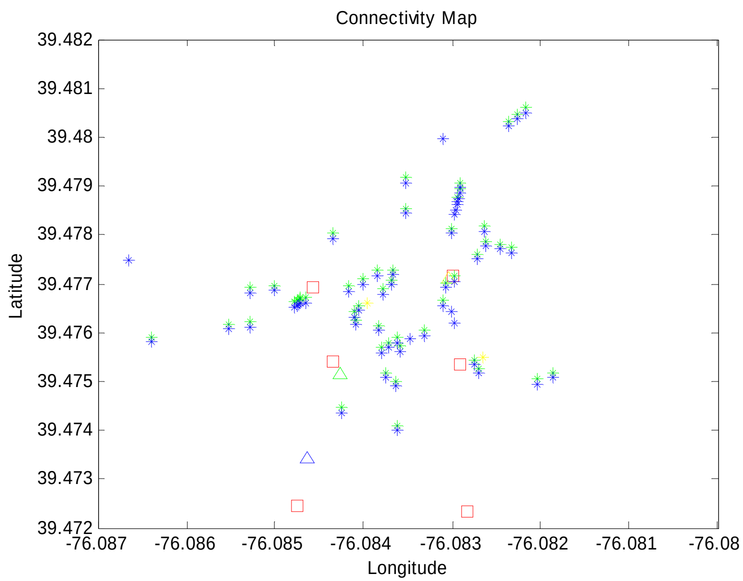




Waypoint Tracking and "Pinging"







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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