Swarm Intelligence: a New C2 Paradigm with an Application to the Control of Swarms of UAVs

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Overview

- UAVs: Definition and Examples
- Complex Systems and Swarm Intelligence
- Agent-Based Modeling
- ABM for the control of UAV Swarms
- Conclusions and future work
UAV: Definition

A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload.

Source: DoD UAV Roadmap 2002
Many Types of UAV
Predator a lethal eye in the sky

WASHINGTON (CNN) -- The Predator drone was designed to gather intelligence on enemy forces without putting U.S. pilots at risk, but it's also found a role as a deadly offensive weapon in America's war on terrorism.

The small, unmanned aircraft has a range of about 460 miles and can stay in the air for up to 24 hours. It can beam real-time video to controllers on the ground without landing.

Predators have been used as reconnaissance planes since 1995. They were equipped with Hellfire anti-tank missiles in February 2001 -- just months before the September 11 attacks and the war in Afghanistan.
UAVs in the press (2)

From Doonesbury, July 2002 - © 2002 Garry Trudeau
Controlling Multiple UAVs

Problem Statement:

- Current UAVs require \textit{at least} one operator per UAV
- Technological advances make multi-UAV missions a near-term reality

\textit{Need control strategies that allow one operator to monitor/control multiple UAVs}
UAV Swarms as Complex Systems

A system is complex when:

1. It consists of a large number of elements
2. Significant interactions exist between elements
3. System exhibits emergent behavior: cannot predict system behavior from analysis of individual elements

Traditional “reductionist” approaches cannot cope with complex systems
The Icosystem Game
The Icosystem Game

Combinatorial business chemistry

AGGRESSORS - DEFENDERS
Rule: Defender

Each agent is the protector of a victim threatened by an aggressor. The agents move to position themselves between the victim and the aggressor.

Initially, each agent chooses, at random, a victim and an aggressor within its sight.

Pick new partners  ShowHide relationships

Population : 50

Sight : 22

Simulation speed : 58

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The Bad News

- Cannot predict **emergent behavior** from individual rules, even for such a “simple” complex system

- Individual participants are **unaware of overall system behavior**

- Small changes in rules lead to **dramatically different emergent behaviors**
The Good News

• It is possible to manipulate the behavior of a complex system by changing the rules that control individual elements

• We have developed a methodology to predict emergent behavior in complex systems using bottom-up simulation

Agent-Based Modeling!
Sample Complex Systems
Controlling Emergent Behavior

- How can we control emergence?
- How do we define individual behaviors and interactions to produce desired emergent patterns?

“Here is where we think the problem is..."
Agent-based modeling

- Shift viewpoint from system (centralized) to individual elements (de-centralized)
- Each agent follows local rules
- Behavior depends on interactions with other agents
- Overall system behavior emerges from local interactions
Example: Flow Simulations

- Traditional approach: mathematical description at macroscopic level.
- Example: fire diffusion in airplane cabin
Limitations of Traditional Approaches

- Previous simulation requires extensive computation
- Any modification (e.g., number of seats, load, initial conditions) requires new computation

*Compare to agent-based approach*
Agent-based Flow Simulations

- The Game
- Boids
- Traffic
Swarm Control of UAVs
Supported by Air Force Research Labs SBIR

- Create Agent-Based Model of UAV swarm
- Test various swarm control strategies for two mission types:
  - Search (area coverage)
  - Search, track and hit targets (SEAD)
- Measure performance systematically under various scenarios and conditions
The UAV Agent-Based Model

- Rectangular search area
- 3-D motion: thrust, pitch, yaw control
- GPS for localization
- Probabilistic ground/target sensor
- Circular collision sensor
- Pheromone emitter & probabilistic sensor
- Communications (noisy) to central control
- Stationary or moving targets
Simulation: Area Coverage/Search

Parameter Settings Panel

3-D View Panel

Area Coverage Grid
Navigation Strategies

- **Baseline**: fly straight until border is detected, turn to stay within search area
- **Random**: inject small “jitter” in heading
- **Repulsion**: avoid UAVs within radius $r$
- **Pheromone**: avoid areas already covered (by self or others)
- **Global Search**: favor navigation toward unexplored sectors

*(Strategies can be combined arbitrarily)*
Sample Coverage Patterns

Repulsion ($r=60$)

Pheromone
Systematic Evaluation

Goal: Understand impact of strategies, parameter choices and scenarios:
• 2000x2000 area, single UAV entry point
• 1000-sec simulation
• Swarm size (1-10, 10-110)
• Navigation strategies (individual & combo)

Metrics:
• Area coverage
• Swarm coverage efficiency
• Per-UAV coverage efficiency
Baseline Strategy

Per-UAV Efficiency of Swarm Strategies

Coverage per UAV

UAVs

Coverage

Base
Random Noise Strategy

Effect of random jitter is largely independent of swarm size
Pheromone Strategy

- Inspired by insect behavior
- Example of *stigmergy* (communication through the environment)
- Each UAV lays “pheromone”
- Each UAV can sense local pheromone trace
- Navigation favors uncovered areas (*Urea Strategy?*)
Pheromone strategy results

Efficiency of Swarm Strategies

Per-UAV Efficiency of Swarm Strategies

Pheromone strategy is more effective for larger swarms

Coverage per UAV

UAVs
Combining Strategies

Even a relatively simple, decentralized strategy can yield significant improvement in swarm efficiency!
Extending to Large Swarms

Swarm coverage efficiency

Coverage

UAVs

0.0%
5.0%
10.0%
15.0%
20.0%
25.0%
30.0%
35.0%

10 30 50 70 90 110
Additional Results: SEAD

- Allow targets to move randomly over search area
- Extend UAV behavior to track targets
- Modify simulator to carry out search and suppress missions
- Apply evolutionary computing to identify robust strategies, parameters
Sample SEAD Results

Cumulative Hit Probability

% Targets Hit

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

4 8 16 32

UAVs

4 Targets
8 Targets
16 Targets

4 Targets
8 Targets
16 Targets
Future Work

- Systematic evaluation of other mission types, criteria, performance metrics
- Evolutionary design of control strategies
- Human-in-the-loop control
- Extend approach to *Unmanned Ground Vehicles* operating in urban scenario
- Commercialize these and other results