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

Controlling Multiple UAVs

Problem Statement:

- Current UAVs require *at least* one operator per UAV
- Technological advances make multi-UAV missions a near-term reality

Need control strategies that allow one operator to monitor/control multiple UAVs

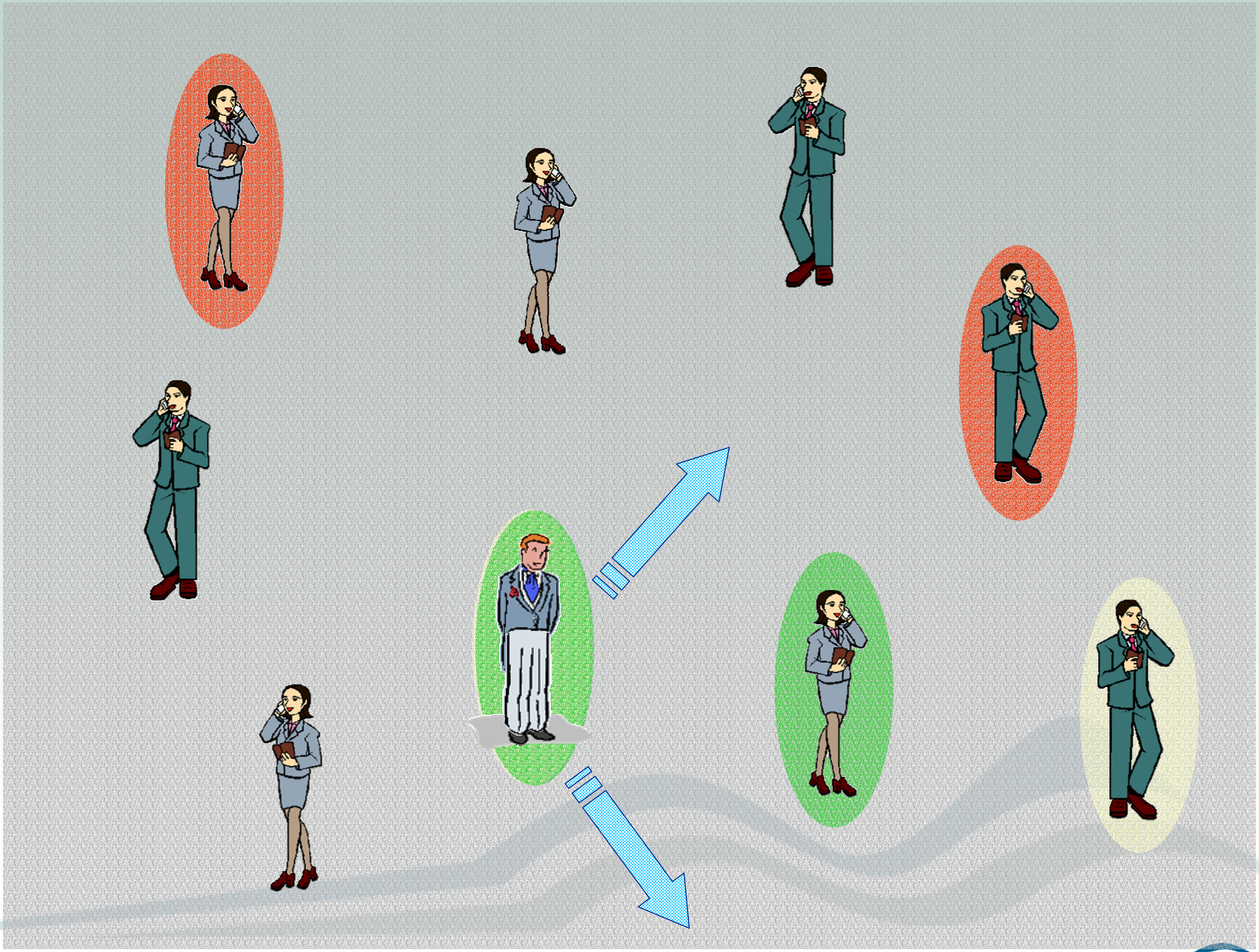
UAV Swarms as Complex Systems

A system is *complex* when:

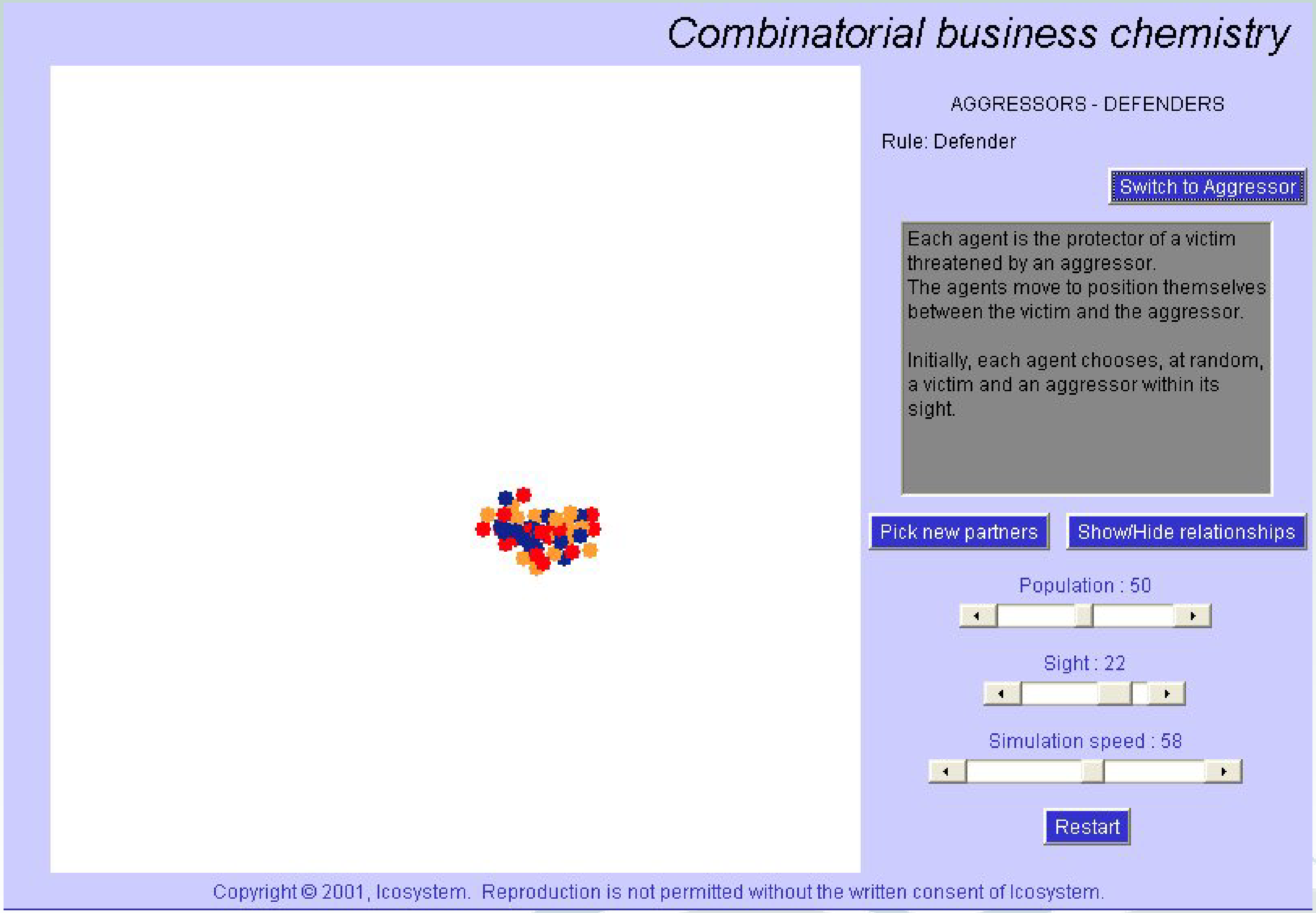
1. It consists of a large number of elements
2. Significant interactions exist between elements
3. System exhibits *emergent behavior*: cannot predict system behavior from analysis of individual elements

Traditional "reductionist" approaches cannot cope with complex systems

The Icosystem Game



The Icosystem Game



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*

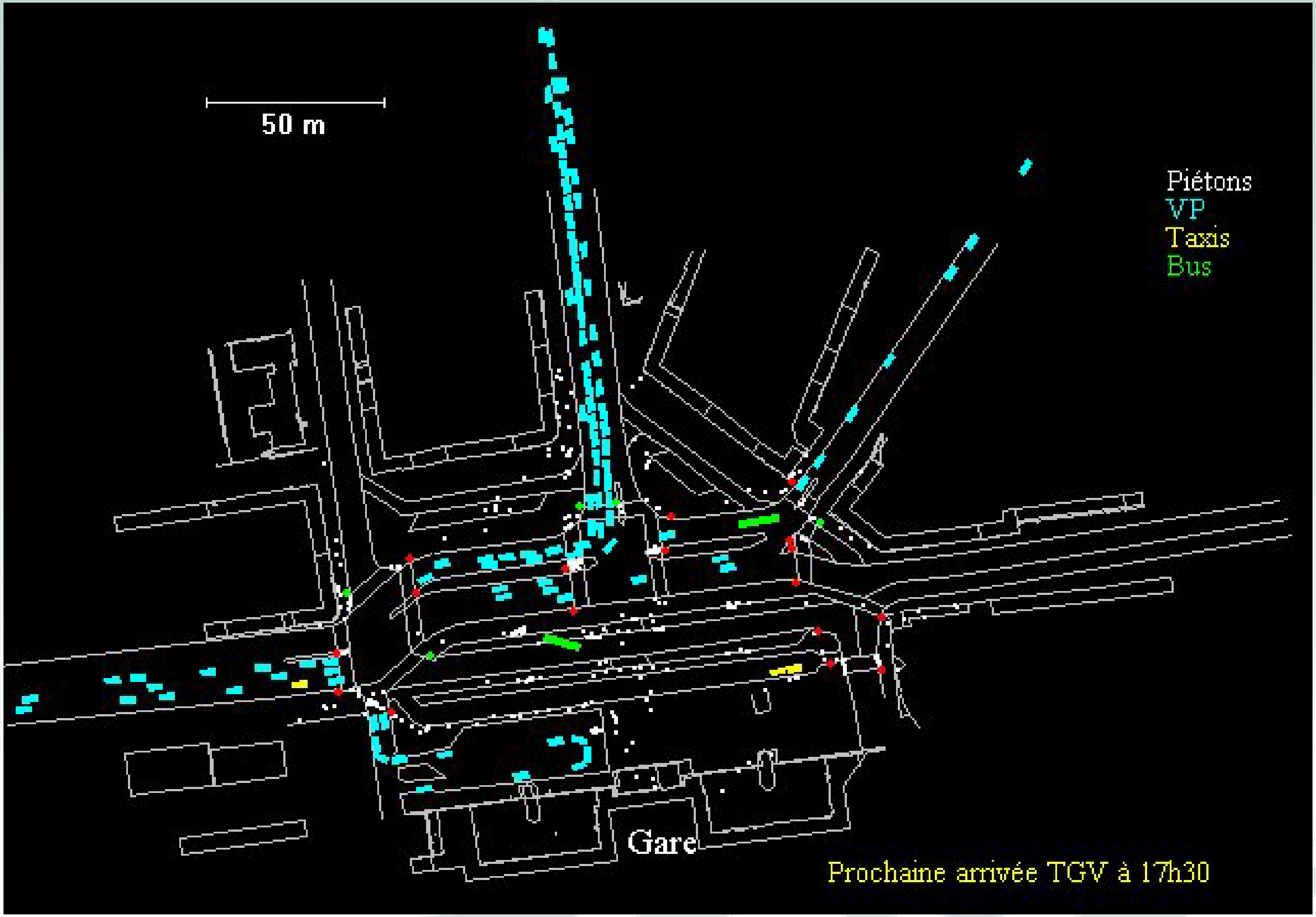
The Good News

- 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

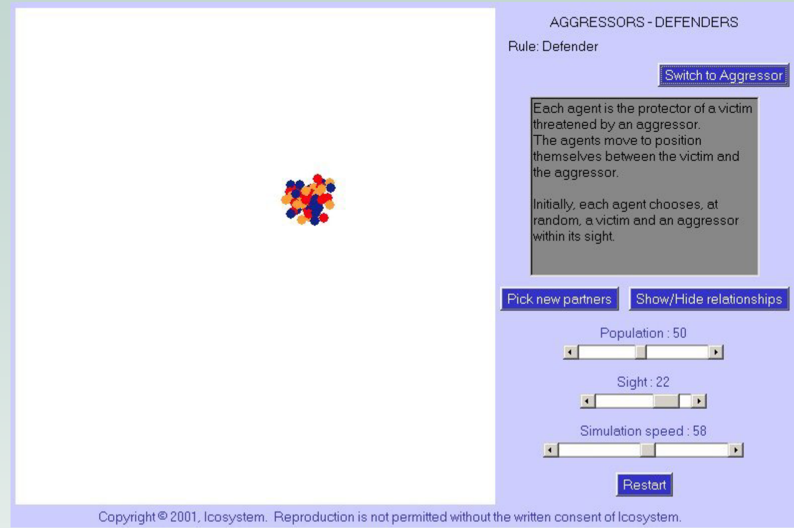
Limitations of Traditional Approaches

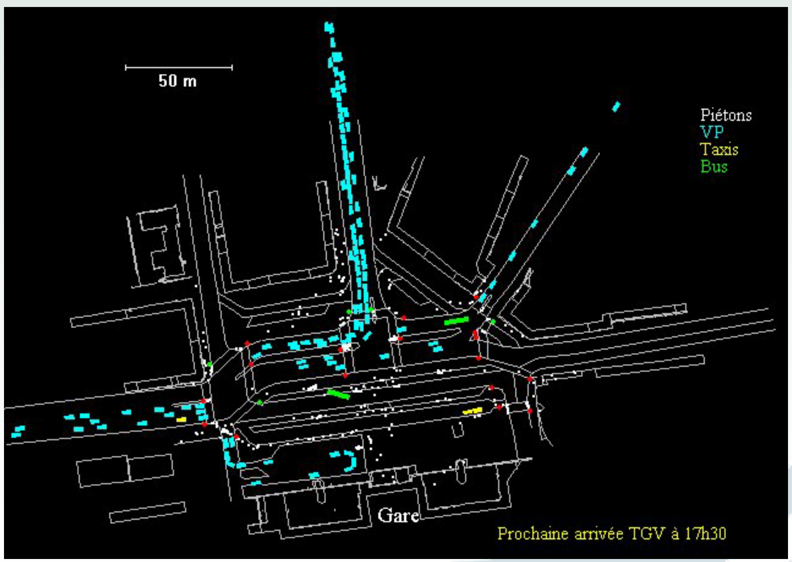
- Previous simulation requires extensive computation
- Any modification (e.g., number of seats, load, initial conditions) requires new computation

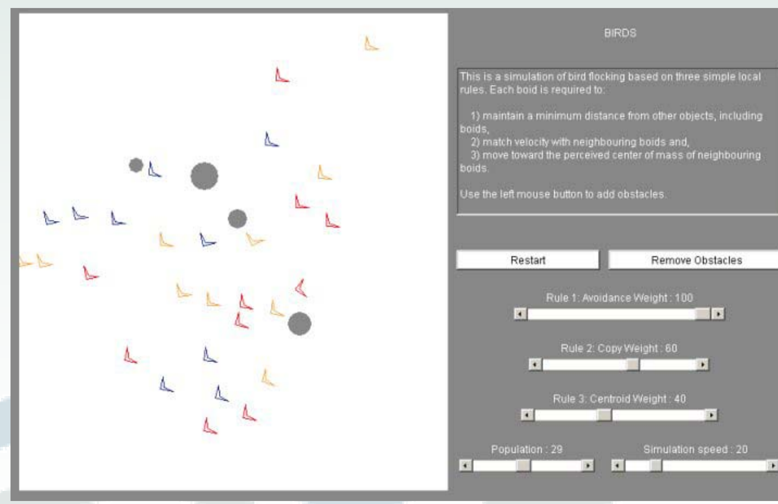
Compare to agent-based approach

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

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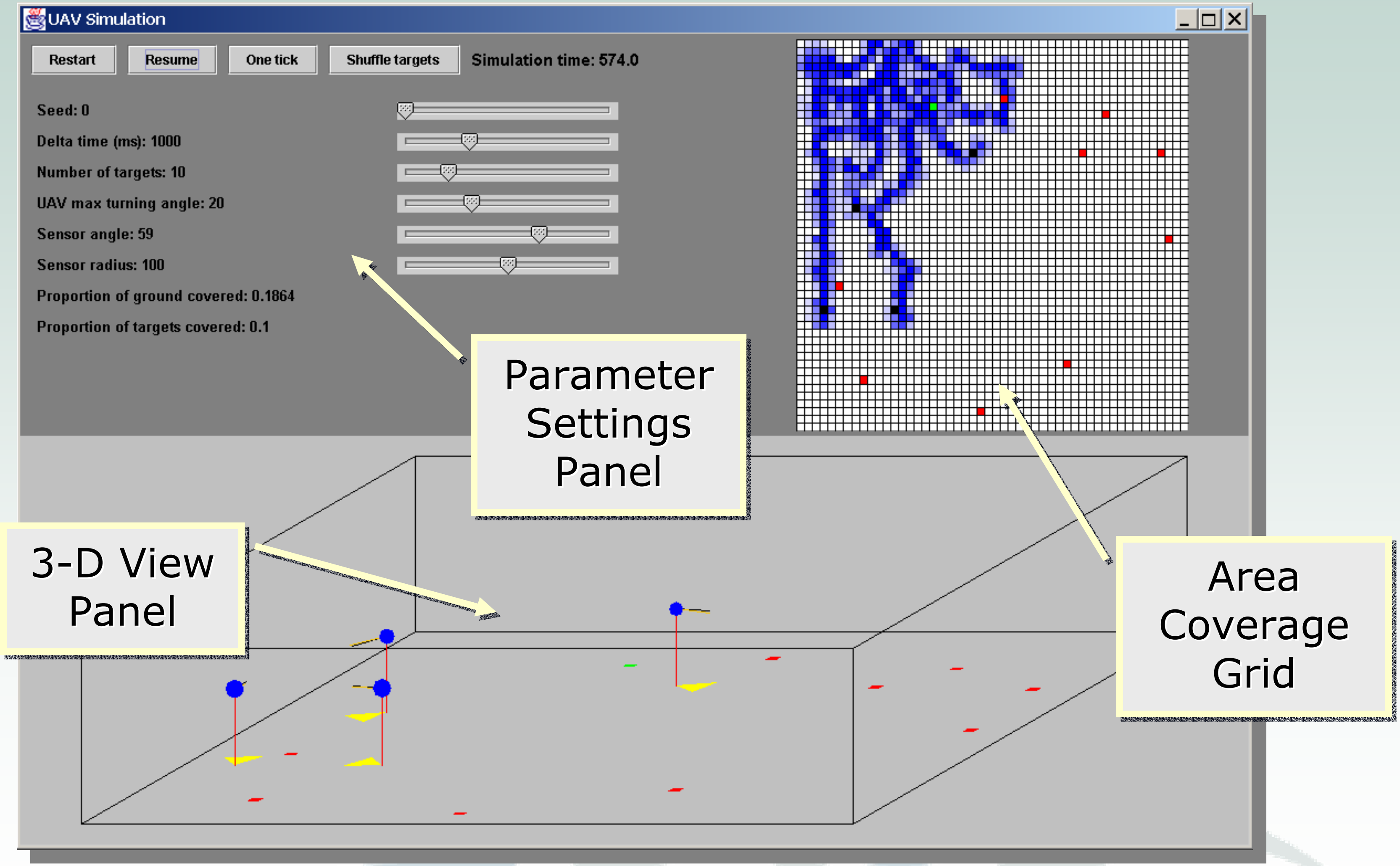
The UAV Agent-Based Model

- 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

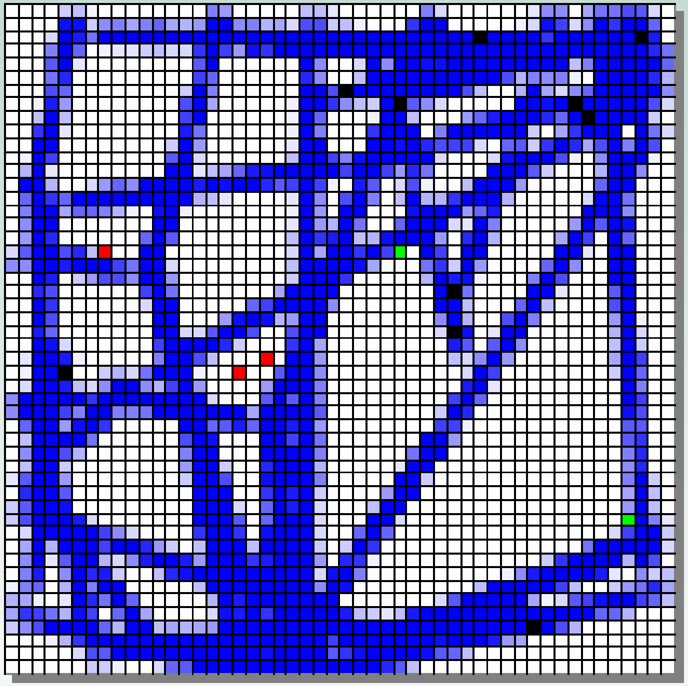


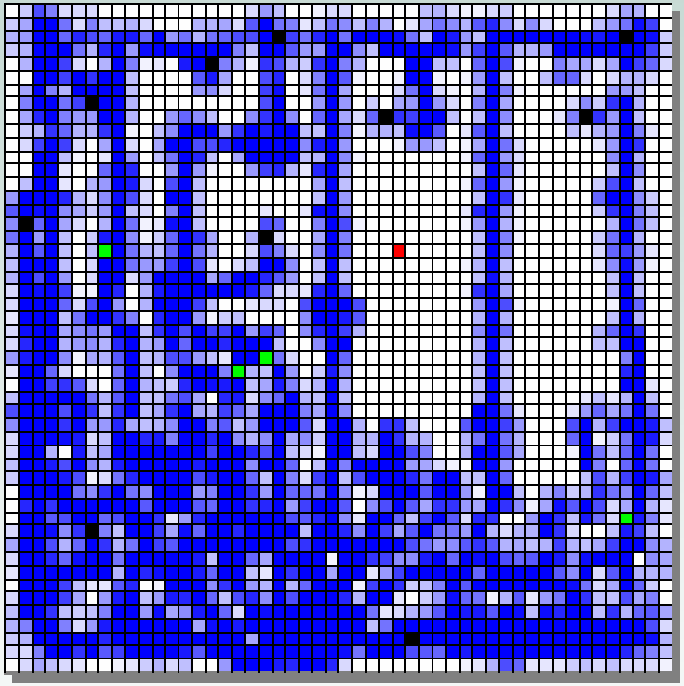
Navigation Strategies

- *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

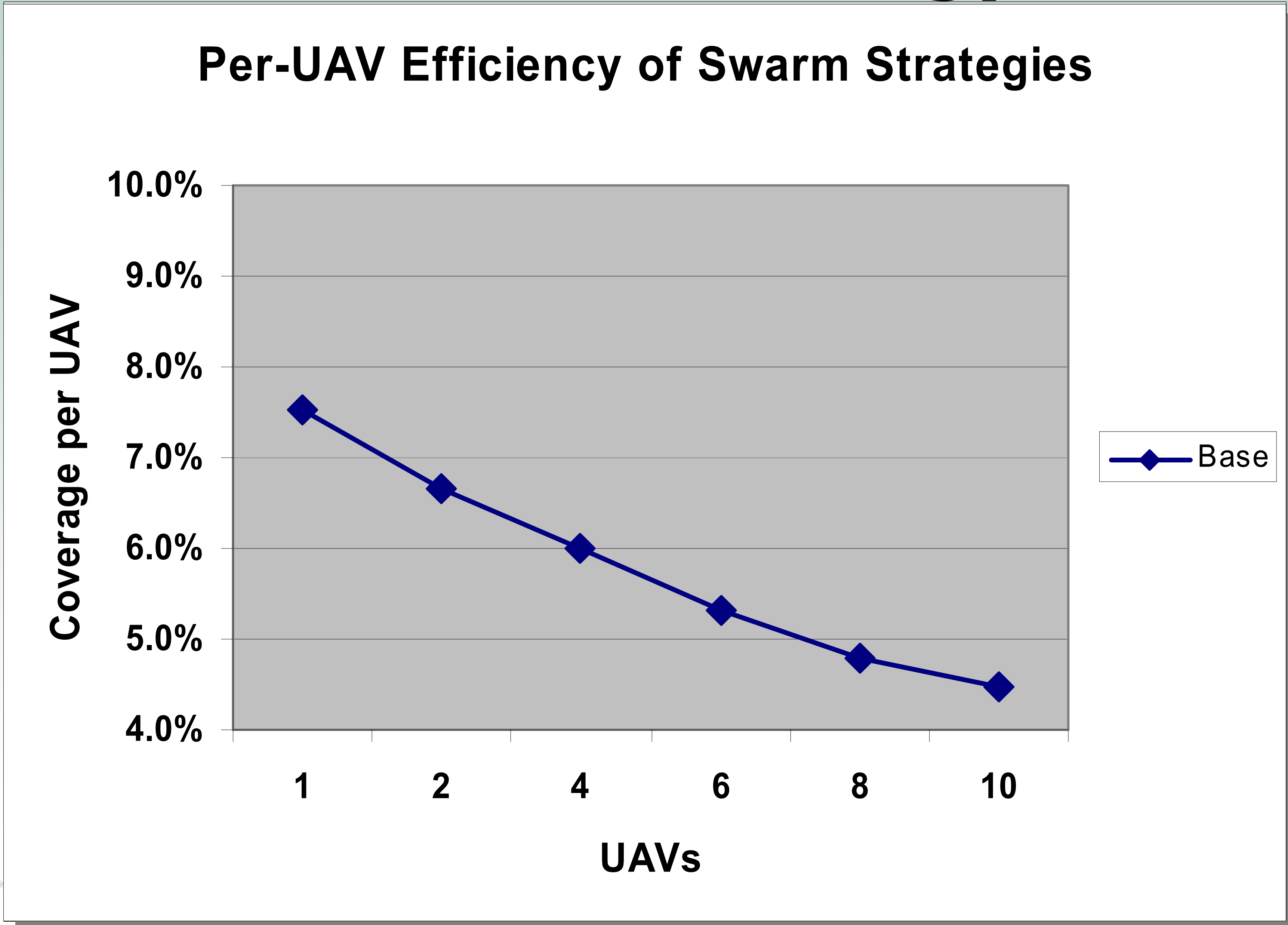
Goal: Understand impact of strategies, parameter choices and scenarios:

- 2000x2000 area, single UAV entry point
- 1000-sec simulation
- Swarm size (1-10, 10-110)
- Navigation strategies (individual & combo)

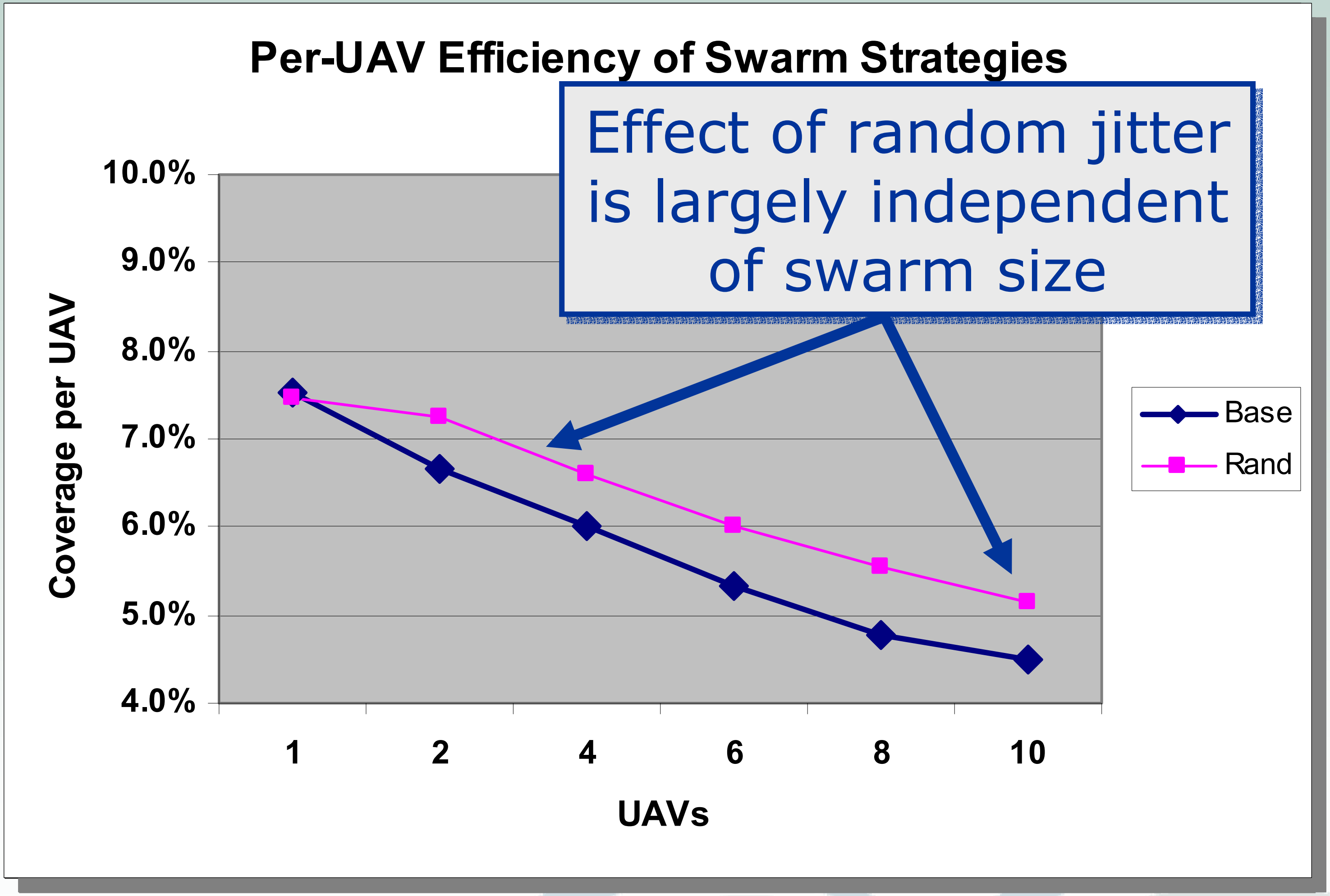
Metrics:

- Area coverage
- Swarm coverage efficiency
- Per-UAV coverage efficiency

Baseline Strategy

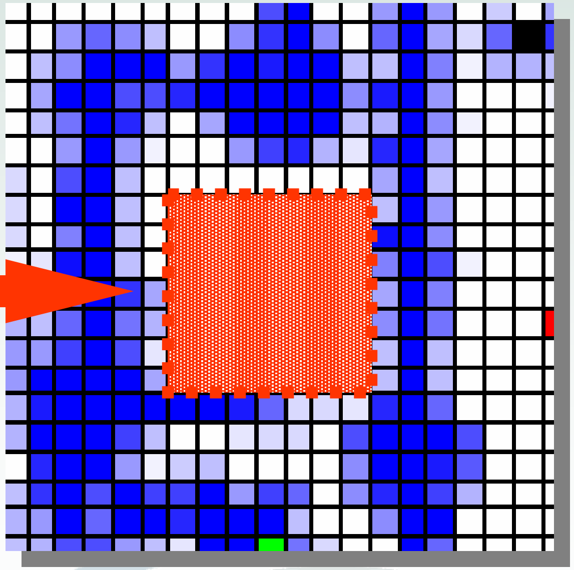


Random Noise Strategy

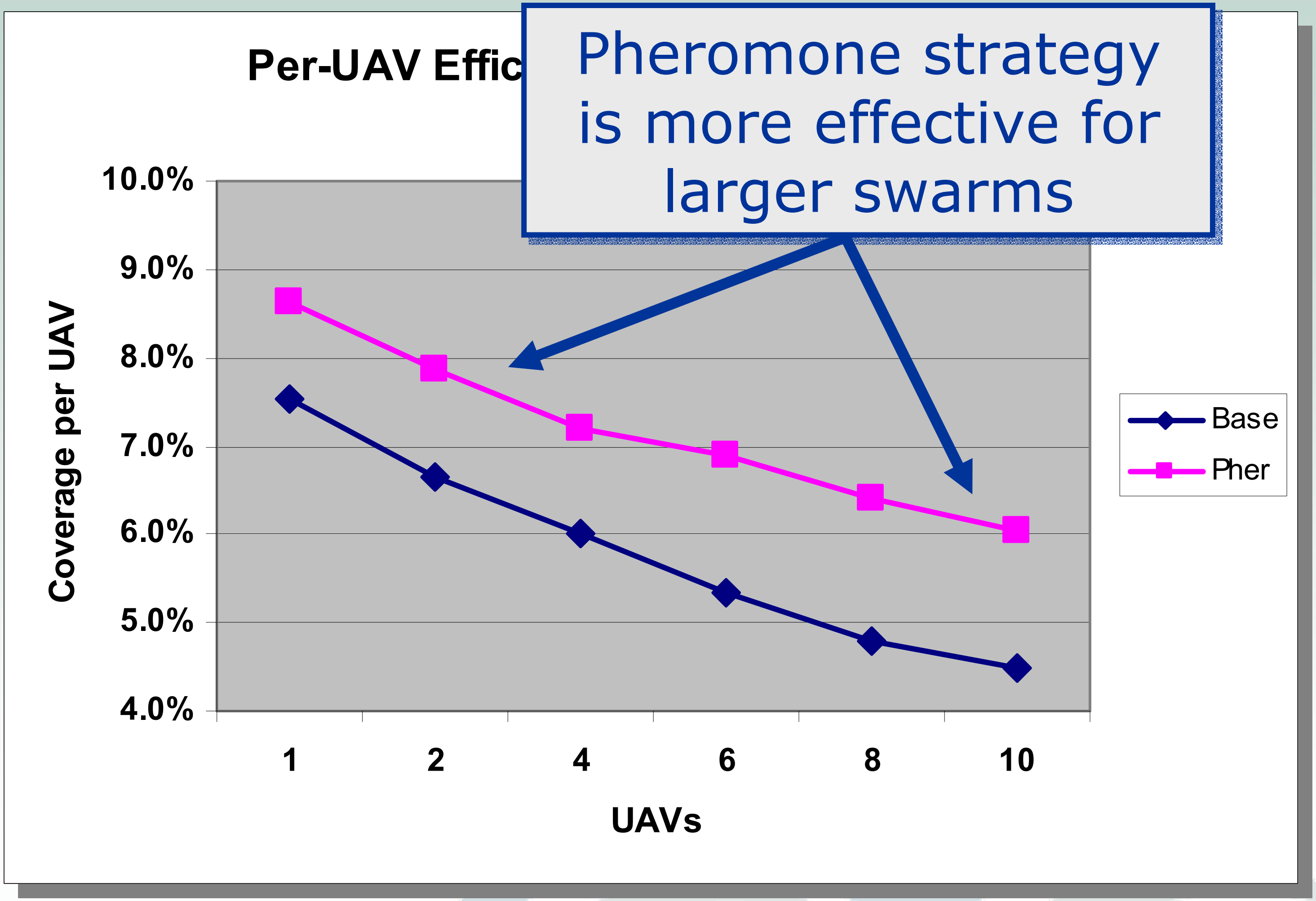


Pheromone Strategy

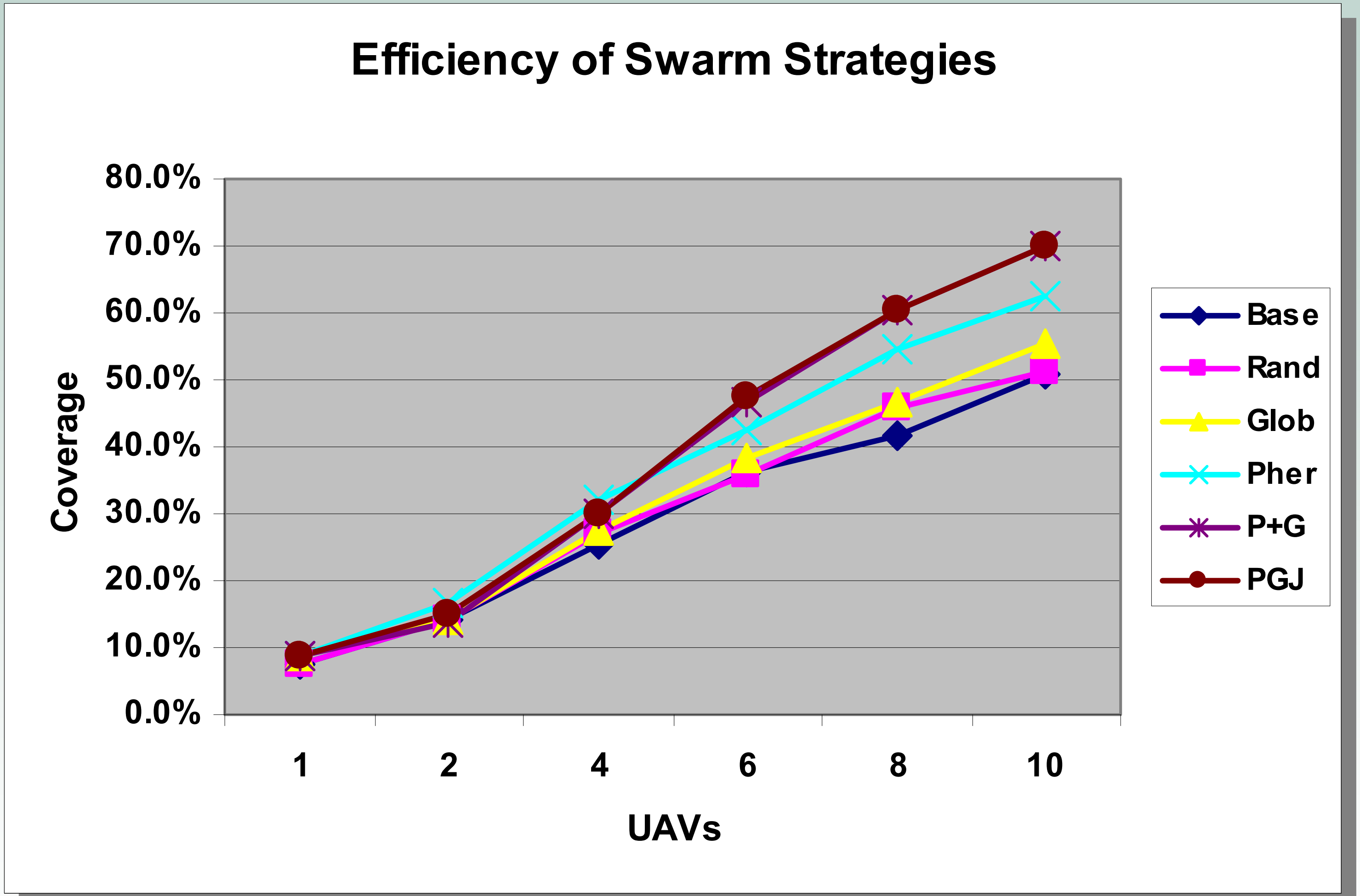
- Inspired by insect behavior
- Example of *stigmergy* (communication through the environment)
- Each UAV lays “pheromone”
- Each UAV can sense local pheromone trace
- Navigation favors uncovered areas **(*Urea* Strategy?)**



Pheromone Strategy Results

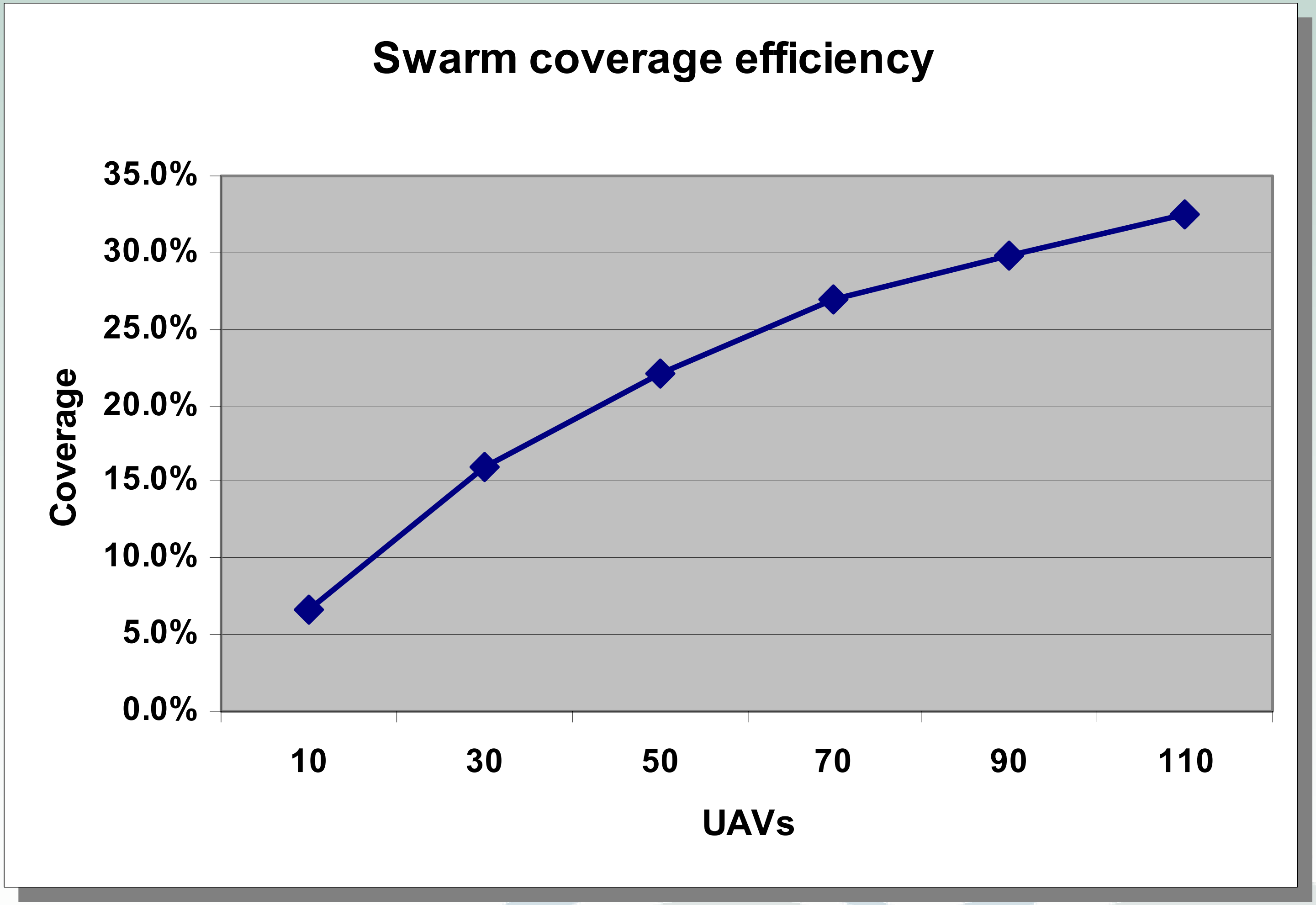


Combining Strategies



Even a relatively simple, *decentralized* strategy can yield significant improvement in swarm efficiency!

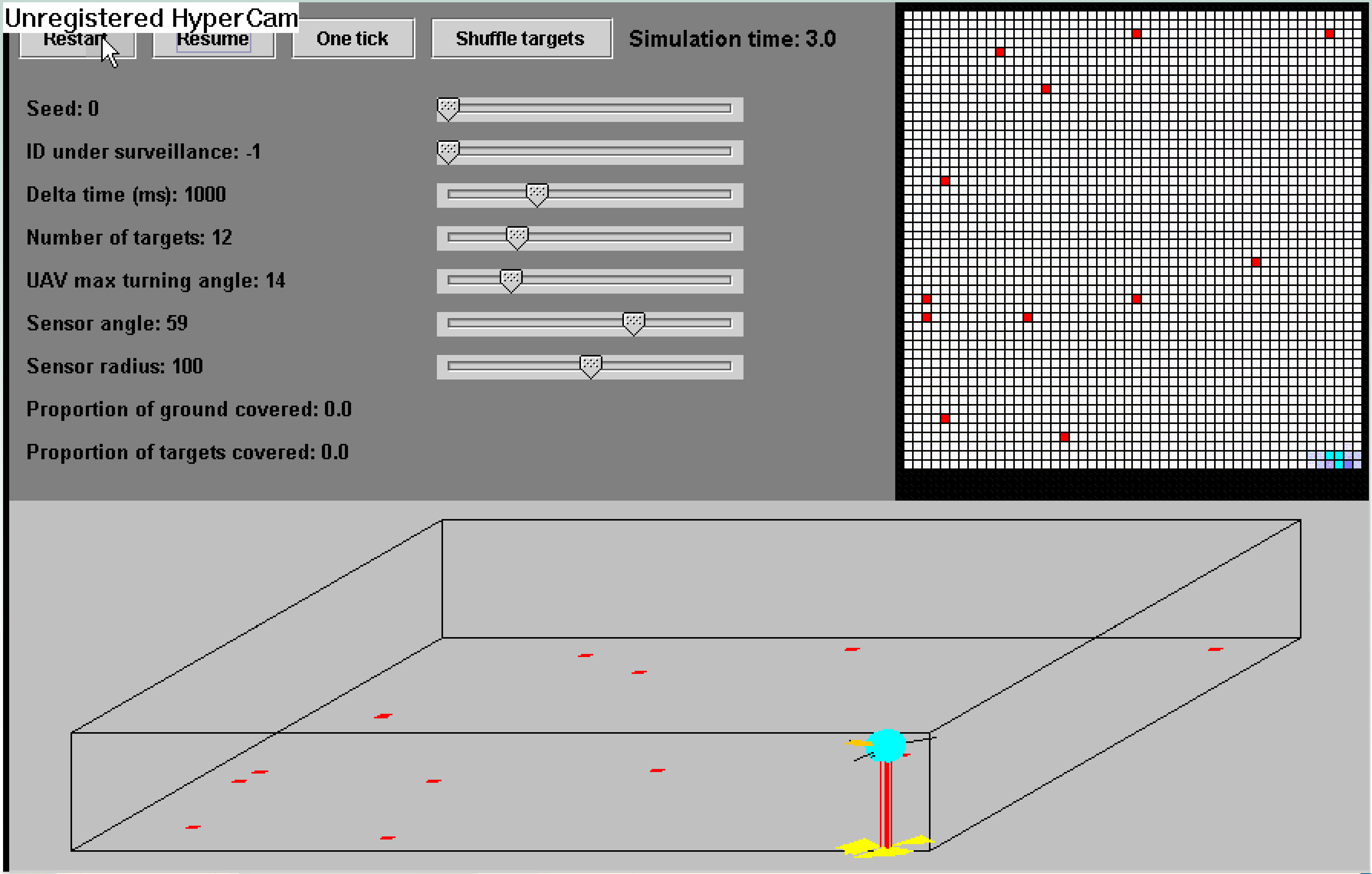
Extending to Large Swarms



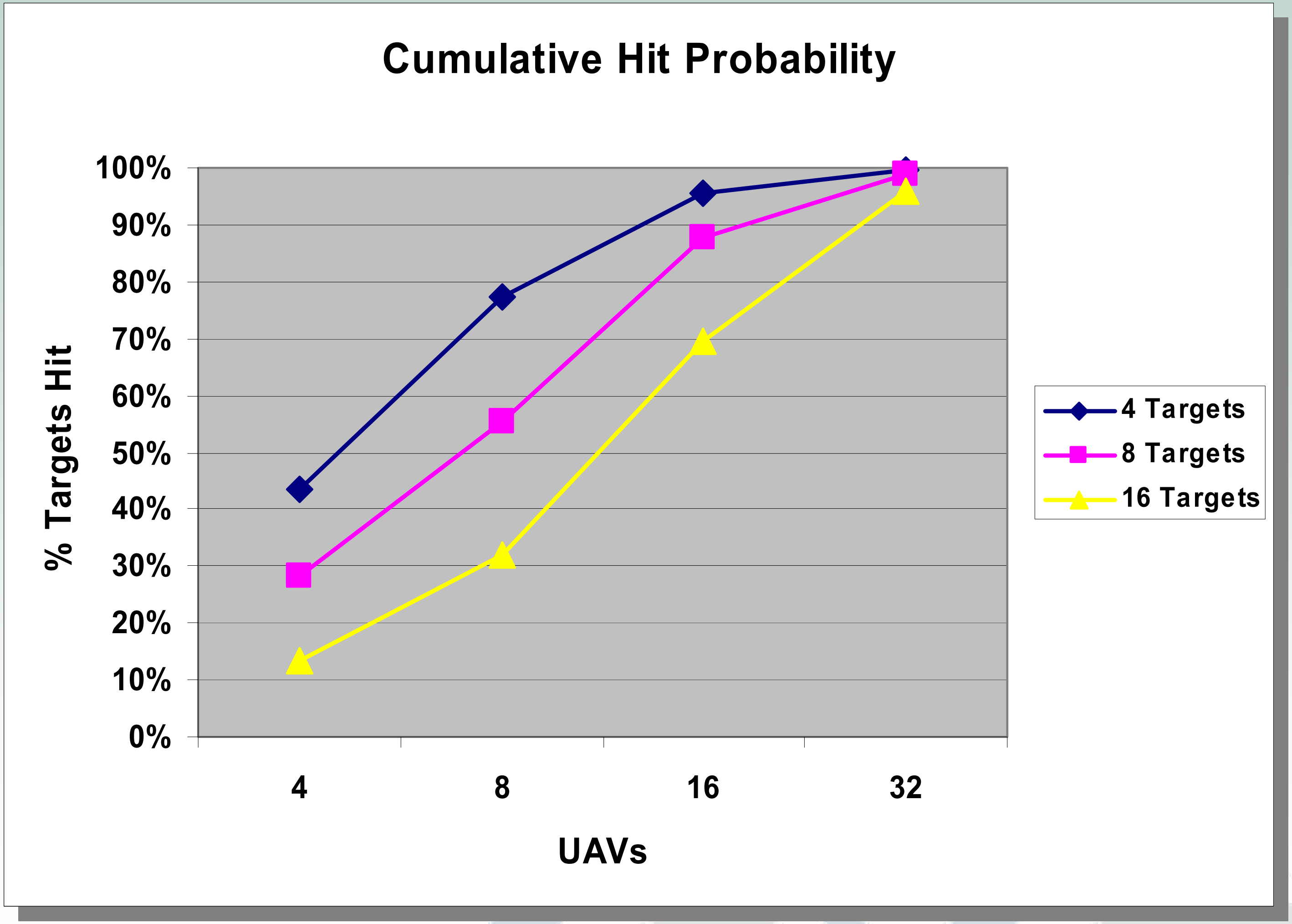
Additional Results: SEAD

- 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

Extended Simulator Demo



Sample SEAD Results



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