# Unmanned Aerial Vehicle Swarms:
## The Design and Evaluation of Command and Control Strategies using Agent-Based Modeling

*Alexander G. Madey, Trinity School at Greenlawn and University of Notre Dame, South Bend, IN, USA*

## ABSTRACT

*Unmanned aerial vehicles (UAVs) are being widely used for both military and civilian purposes. The advent of smaller, lighter, less expensive UAVs opens opportunities to deploy a large number of small, semi-autonomous UAVs in a cohesive group or "swarm". Swarms offer numerous advantages over single UAVs, such as higher coverage, redundancy in numbers and reduced long-range bandwidth requirements. Engineering a swarm requires designing the swarming behavior and finding effective ways to control the behavior so that the swarm can be directed to complete its mission. This paper presents an approach to developing UAV swarming behaviors and command and control (C2) strategies to govern them. The agent-based modeling toolkit NetLogo is used to create two mission types: contaminant plume mapping and vessel tracking. Performance metrics are used to evaluate success as parameters are changed. This research demonstrates the potential usefulness of agent-based modeling in the engineering of UAV swarms.*

*Keywords:* *Command and Control (C2), Emergent Behavior, NetLogo, Swarming, Unmanned Aerial Vehicles (UAVs)*

## INTRODUCTION

In recent years, the use of unmanned aerial vehicles (UAVs) has increased dramatically for both military and civilian purposes (Miller, 2006; Phillips, 2008). UAV technology has already solved an array of problems faced by manned aerial vehicles (MAVs). Since UAV pilots operate from the ground, pilot fatigue is less of an issue in long, "dull" missions. More importantly, pilots no longer must risk their lives in "dirty" or "dangerous" missions (Office of the Secretary of Defense, 2002). There are already a wide range of UAVs being used or developed by the military for purposes ranging from intelligence, surveillance, and reconnais-

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sance (ISR) to electronic warfare (Cevik et al., 2013). Although civilian uses can range from detecting, mapping, and monitoring wild fires (Ollero et al., 2006; Restas, 2006) to meteorological applications, the greatest potential use is in 'precision' agriculture, for pest control and monitoring plant growth (Miller, 2006; Costa et al., 2012).

Despite the many advances in UAV technology, problems still arise. Even though they are remotely controlled, most UAVs still require one or more operators on the ground. With demand for UAVs rapidly growing, there is a looming shortage of UAV pilots. Another problem is the rapidly growing long-range bandwidth requirements needed for communication between UAVs and ground control, which can often be thousands of miles apart.

One potential solution to these problems is made possible by the ongoing development of fixed-wing or helicopter-type 'mini' and 'micro' UAVs that can be deployed in groups (e.g., Miller, 2006; Paul et al., 2008; Michael et al., 2010). These small, relatively inexpensive UAVs could each be given certain behaviors that cause them to form into a 'swarm' (e.g., Miller et al., 2006; Cevik et al., 2013; Madey & Madey, 2013; McCune et al., 2013; Purta et al., 2013; Wei et al., 2013) similar to, for example, a flock of birds or a school of fish. The swarm would then be able to perform complex missions by the individual UAVs acting together, as a whole. The individual UAVs would be semi-autonomous but with a human providing 'strategic and innovative decision-making capabilities' that have been shown to be essential to UAV operation (Draper et al., 2006). In essence, the human pilot would 'fly the swarm.' Swarms of 'mini' or 'micro' UAVs would offer advantages such as: low power requirements; low observability and stealth properties, including small radar, infrared and acoustic signatures; reduced mission risk as the swarm can be spread out; operational flexibility; mission sustainability because even if some individual UAVs are lost, the remaining swarm can complete the mission; and cost effectiveness because each small UAV is relatively cheap (Cevik et al., 2013). Algorithms used for swarm behavior should not be so computationally intensive that they cannot respond quickly to changes such as the loss of a member of the swarm nor so expensive to develop that they increase the mission cost prohibitively (Miller, 2006).

The first challenge to engineering a swarm is designing the low-level behaviors that cause the UAVs to form a swarm. Swarming behaviors such as those of a flock of birds have already been demonstrated by simulations such as Reynold's BOIDS (Reynolds, 1987). Recent research has begun to focus on developing behaviors for UAV swarms (Bugajski, 2010; Ha, 2010; Madey and Madey, 2013). Another challenge to designing a functional swarm is finding ways in which the UAVs' behavior can be altered to give operators better control over the swarm as a whole (Hexmoor et al., 2005).

This paper explores an approach to designing UAV swarming behaviors and a way to command and control these behaviors in the completion of two mission types. Using 2-dimensional NetLogo simulations, two possible applications of UAV swarms are explored. The first (Plume Mapping Scenario) involves detection and tracking of a contaminant plume, resulting, for example, from a chemical spill, a dirty bomb, or a chemical or biological weapon, or even a plume of smoke from a fire. The second (Vessel Tracking Scenario) focuses on patrolling a defined body of water for detection and tracking of vessels of interest such as smugglers or enemy vessels.

The remaining portions of this paper provide some background on current UAV technology and swarming concepts. Next, the detailed methodology used to develop and implement the NetLogo simulations is discussed, followed by some preliminary results. The manuscript concludes with some summary observations and suggestions for future research.

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