

Decentralized Search by Unmanned Air Vehicles using Local Communication

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Abstract: We present a model consisting of an emergent procedure for n unpiloted, autonomous flying munitions to cooperatively conduct a parallel sweeping search of a geographic area for specific targets. The control of the unmanned air vehicles (UAVs) is decentralized and follows the reactive, behavior-based design philosophy. Global communication is not available to the UAVs; rather, they rely on passive sensors and minimal amounts of short-range, inter-UAV communication. The model is implemented and successfully demonstrated in an agent-based, simulated battlefield environment. The results of the simulation indicate that the emergent, behavior-based search procedure for UAVs is effective, robust, and scalable. It is especially well suited for numerous, small, inexpensive, and expendable UAVs.

Key-Words: Adaptive Flying Munitions, Autonomous Behaviors, Emergent Intelligence, Cooperative Search, Unpiloted Air Vehicles.

I. INTRODUCTION

We have developed a model for emergent formation of unmanned air vehicles (UAVs) into functional teams that cooperatively complete a mission in which they search for and attack specific targets. The model is known as ASAS – Autonomous Search and Attack System. ASAS is part of an ongoing investigation into bottom-up approaches to parallel, decentralized control of unpiloted air vehicles (UAVs). ASAS employs emergent team formation involving the creation of teams without centralized control; it is based on autonomous decisions and local information. The motivation to develop ASAS came from a desire to provide a cooperative control mission planning model that is an alternative to approaches that require full situational awareness, which would be available only through complete global communication and information sharing among the UAVs. Mission planning models with full information are capable of generating solutions with optimal or near-optimal performance measures. However, we assert that such models could easily fail under battlefield conditions. Failures could be caused by such things as loss of global positioning, communication network

jamming or saturation, lack of battlefield intelligence, highly dynamic battlefield conditions, and the mere presence of many UAVs within the operational environment.

ASAS is guided by ideas from emergent intelligence and their emphasis on bottom-up, decentralized, and behavior-based control. We believe the bottom-up approach is robust with respect to accomplishing tasks in uncertain and dynamic environments. The emergent intelligence of the ASAS requires that all of the UAVs have automatic target recognition (ATR) capabilities, basic advance knowledge of the geographical area, and the style of the search tactic. There is no dependence on *a priori*, situational knowledge or high-bandwidth, inter-agent communication. The ASAS is able to conduct missions that are highly adaptive and flexible, and operate in environments that are complex, dynamic, or uncertain.

II. RELATED WORK

An agent-based simulation framework previously developed by the group was instantiated for the mission planning model [2]. This provides a realistic way to simulate UAVs using virtual agents. The inspiration

for the actions and behaviors given to the simulated UAVs (agents), comes from graphical Turtles that are used to explore predator and prey interactions [1,5]. These interactions depend on models of sensations such as sight and smell. Reynolds used multiple Turtle-like agents with limited sensory abilities to model flocking in his Boids system [7]. StarLogo is a massively parallel extension of Turtle graphics in which thousands or tens of thousands of Turtles interact as independent processes [6]. Similar to our simulation framework, StarLogo was designed to explore and exploit emergent phenomena. Our framework involves many Turtle-like agents with varied, but realistic, sensory and behavioral capabilities.

Behavioral designs can follow bottom-up or top-down approaches. At the individual agent level, our work is inspired by reactive, behavior-based approaches [3]. At the group-level, we follow the basic design philosophy approach of Mataric, in which a small set of basic, group-level interactions serve as building blocks for system-wide behavior [4]. These basic interactions include *Avoidance*, *Attraction*, *Following*, *Dispersion*, *Aggregation*, *Homing*, and *Flocking*.

III. AGENT ARCHITECTURE

The basic framework simulates UAVs as virtual agents [2]. Each UAV agent was provided with the simulated characteristics of small low cost, expendable combat UAVs. This includes reasonable limitations on the computational processing power, memory, and communication capability of each UAV. In addition, their sensors, actuators, and control systems are subject to noise and failures. These limitations are inspired by the designs of current-generation small UAVs such as the U.S. Navy's Aerolight, Exodrone, and Tern, which weigh about 40 kg, travel between 100 to 160 kph with an endurance of 1 to 5 hours, and have some navigational autonomy [8].

Individual UAV agents rely on local information obtained from their sensors, and process that information locally. An agent has minimal dependence on the state or presence of other agents. However, the agents are opportunistic in that if information about another agent is available, that information is utilized. Simple, low power and inexpensive signal transmitters and sensors are attached to the agents to allow for limited range, broadcast or directional communication for opportunistic cooperation between agents. Signal reception is often limited to an agent's nearest neighbor. Therefore, an agent may be unaware that its cooperation with a close neighbor may propagate and result in team formation; teams are epiphenomena of individual agent behavior.

The UAV agents have basic simulated control surfaces and actuators inspired by those of real UAVs. This allows the agents to simulate realistic turning (a virtual, coordinated roll and bank) and acceleration based on a simple, discrete set of velocities: *slow*, *cruise*, and *pursuit*. These capabilities allow the agents to model the rudimentary functionality of operational UAVs.

The control philosophy for the agents is based on task achieving modules with tight sensor-actuator coupling. Providing for the persistence of behavior in the absence of a triggering sensation requires some state information. The agents employ discrete states and may act differently to similar sensations in different states.

IV. PARALLEL SWEEPING SEARCH

Searching and reconnaissance are essential elements in many operations, especially in a battlefield environment. The objective of the parallel sweeping search is to cooperatively search a bounded area with n UAV agents. In the design of an emergent coordination mechanism for the search, we enforced several realistic constraints, including: i) very limited quantity and range of communication, ii) no *a priori* knowledge of the number of UAVs, iii) alignment

maintained by the UAVs as they search in parallel, iv) complete and uniform coverage of the search area, and v) scalability of the solution to many UAVs.

Each agent uses a small set of virtual beacons to navigate the search area. This is similar to waypoints set in a GPS map. However, the agents do not rely on GPS, rather, they may use dead reckoning (compass and clock), or inertial guidance. Beacons provide a mechanism to enforce persistence of behavior over time. Each agent tracks to the appropriate beacon. If an agent is diverted, say in response to a possible collision, the persistence of the beacon in memory allows the agent to return to its task. Arrival at a beacon causes a state change, change in behavior, and the setting of subsequent beacons.

Maintaining Alignment

In a parallel sweep search it is essential to maintain a parallel alignment of the participants. Each agent is equipped with a virtual sensor that allows for the detection of objects through a range of 170° centered on the front of the agent. Additionally, each agent can transmit (and receive) a “wait” signal indicating that it detects it is falling behind another agent. At the beginning of a search operation, all agents are moving at cruise speed (figure 1). Each agent executes a simple set of rules to maintain alignment. These rules are:

If no agent in visual field then
 Remain in cruise speed
 Else if agent in visual field then
 Accelerate to pursuit speed and
 Transmit a wait signal
 Else if wait signal received
 Decelerate to slow speed

By following this set of rules, agents that fall behind attempt to catch up while those pulling away from other agents slow down upon request. Figure 1 shows a group of four UAVs following their beacons and maintaining alignment while sweeping through the search area (the rectangular box).

In front of each UAV, a radar-type sensor projects a conical footprint downward scanning for targets.

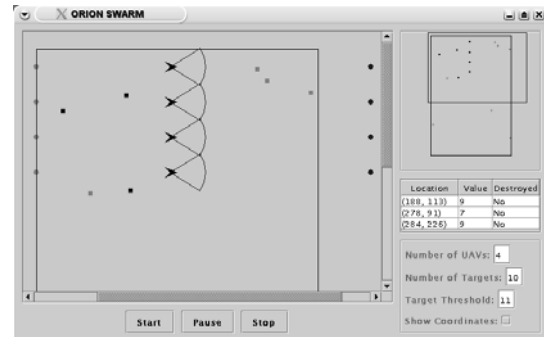


Figure 1 Aligned UAVs sweeping through the search area discovering targets.

Coordinating Extended Searching

A major accomplishment within the parallel sweeping search was the development of the behaviors for coordinating the end-of-search-legal turn and reentry into the region for the next sweep. These behaviors must function independently of the number of agents and with no assumed knowledge of the presence of other UAVs. Our solution may be summarized as “stop, look, and listen.” As the UAVs turn at the end of their search leg, each looks for other UAVs ahead of it. If a UAV does not detect a UAV ahead, it will travel one search track width, turn, and begin orbiting near the edge of the search area in preparation for reentry. If, on the other hand, another UAV is seen ahead, the UAV will extend its travel by one additional search track width, and take another look after that extension. This process is repeated by each UAV until all are in an orbital holding pattern as is illustrated in figures 2(a), 2(b), and 2(c).

When a UAV does not detect another UAV in front of it, it begins orbiting. This is accomplished by setting 4 beacons in memory – for the search track, the entry point of the orbit, the center point of the orbit, and the point of reference for the next search leg on the opposite side of the search area. If another UAV passes by while the UAV is orbiting, it extends its time in orbit a

set number of additional orbits; otherwise it enters the search area after completing a given number of orbits. While in orbit, the UAVs each propagate a signal toward the direction of the previous sweep leg. The signal contains a message directing the recipient to continue orbiting. Eventually, all UAVs will be in sustained orbits as illustrated in figure 2(c).

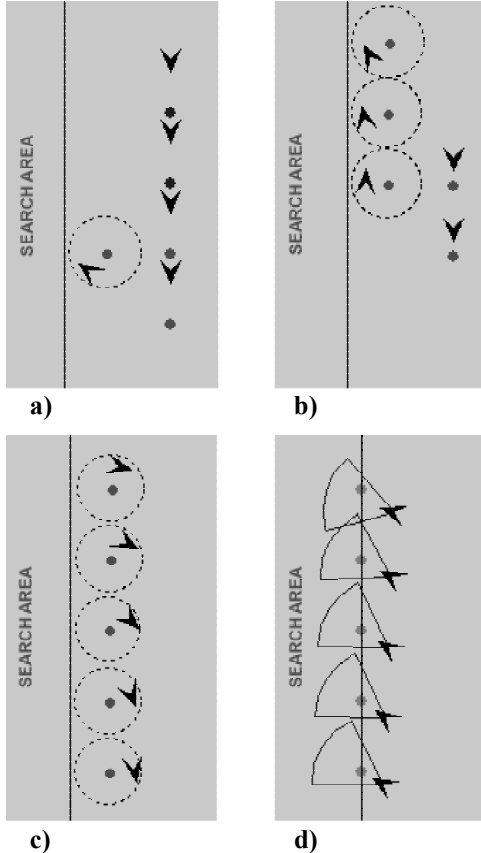


Figure 2 UAVs coordinating their extension of the sweep search.

The next search sweep is initiated when the UAV that is orbiting the furthest distance from the region previously searched completes the pre-specified number of orbits and propagates a signal to the other UAVs to stop orbiting and resume searching, as shown in figure 2(d). It is important to note that the UAV the furthest from the region previously searched completes the pre-specified number of orbits because the *continue-to-orbit* signals are directionally transmitted toward the area most recently searched; thus, it does not receive those messages. All UAVs who

receive the *resume* signal repeat it and resume their new leg of the parallel sweeping search. The relay of the *resume* signal by UAVs to their nearest neighbors provides an effective and robust method for the coordination of the group. In addition, the signal requires little transmission strength and, thus, limits unwanted detection.

Striking Targets and Closing Ranks

While a UAV is sweeping across the search area it may discover targets. Using an evaluation function, the UAV decides to either strike the target at the moment of discovery or continue to search. If it decides to strike the target immediately (considered a terminal task for these UAVs), a gap will be left in the search pattern. To compensate for this, the striking UAV transmits a short *close-ranks* signal just before it strikes the target. The UAVs that neighbor the striking UAV, on the side closest to the un-searched area, propagate this signal and close ranks by moving one search track toward the searched area. This cascading process closes the gap left by the striking UAV. Figure 3 is a state diagram consisting of the states and actions the UAV agents cycle through as they conduct the parallel sweeping search.

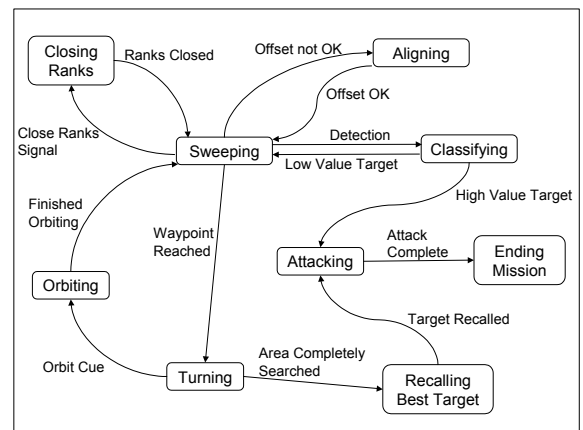


Figure 3 State diagram for UAV agents executing the parallel sweeping search.

V. RESULTS

ASAS has several desirable characteristics: (1) scalability, (2) fault tolerance, (3) reduced cost and complexity, and (4) distributed intelligence.

Scalability: ASAS will function with an arbitrary number of UAVs; it can incorporate 50 agents just as easily as 5. Because the agents are homogeneous and each one makes its own decisions based on local sensation, no special rules or structures are necessary to accommodate large numbers of agents. Communication network saturation is a non-issue as the number of agents grows because the bandwidth required is extremely low. ASAS also demonstrates dynamic scalability, in that UAVs may be added or removed at any time throughout the execution of a search and attack mission.

Fault tolerance: Even with a catastrophic loss of communication with neighboring UAVs, ASAS will continue to complete its assigned mission with graceful performance degradation. The key reasons for ASAS' robustness include: (1) the loose coupling between inter-agent communication and task execution, (2) the opportunistic yet non-dependant relationship among UAV agents within a searching team, and (3) the high level of autonomy of each UAV.

Reduced cost and complexity: Simple rule-based programming permits lower cost and lower power computing requirements. Agent homogeneity further reduces complexity.

Distributed Intelligence: In ASAS, there is no designated leader or central controller; each UAV intelligently makes its own decisions based on its own local sensations. However, ASAS clearly demonstrates coordinated teamwork. The parallel processing of a swarm of UAV agents along with local, opportunistic knowledge sharing represents a loosely coupled, intelligent distributed system.

VI. FUTURE WORK

There are several areas that are being explored to expand and extend the current multiagent model. The agents could be augmented with a greater behavioral repertoire allowing them to perform a variety of search tactics as well as other coordinated

movements. One avenue of investigation into behavioral diversity concerns agent behavioral heterogeneity. This would allow for potential agent specializations such as scouts and attackers. To accomplish this, an interface that allows a rapid translation of high-level requirements to behavioral rules is needed. The role of learning and evolution should be more broadly applied in the operation of the agents as well as the development of higher-level strategies and tactics. Ultimately we would like to implement this model in a system of actual physical agents such as experimental aircraft.

VIII. CONCLUSIONS

The use of virtual beacons, broadcast, signal-based communication, and simple rules provide a robust and effective method for the coordination and execution of a parallel sweeping search for n UAVs. The model presented demonstrates that neither high-level control nor high-bandwidth communication is necessary for this seemingly complex task.

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