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# MultiUAV2 Agent Swarming for Distributed ATR Simulation

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# MULTIUAV2 AGENT SWARMING FOR DISTRIBUTED ATR SIMULATION

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## ABSTRACT

Traditional automatic target recognition (ATR) is performed by unmanned aerial vehicles (UAVs) depending on a central control tower to provide the high level organization of the system. The UAVs fly through a region of interest to identify targets and relay all communication through a central control tower. The centralized approach to ATR has limited fault-tolerance, scalability with regards to the number of UAVs, and susceptibility to malicious attacks on the central tower [2]. A swarm-driven alternative [1] is extended with a communication control scheme to address fault-tolerance and scalability while utilizing the higher onboard processing power now available for UAVs [2]. The purpose of this paper is to compare the organization systems, centrally controlled versus distributed swarm, and extend on swarm research in the area of communication to aid in the comparison. A swarm communication algorithm is proposed and simulated during search and destroy missions in the MultiUAV2 simulation framework. Highlighted algorithm properties will be time to message completion, bandwidth costs of each configuration, scalability, and quality of service.

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## TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.1 Problem

Traditional automatic target recognition (ATR) is performed by unmanned aerial vehicles (UAVs) depending on a central control tower to provide the high level organization of the system. The UAVs fly through a region of interest to identify targets and relay all communication through a central control tower. The centralized approach to ATR has limited fault-tolerance, scalability with regards to the number of UAVs, and susceptibility to malicious attacks on the central tower [1].

A centrally controlled UAV system was introduced into practice by envisioning a single craft system to operate autonomously and complete directed tasks. Imagine two systems, one comprised of a single productive worker, and the other of N workers who each have 1/N the productivity of the single worker. If the system with a single worker loses its only worker to any malfunction then the entire system halts to a stop. If the second system loses a worker, then system productivity falls by an amount near 1/N. Further fault-tolerance is introduced by eliminating the need for a central control tower, another system component which would halt the entire system if lost. From a system view the central tower represents both a financial and functional cost that can be removed if the swarm scheme is implemented. Current systems, such as the MQ-1 Predator [3], require sophisticated oversight in the control tower that increases in difficulty and number of operators required with an increase of the technical complexity and number of UAVS operated [4].

Military contracts, such as the U.S. Air Force Predator that entered a production stage in 1997, show UAV technology reaching the critical mass necessary to leave the laboratory, but most of these systems cling to the traditional UAV setup. Technology entering the production stage builds a firm foundation for similar, future work because the manufacturing tools, knowledge of use, and acceptance of current technology exists. Evaluating the tradeoffs between swarm-driven UAV systems and recently produced UAV technologies at an early stage gives swarm technology a demonstration before the switching cost from traditional systems to swarm controlled becomes more discouraging. A shift to swarm control at an early stage where the switching costs are low could also prevent a more costly switch in the future if these weaknesses prove to break the traditional system.

## 1.2 Thesis Statement

A transition from traditional UAV system control to a swarm-driven organization provides a more scalable, easier to maintain, and fault-tolerant design. Evaluation of the tradeoffs between traditional and swarm systems at an early stage of development of the technology carries a lower switching cost if pursued, and academic comparison of the two systems can provide the basis for a decision. A further investigation into swarm communication algorithms is made through a proposed and simulated blind counter rumor mongering algorithm.

## 1.3 Approach

Communication drives the inputs to all other managers of UAV action such as flight control, path planning, and task allocation. This central information source is a prime location to isolate and solve problems associated with switching from a centrally controlled to a swarm-driven UAV system in the communication layer. Successful and timely delivery of all messages, to all parties required, can eliminate the propagation of effects from switching control schemes. If a communication technique can ensure, with high confidence, successful communication to UAVs, then the time delay and extra processing load should be evaluated against the gain in fault tolerance of the system.

Two different communication schemes were tested in MULTIUAV2, a MATLAB based simulation framework provided by the Air Force Research Laboratory. Communication bandwidth and completion time metrics were applied to both the basic swarm flooding and blind counter rumor mongering techniques.

Both systems were exposed to three different scenarios for test runs. The variable changed between runs was the presumed UAV broadcast range, which alters the properties of the network topology. Primary results are comparisons in time to message completion, bandwidth costs of each configuration, scalability, and quality of service.

### 1.4 Potential Impact

An academic contribution that encourages further investigation in swarm control could further diversify the academic and industry research thrusts in UAV systems. A more diverse set of tools could provide solutions to a greater number of problems, and find more optimal solutions to existing problems in UAV system design.

### 1.5 Organization of this Thesis

Chapter 2 covers the background of UAV development and describes the tradition and swarm-driven UAV setups. The basic swarm flooding and blind counter rumor mongering techniques are also described. Chapter 3 discusses the high level design of the communication algorithms, and the framework they are tested in. Chapter 4 contains simulations setup background and parameters. Chapter 5 provides the simulation results and data analysis.

# 2. BACKGROUND

## 2.1 Key Concepts

The key concepts of this thesis are the layouts of the traditional and swarm-driven UAV systems, the basic flooding algorithm, and the blind counter rumor mongering algorithm.

### 2.1.1 Traditional UAV System

The traditional UAV model is based on centralized control. The RQ-1A/B Predator system will be examined as an example of such a system [3]. A fully operational Predator system consists of 4 UAVs, a ground control station, at least one satellite link, and ~ 55 personnel [3]. The central control station provides central control in task planning and assignment, and is the conduit for all communications within the system. This communication hub is also located in the data flow of the system to act as an information processing unit for some types of data, such as images for ATR.

The central control station is run by a number of human operators, and provides all decisions and assignment control in the system. An open issue this paper is concerned with is the "vulnerability attendant with loss of the data link between operators and vehicles in a combat situation" in this setup because of problems originating in the control tower, or attacks on the tower (e.g., communication jamming) [4]. The system lacks fault tolerance because if one component fails, the system fails.

### 2.1.2 Swarm-driven UAV System

The swarm-driven model for high-level organization in a UAV system is based on approaching problems in a distributed, rather than centralized, manner. Formally, a swarm is a collection of autonomous agents relying on local interaction and reactive behaviors such that a global intelligence emerges from the interactions [5]. The difference between a swarm system and the traditional UAV system begins with the lack of a central control tower. The effects of this difference propagate through several characteristics of the system, with communication and information processing being highlighted in this paper. From a swarm system view, the central tower is an expensive component that can be removed because all central tower responsibilities are now done onboard the UAVs. Information processing in the swarm system is implemented in a distributive manner across several UAVs for many information processing tasks, such as image processing for ATR. This approach is becoming more feasible as onboard UAV processing power continues to improve, but it is not yet to a point where image identification can be done solitarily on-board one UAV [1].

### 2.1.3 Basic Swarm Flooding Algorithm

The non-static nature of the swarm network topology and distributive information processing required for swarm implementation suggests a broadcast method based on a generic network model. This lack of need for access to network information allows the communication scheme a dynamic nature where nodes can frequently join or leave the network. A simple and fault-tolerant solution to the problem is a basic flooding algorithm that transmits each message received to every node in communication range.

The basic swarm flooding algorithm has each act as a router and forwarder for each message, resulting in a maximum bound of N(N-1) messages being sent per message generated in the system. This polynomial cost suggests poor scalability of the system for large networks, or topologies with a high number of redundant links [2]. The cost and scalability of this method preclude it from implementation in swarm systems, but its fault-tolerant property is a characteristic the new system should attempt to retain.

### 2.1.4 Blind Counter Rumor Mongering

Many reliable broadcast protocols do not scale well to a large number of nodes, but a class of solutions designed for this purpose is called epidemiological algorithms, or gossip protocols [6] [7]. The particular gossip protocol proposed here for swarm-driven UAV systems is the blind counter rumor mongering algorithm. The algorithm [2] [6]:

```
A node initiates a broadcast by sending the message m to
 B of its neighbors, chosen at random.

When (node r receives a message m from node s)
        If (r has received m no more than F times)
                R sends m to B randomly chosen neighbors
                that r knows have not yet seen m.
```

The parameter B determines the maximum number of neighbors a message m is forwarded to. The parameter F determines the number of time a node forwards a particular message to B of its neighbors. The upper bound cost (N * B * F) can be seen as N nodes can only transmit each message F time to B neighbors. The upper bound is not a polynomial like the basic flooding algorithm, and scales better to larger networks and those with many redundant links.

## 2.2 Related Work

### 2.2.1 Past UAV Proposed Solutions

UAV technology has rapidly progressed over the recent years to bring several systems to experimental status, and projects such as the Predator to production levels. Other efforts that have seen flight-tested designs include Lockheed Martin/Boeing Darkstar [8], the Northrop Grumman RQ-4A Global Hawk [9], the Northrop Grumman Pegasus [10], and the micro-UAV Black Widow [11]. These designs are militarily minded designs with a primary objective of reconnaissance. A peer from academia is the Avatar UAV, a lightweight UAV purpose-built for small-scale, autonomous reconnaissance. A swarm-driven design is investigated in this paper as an alternative to both the high-power single UAV and centrally controlled multi-UAV systems.

The motivation of this work lies primarily in ideas presented by Dr. Prithviraj Dasgupta for a multi-agent UAV swarm solution to distributed ATR [1]. Secondary influences were given by previous swarm control work done in [4] [5].

Work on cost effective broadcasting in MANETs has mainly been investigated in peer to peer networks such as Gnutella and Napster [2] [12].

# 3. APPROACH

## 3.1 High Level Design

Communication drives the inputs to all other managers of UAV action including flight control, path planning, and task allocation. This central information source is a prime location to isolate and solve problems associated with switching from a centrally controlled to a swarm-driven UAV system in the communication layer. Successful and timely delivery of all messages to all parties can eliminate the effects from switching control schemes. If a communication technique can ensure, with high confidence, successful communication to UAVs, then the time delay and extra processing load should be evaluated against the gain in fault tolerance of the system.

Simulations of both the basic flooding algorithm and blind counter rumor mongering will make use of the software components already present in MULTIUAV2.

MULTIUAV2 works off a redundant central optimization (RCO) to control the vehicles communication and task assignments for UAVs. UAVs are seen as forming teams that are controlled by a team agent. The team agent coordinates team member assignments through the use of a centralized optimal assignment algorithm that is based on partial information. The redundant nature of this setup is that each UAV has its own local copy of a team agent and calculates assignments for everyone, but only directs its own actions. The team agent represents the onboard information processing that will occur on the UAVs.

### 3.1.1 Blind Counter Rumor Mongering Design

The algorithm [2] [6]:

A node initiates a broadcast by sending the message m to
B of its neighbors, chosen at random.

When (node r receives a message m from node s)
    If (r has received m no more than F times)
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The parameter B determines the maximum number of neighbors a message m is forwarded to. The parameter F determines the number of time a node forwards a particular message to B of its neighbors. The upper bound cost (N * B * F) can be seen as N nodes can only transmit each message F time to B neighbors. The upper bound is not a polynomial like the basic flooding algorithm, and scales better to larger networks and those with many redundant links. The algorithm as proposed is assumed to never have F=1 and B=1.

### 3.1.2 Basic Flooding Design

The basic flooding design is a general multicast solution which forwards messages from each node to all other nodes in reach upon receipt of a message. To terminate the message life a time to live (TTL) counter is attached to the message, or a number of times to forward messages variable is attached to each node. The basic flooding design is actually a simplistic form of rumor mongering, where F=1 and B=2. After generalizing the basic flood design and seeing that F=1 and B=∞, one can see the origins of the blind counter rumor mongering solution.

# 4. SIMULATION

## 4.1 Simulation Configuration

MultiUAV2 simulation is a SIMULINK/MATLAB/C++-based simulation that allows graphical and textual study of UAV flight path trajectories and communication bandwidth requirements over time [13] [14]. A use for the MultiUAV2 simulation is to accurately simulate researchers' custom UAV systems for pre-defined mission types. It is a non-real-time simulation that allows user-defined UAVs and targets with six-degree-of-freedom vehicle control blocks.

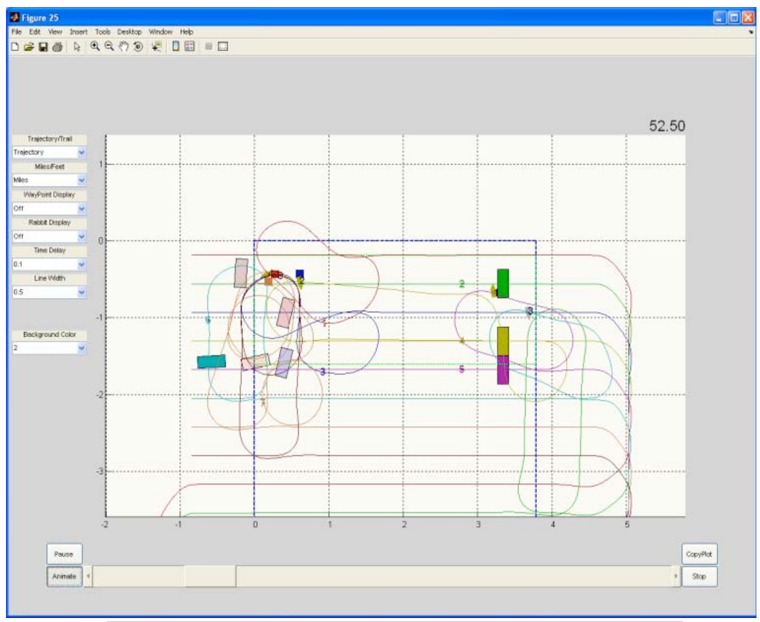


Figure 2: MultiUAV2 Trajectory Plot Output Ex.

## 4.2 Initialization Parameters

The simulation requires a number of initial parameters to construct the user-defined mission and environment. The following particularly define the system being tested.

| | |
|---|---|
| g_ActiveVehicles | Number of active UAVS |
| g_ActiveTargets | Number of active targets |
| g_SearchSpace | 2-Dimensional space UAVs search (in ft.) |
| g_TargetSpace | 2-Dimensional space targets may inhabit |
| g_TargetPosition | Target Distribution in g_TargetSpace |
| g_StopTime | Run-time of simulation |
| g_SampleTime | Sample time for simulation |

The setup of the simulation is chosen compare a traditional UAV system to that of a swarm network. Ten simulations were completed for each scenario using the following static variables:

| | |
|---|---|
| ActiveVehicles | 8 |
| ActiveTargets | 4 |
| SearchSpace | [0, 20000, -60000, 0] |
| TargetSpace | [0, 20000, -7500, 0] |
| TargetPosition | Uniform Distribution |
| StopTime | 250 seconds |
| SampleTime | .1 Seconds |

And the following parameters that were altered for every simulation series:

<table>
<tr><th>UAV Broadcast Range</th><th>Rumor Mongering Variables</th></tr>
<tr><td rowspan="3">1.5 Miles</td><td>F = 1 B = 8</td></tr>
<tr><td>F = 2 B = 3</td></tr>
<tr><td>F = 3 B = 2</td></tr>
<tr><td>2 Miles</td><td>" ... "</td></tr>
<tr><td>4 Miles</td><td>" ... "</td></tr>
</table>

The parameters are chosen to highlight differences between basic flooding and rumor mongering in scalability.  The search space and target space are chosen to constrain the problem area and minimize error in the simulation.  The distribution and timing variables are set to create randomness in testing distributions and allow time for simulations to run to completion.

### 4.2 Runtime Control

The simulation is controlled by a collection of embedded flight software agents that provide control for the individual UAVs.   Managers included are:  Tactical Maneuvering, Sensor, Target, Cooperation, and Weapons.  These managers control the major responsibilities of high-level organization:  deployment, search and discovery, communication, task allocation, and micromanagement for task execution.

Before simulation begins, a UAV and target deployment phase occurs.  All targets are uniformly distributed in the allowed target space, while UAVs originate from a UAV deployment point outside of the search and target spaces.  UAVs use a combing algorithm during runtime to deterministically cover the pre-defined search space in an 'S' shaped pattern.  Each UAV has a customizable sensor footprint that defines its field of view for ATR.  When a searching UAV encounters a potential target within its region of interest, a gossip communication method is employed to disseminate target information to other UAVs.  Target information is then used by the Cooperation Manager to perform task allocation on available target landscape knowledge.  ATR is simulated by creating targets as 3-dimensional objects rather than points on the plane.  The confidence level reported is proportional to the amount of target the UAV can physically see, dependent on its heading angle in relation to the target and the target's shape.

## 5. RESULTS AND ANALYSIS

### 5.1 MultiUAV2 Results

Comparison metrics will be centered on bandwidth usage, message completion time, and quality of service. Each simulation group will have its communication data averaged over all runs to deliver accurate bandwidth minimums, maximums, averages over time, and standard deviation measurements. An average of total number of messages required per simulation is provided, and also the number of average and peak number of hops in the simulations. Based off the total number of messages sent a quality of service percentage is calculated the represents the number of partial message distributions as a percentage of the overall number of messages that occurred in the simulation.

| Broadcast Range | Simulation Metrics | F1/B8 | F2/B3 | F3/B2 |
|---|---|---|---|---|
| 1.5 Miles | Avg. | 14.74 kbps | 17 kbps | 16.7 kbps |
| | Peak | 3425.8 kbps | 2600 kbps | 2337 kbps |
| | Std. Dev | 126.6 kbps | 134 kbps | 135 kbps |
| | Msgs/run | 13314 | 15695 | 15849 |
| | Avg. Msg Hops/run | 2.9 | 3.34 | 5.97 |
| | Peak Hops/run | 5.6 | 6.8 | 10 |
| | Error | ~1% | 3.90% | 3.50% |

| | | | | |
|---|---|---|---|---|
| 2 Miles | Avg. | 21.36 kbps | 23.68 kbps | 20.6 kbps |
| | Peak | 3463.9 kbps | 2685.6 kbps | 3034 kbps |
| | Std. Dev | 162 kbps | 165.7 kbps | 157 kbps |
| | Msgs/run | 19806 | 20610 | 19346 |
| | Avg. Msg Hops/run | 2.93 | 4.36 | 6.65 |
| | Peak Hops/run | 5.5 | 7.75 | 10.5 |
| | Error | ~1% | 3% | 3.30% |

| | | | | |
|---|---|---|---|---|
| 4 Miles | Avg. | 32.58 kbps | 29.3 kbps | 28.6 kbps |
| | Peak | 3768 kbps | 3176.2 kbps | 2729 kbps |
| | Std. Dev | 231.32 kbps | 217.8 kbps | 209.2 kbps |
| | Msgs/run | 28789 | 26599 | 26119 |
| | Avg. Msg Hops/run | 2.43 | 4.44 | 6.92 |
| | Peak Hops/run | 4.4 | 7 | 10.2 |
| | Error | ~1% | 2.10% | 2.20% |

### 5.2 MultiUAV2 Output Analysis

Neither the basic flooding (F=1 and B=8, for the 8 UAV case) or blind counter rumor mongering techniques display superiority in each scenario.

The basic flooding technique showed superiority in every metric except peak bandwidth used in the case of a 1.5 mile UAV broadcast range. The 1.5 mile broadcast range was chosen to create a network topology with fewer redundant links, and smaller sets of UAVs that each UAV was in contact with. This sparse network graph was then traversed with few recipients available to each node, reducing the effects of the flooding mechanism. Even though the recipient sets were smaller the rumor mongering techniques were still able to find enough recipients per round that the F > 1 parameter caused the message forwarding feature of rumor mongering to accumulate a higher total messages per simulation count. This higher message count effect propagated through the rest of the communication test metrics.

The simulations series with a 2 mile broadcast range showed nearly similar results for the basic flooding and rumor mongering techniques. This occurred because the network topology became more connected with redundant links as the broadcast range grew, hurting the flood mechanism because a larger recipients set was possible for each

UAV transmission. The number of messages per node was increased for the flooding mechanism, but remained more static for the rumor mongering technique.

The simulations with a 4 miles broadcast range created an even more connected graph, and further displayed the effect of redundant network links. The rumor mongering technique is now shown to be superior in the communication bandwidth metrics.

All simulations series displayed the message forwarding effects of each technique. The basic flooding had few forwards, or average hops per message, while the rumor mongering techniques displayed a high average and peak message hops value. The message hops value corresponds to the number of rounds a message is alive. A technique with a higher average or peak hops count, or message life time in rounds, has a longer average and maximum time to message completion.

The quality of service, or error % presented in the charts, represents the number of inconsistent message distributions throughout the simulation. The error percentages were relatively similar, with a decrease in errors as the broadcast range increased and formed a more connected network graph. Error correction was not attempted in this paper, but an anti-entropy solution proposed in [15] is shown to address the issue for networks where dropped messages can significantly affect the system.

# 6. CONCLUSIONS

## 6.1 Summary

Swarm networks that call for the use of many relatively simplistic robots to attack a complex task call for the use of scalable communication schemes. The blind counter rumor mongering technique provides a viable solution if given a UAV network graph that contains a large number of nodes or redundant links.

## 6.2 Contributions

This thesis contributes to the field of UAV Coordination by further investigation into communication schemes appropriate for swarm networks. The paper also provides an academic comparison of traditional UAV systems to swarm-driven UAV systems, and how the swarm setup and rumor mongering technique provide an alternative solution to traditional UAV system development.

## 6.3 Future Work

Future work could be done to alter the MultiUAV2 simulation framework to allow a large number of UAVs to further test the scalability of gossip protocols, rather than test in an indirect manner by graph connectedness. Also, the anti-entropy scheme [15] could be implemented on top of the blind counter rumor mongering algorithm to view the tradeoff between increased quality of service and increased bandwidth usage.

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