AFRL-VA-WP-TR-2003-3089

LARGE NUMBER OF AIR VEHICLES SIMULATION (LNAVSIM)

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MAY 2003

Final Report for 31 May 2001 – 31 May 2003

THIS IS A SMALL BUSINESS INNOVATION RESEARCH (SBIR) PHASE II REPORT

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STINFO FINAL REPORT

AIR VEHICLES DIRECTORATE
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NOTICE

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
May 2003	Final	05/31/2001 – 05/31/2003

4. TITLE AND SUBTITLE
LARGE NUMBER OF AIR VEHICLES SIMULATION (LNAVSIM)

5a. CONTRACT NUMBER
F33615-01-C-3116

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
65502F

6. AUTHOR(S)
Dr. Rubin Johnson

5d. PROJECT NUMBER
3005

5e. TASK NUMBER
30

5f. WORK UNIT NUMBER
9I

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
OR Concepts Applied (ORCA)
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8. PERFORMING ORGANIZATION REPORT NUMBER
A001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Vehicles Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7542

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/VACD

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-VA-WP-TR-2003-3089

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
This report contains color. THIS IS A SMALL BUSINESS INNOVATION RESEARCH (SBIR) PHASE II REPORT.

14. ABSTRACT ***(Maximum 200 Words)***
The Large Number of Air Vehicles Simulation (LNAVSIM) is an environment for modeling, planning, and simulating an air war. LNAVSIM addresses the Air Force's need for command and control tools for unmanned combat air vehicles (ucavs) and unmanned air vehicles (uavs), and represents a leap-forward for modeling and simulation of military aircraft missions. LNAVSIM provides tools for planning coordinated and synchronized missions involving multiple vehicles. The data-driven LNAVSIM tools can model and simulate new and emerging weapons systems and missions. LNAVSIM provides a research environment for analysis and simulation of missions, and to assess the effectiveness of command, control, communication, and intelligence strategies for groups of aircraft. LNAVSIM provides state-of-the-art automated mission planning tools through the Large Number of Air Vehicles Generator (LNAVGEN) component, a prototype mission planning station for controlling groups unmanned vehicles. LNAVGEN accesses ORCA Planning and Utility System (OPUS) services for target allocation, autorouting, analysis, evaluation, data management, and simulation. LNAVGEN includes algorithms to generate routes for groups of vehicles using techniques that mimic bird flocking behaviors. ORCA's fast and efficient algorithms allow an LNAVGEN operator to dynamically replan missions while vehicles are in flight due to changing conditions such as pop-up threats and emergent time-critical targets.

15. SUBJECT TERMS
SBIR Report, Unmanned Air Vehicles, UAV, Unmanned Combat Air Vehicle, Simulation, Mission Planning, OPUS, Command and Control, Modeling, Flocking

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Edwin C. Allen
Unclassified	Unclassified	Unclassified	SAR	32	19b. TELEPHONE NUMBER *(Include Area Code)* (937) 904-6521

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Table of Contents

1 Introduction ... 1
1.1 Problem Identification ... 1
1.2 The LNAVSIM Vision ... 2
1.3 "Large Numbers" of Air Vehicles ... 3
2 LNAVSIM Mission Planning Technologies ... 4
2.1 Target Allocation ... 4
2.1.1 VRP and HEX ... 4
2.1.2 Synergetic Effects Model (SEM) ... 5
2.2 Route Planning ... 6
2.2.1 Autorouting ... 6
2.2.2 Deconfliction ... 7
2.2.3 Swarm Management ... 7
2.3 Dynamic Tasking and Planning ... 8
2.4 Analysis ... 9
3 LNAVSIM Concepts of Operation ... 9
3.1 LNAV Analysis Environment ... 9
3.2 UAV Command and Control ... 10
3.2.1 Actionable Intelligence ... 10
3.2.2 Span of Control ... 11
3.2.3 Managing the SEM ... 11
3.3 Pod Control Concepts ... 11
3.3.1 Pod Control ... 11
3.3.2 Multiple Operators ... 11
3.3.3 Dynamic Planning ... 11
4 LNAVSIM Software ... 12
4.1 LNAVSIM Architectural Design ... 12
4.2 Components ... 13
4.2.1 LNAVGEN ... 13
4.2.2 JFACC ... 15
4.2.3 AnySim ... 15
4.2.4 BOSS ... 17
4.2.5 Simulation ... 18
4.2.6 Route Export to VBMS ... 19
4.3 LNAVSIM and OPUS ... 19
4.3.1 OPUS API ... 19
4.3.2 OPUS Services ... 19
4.4 HLA Compliance ... 20
5 LNAVSIM Studies ... 20
5.1 Study 1: Sensor, Jammer, Shooter ... 20
5.2 Study 2: Hunter-Killer ... 21
5.3 Study 3: UCAV Command and Control ... 21
6 LNAVSIM: The Future ... 21
6.1 Architecture and Design Assessment ... 22
6.2 Enhanced Tools ... 22
6.2.1 Improved Set of FOMS ... 22

6.2.2 Flocking 22
6.2.3 Deconfliction Tools 22
6.2.4 Automated Tools for the JFACC 23
6.3 New Features 23
6.3.1 Vehicle Communications Models 23
6.3.2 Incorporate Other Simulations 24
7 Conclusion 24

List of Figures

Figure 1 The LNAVSIM Vision 3
Figure 2 The SEM Concept 5
Figure 3 JFACC SEM Tool 6
Figure 4 LNAVSIM Architecture 12
Figure 5 LNAVSIM Component Communications 13
Figure 6 Pod Operator Planning Interface (POPI) 14
Figure 7 POPI Planning Dialog with Figures of Merit 14
Figure 8 JFACC Component GUI and SEM Tool 15
Figure 9 AnySim GUI 16
Figure 10 Mail Message Details 17
Figure 11 BOSS GUI 17

1 Introduction

This document is the final report of ORCA's LNAVSIM Phase II SBIR effort for AFRL/VACD. During the LNAVSIM program, ORCA has researched methods and designed software tools for modeling, planning, and simulating missions involving large numbers of air vehicles. Through the LNAVSIM R&D effort, ORCA has gained valuable knowledge about the needs for mission modeling and simulation tools, and the challenges of implementing software tools to support operations and studies involving large groups of vehicles. This report will review our Phase II effort, summarize the results of our research, and describe the LNAVSIM tools and software designed over the last two years. All documents, reports, and briefings prepared during Phase II can be accessed through ORCA's LNAVSIM website www.ORConceptsApplied.com/lnav.

In the remainder of this section, we will identify the problem this research effort addresses, briefly describe our vision of the solution, and define "large numbers" for the purposes of this program. Section 2 discusses mission planning technologies identified as necessary for groups of vehicles. Section 3 gives the LNAVSIM Concepts of Operations. In section 4, we describe the final software product of Phase II, LNAVSIM Version 1.0. Section 5 summarizes the three LNAVSIM studies performed during Phase II. Finally, Section 6 provides a glimpse at the possibilities for future versions of LNAVSIM.

1.1 Problem Identification

The use of large numbers of air vehicles (LNAV) such as uninhabited air vehicles (uavs) for theater reconnaissance, surveillance, target detection and location, defense, electronic warfare, and unmanned combat air vehicle (ucavs) for tactical operations, will continue to alter the theater dynamic. The evolution in strategies and tactics is well underway, as can be seen in recent operations in Afghanistan, in other engagements in the war on terrorism, and in Iraq. However, recent uses of unmanned vehicles have been limited mainly to single vehicle missions.

The Air Force is investigating ways to utilize groups of coordinated air vehicles such as uavs, and ucavs as a means to locate high-value, strategic, movable targets, enhance situation awareness, and deliver frontal wave firepower more precisely, and with less collateral damage and injury to civilian populations than traditional means. This underscores the need for continuing investments in mission planning analytical tools, modeling, and mission rehearsal simulation capabilities that can address operational scenarios involving groups of highly synchronized uav/ucav vehicles. For a growing number of challenging missions that involve large numbers of vehicles, the USAF envisions an advanced mission planning and simulation environment that is rapid, flexible, and possesses a full suite of mission scenario development tools to study coordinated and collaborative force structures. Through simulation, the critical assessment of command, control, and optimization of force components for planned and postulated battlefield conditions can be realized. Furthermore, through simulation, mission planning specialists can evaluate the effectiveness that groups of vehicles offer as part of a much larger task force structure.

Many current mission level models and simulation tools are not adequate to conduct effectiveness studies for the class of LNAV problems. Most mission planning, modeling, and simulation systems presume small numbers of aircraft for each mission. For a given class of aircraft with unique characteristics in vehicle performance, susceptibility, and weapon delivery, each vehicle's optimized route is largely determined by the mission objectives, threat exposure, target locations, and risk element. For multiple missions, the "single" vehicle mission context is extended to other vehicles over the number of vehicles utilized in the airspace simultaneously. Although this may appear as a coordinated and synchronized effort, each route being simulated is essentially deterministically derived and calculated according to the prescribed mission input data governing that mission and the vehicle route optimization routines being utilized. Each vehicle route generated is independently determined without knowledge from the other aircraft executing their missions. Today's approaches in aircraft mission planning and simulation are characterized as simultaneous, but asynchronous and uncoordinated with respect to vehicle collaboration (except through the initial assignment of targets and objectives.) The sub-optimality of such a solution will tend to grow with force size. The approach is not ideally suited for controlling multiple air vehicles that are attempting to cooperate. The work we are undertaking in this project seeks both to model this cooperation and to offer new methods and concepts of operations for collaborative planning. We also introduce a method for measuring plan robustness.

This research effort addresses generic air vehicles with a focus on unmanned vehicles. Although there may be references to actual systems (e.g., Predator, Global Hawk, or the DARPA UCAV under development), our goal is to be able to examine all types of air vehicles, real and imagined. The concern is not just with the capabilities of individual air vehicles but also the mission planning and command and control elements needed to make large numbers of air vehicles work together.

1.2 The LNAVSIM Vision

During this program, ORCA has done extensive research into LNAV mission needs, requirements, and concepts of operation. We have identified necessary LNAV technologies and algorithms, developed tools based on these technologies and algorithms, and designed an architecture for the LNAVSIM environment.

ORCA's vision for LNAVSIM is an air war planning and simulation environment that is indistinguishable from a real-life situation. We see an environment in which multiple operators each control a group ("pod") of vehicles. A commander, (e.g., the Joint Forces Air Component Commander – JFACC), sets values for mission objectives, and assigns vehicles and objectives to the individual pod operators. Operators develop detailed assignments of objectives and route plans for the vehicles under their control with the aid of automated mission planning tools available though the LNAV Generator (LNAVGEN) server. As new events are reported, the JFACC makes new assignments of objectives. Operators respond to new objectives and pop-up threats by analyzing existing plans for significant changes in figures or merit (FOMs) and replanning if necessary. The Broad Overseer of the Scenario and Simulation (BOSS) can manipulate the initial scenario and simulation events by adding, deleting, or moving entities. Scripted events can be provided to the JFACC and pod operators through the BOSS. We see the possibility of a Red Commander who could be in charge of the threat laydown.

This environment represents a leap-forward for modeling and simulation of military missions. The high-level vision of the LNAVSIM air war planning and simulation environment is captured in the picture below.

Figure 1 The LNAVSIM Vision

1.3 "Large Numbers" of Air Vehicles

One of the first steps in Phase I of this SBIR program was to research AFRL needs for LNAVSIM. In ORCA's Phase I SBIR proposal, we expressed the willingness to explore swarms of hundreds of micro air vehicles. To address the planning requirements for swarms of that size, ORCA proposed using methods for generating routes for large groups of vehicles, often referred to as flocks or swarms, using the "boids" methodology developed by Craig Reynolds[1] for computer animated bird flocking. However, the group consensus at AFRL was that it is more appropriate to focus on combinations of lethal and non-lethal uninhabited air vehicles numbering between 4 and 32.

To support this change of focus, ORCA investigated a variety of route planning methods, including autorouting individual vehicles, deconfliction methods for groups of vehicles, and the boids approach. Phase II research revealed that the boids methods, while allowing for fast generation of routes for groups of vehicles, do not work as well as autorouting when threats are present. However, in cases where hundreds of vehicles are being employed, the group will be easily detectable and ensuring the survivability of individual vehicles may not be less important than accomplishing mission goals. For small groups, autorouting combined with deconfliction methods is fast and produces more survivable routes.

[1] Craig Reynolds' website: http://www.red3d.com/cwr/boids/

The LNAVGEN component provides OPUS autorouting services through the OPUS API. To support planning for larger groups and to provide an alternative to autorouting, ORCA developed a modified boids approach, called swarm management, for LNAVGEN. Swarm management address some current planning needs and supports planning for large groups should the concept of operations for LNAVSIM evolve in the future.

2 LNAVSIM Mission Planning Technologies

2.1 Target Allocation

For uavs and ucavs, cooperative planning can be essential. Some methods of target location use sensors on multiple aircraft. This means that group, or *pod*, planning is a new element of mission planning that must be addressed.

When tasks are assigned to pods of unmanned vehicles, it is almost certain that the JFACC will not have sufficient insight into pod planning and capabilities to make assignments by tail number. Tasks will be assigned to one or more pods. How the pods assign tasks to individual vehicles is a target allocation problem. This problem may have to be solved under a variety of circumstances—pre-mission and inflight with the possibility of new targets and threats.

Target allocation is the assignment of tasks to resources. The target allocation problem is mathematically equivalent to the problem known in computer science circles as the Vehicle Routing Problem (VRP). Once the target set has been designated, assignments can be made using algorithms developed to solve the VRP. One VRP variation models a fleet of trucks with varying capacity, fuel constraints, and capability to traverse a road network. ORCA worked on such a problem in a military context as well as for an Internet grocery delivery firm driven by tight time windows. Deliveries and pickups are subject to time and dependency constraints. The applicability to aircraft delivering weapons and imaging locations is obvious.

2.1.1 VRP and HEX

ORCA's internally funded research on the VRP began in 1989. An initial success was the development of an algorithm for allocating homogeneous assets. ORCA improved its target allocation methods during a recently completed DARPA JFACC effort and in-house R&D that continued after the JFACC program. The independent R&D program was entitled the *Heuristic Evaluation eXperiment* (HEX) and the result of this effort was the *HEX Target Allocation Algorithm*.

One of the first steps in the target allocation process is to generate and evaluate several possible route plans. The route plans for target allocation need only be rough estimates, rather than the precise routes generated by an autorouter such as OPUS. (After the target allocation is determined, an autorouter can be used to generate the final detailed route plans.) However, a large number of routes—possibly in the millions depending on problem complexity—must be generated quickly. The HEX tool generates simplified routes by using a hexagonal grid to model vehicle flight paths and simplifying other problem parameters such as threat costs.

The HEX tool uses a least cost path algorithm to compute paths between any two nodes in the hex grid. Dynamic costing is then used to compute least cost path for an ordered set of objectives. In dynamic costing, paths are determined based on the order in which tasks must be executed. Finally, the Greedy Random Adaptive Search Procedure (GRASP), a technique for solving the VRP, is used to allocate. GRASP is particularly suitable for target allocation as any initial condition can be used as a starting point. This allows new tasks to be added to existing assignments with minimal or no disturbance to other vehicle plans. During the allocation process, threat and vehicle models have been adopted to provide a "good enough" answer, leaving the details to the route planner.

The output of the target allocation process is an ordered list of tasks for a set of aircraft, similar to the ATO. The task list is input for the autorouter.

2.1.2 Synergetic Effects Model (SEM)

The Synergetic Effects Model (SEM) is used to model the effects of satisfying single objectives and groups of objectives. The SEM is a generalization of the Prioritized Target List (PTL). The current PTL indicates priorities and values for individual objectives, which could be targets or other tasks such as imaging a target. The SEM models the effects of satisfying single objectives as well as combinations of objectives. It expands on the concept of target importance by also attempting to capture the relationship between objectives. Because the SEM models the relationship between objectives, it aids in producing coordinated and cooperative mission plans.

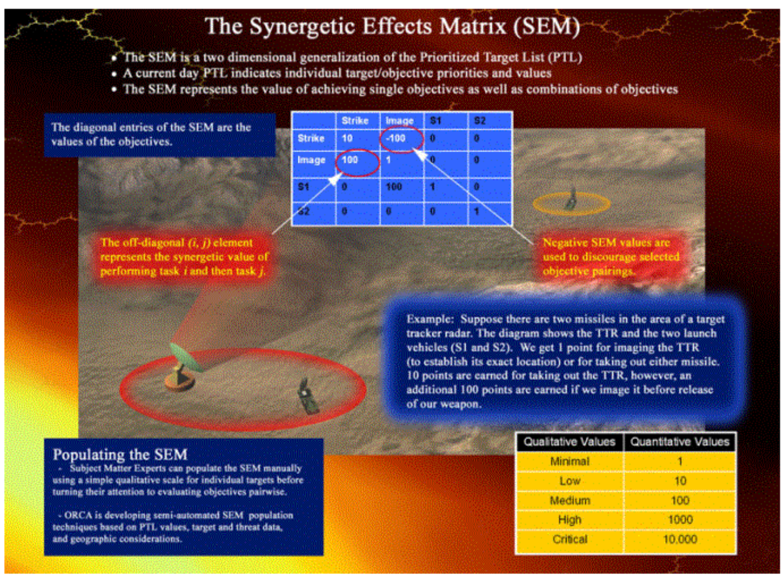

Figure 2 The SEM Concept

We discuss the SEM in conjunction with target allocation tools because it provides quantitative measures of target value and modeling of the relationships between targets that mesh with common sense notions. These values are useful in the objective functions used in the GRASP procedure.

The SEM was conceived and first demonstrated by ORCA during the DARPA JFACC program, as part of ORCA's effort to develop a new command and control process for dynamically allocating aircraft to objectives. In subsequent IR&D, the SEM was incorporated as a key component of ORCA's HEX tool. Extensive experimentation has validated the usefulness of the SEM as a means of modeling objective values in the allocation process and encouraging cooperative behavior.

The JFACC Component of LNAVSIM has a SEM Tool, shown at the right, for assigning values to mission tasks and synergetic pairs of tasks. Through research and experimentation, ORCA has determined that a simple qualitative ranking system for target value is sufficient for translating the decision maker's intent into quantitative values for use in allocation algorithms. The qualitative target values used are as follows: minimal, low, medium, high, and critical. These qualitative rankings map to the quantitative values 1, 10, 100, 1000, and 10000, respectively, in ORCA's target allocation algorithms.

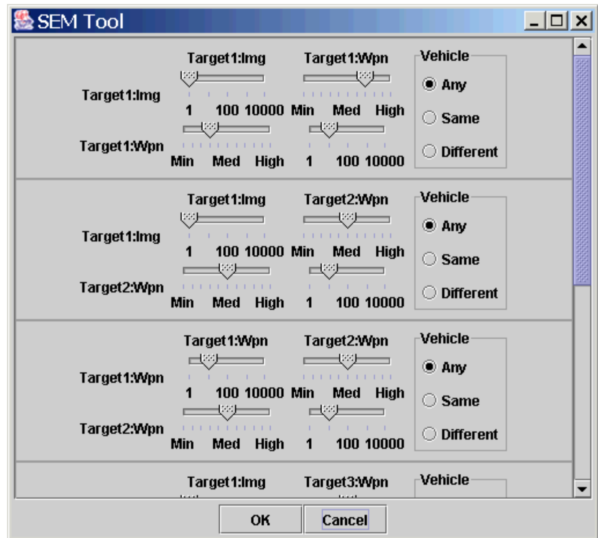

Figure 3 JFACC SEM Tool

Populating the SEM using the tools provided by the JFACC Component is a manual process. ORCA is developing automated and semi-automated population techniques based on PTL values, target and threat data, and geographic considerations. The operator will have the opportunity to modify and change individual values produced by the automated tools.

2.2 Route Planning

Route planning is the lowest level in the mission planning process. The LNAVGEN component provides route planning tools to generate routes for individual vehicles or flocks of vehicles.

2.2.1 Autorouting

Mission planning and autorouting easily break into two categories—pre-mission and inflight. Autorouting usually refers to the generation of the flight path while mission planning incorporates other aspects of the mission including target area planning, sensor management, and communications planning. ORCA tends to attach the broader mission planning definition to autorouting because the flight plan constrains what the aircraft can accomplish just as much as the mission objectives can influence the flight plan.

OPUS autorouting is a fast and effective method for generating terrain-aware, goal-seeking, survivable route plans for individual vehicles. The input for the autorouter is an ordered set of mission tasks or objectives, vehicle performance parameters, threat susceptibility data, and terrain data. The autorouter attempts to generate a route that optimizes some notion of mission effectiveness and not just survivability. The output of the autorouter is a detailed set of way points for a route that accomplishes the goals assigned to a particular sortie while being aware of threats and terrain.

The autorouting algorithms of ORCA are fast enough to generate new routes in response to changes in the threat environment or mission objectives. Using an A* algorithm, a feasible, terrain-aware route is developed that minimizes a non-linear threat costing function that models the enemy Command, Control, Communications, and Intelligence (C3I).

2.2.2 Deconfliction

There are at least three aspects to deconfliction. The first aspect is pro-active: routes can be planned in such a way as to preclude conflict. Exclusion zones, minimum risk routes for safe ingress and egress, and kill boxes are all mechanisms to prevent conflicts.

A second aspect is conflict identification. Routes are compared in order to identify regions where one or more aircraft are scheduled to arrive at too close to the same time. This is typically less of a problem if the aircraft are in the same unit. The distance at which a wingman might fly would be worrisome if the aircraft wasn't part of the lead aircraft's group.

Finally, deconfliction means eliminating any conflicts. To be able to enforce deconfliction without broadcasting the details of each aircraft's routes requires use of airspace management. At ORCA, we have considered broadcasting route details as constraints. Each squadron would be assigned a priority that would let them know who needed to replan in case of a conflict. Other mechanisms (i.e., routing protocols) would be employed to reduce the chance of conflict when generating new route plans.

2.2.3 Swarm Management

Route planning for large groups of vehicles can be a challenge for traditional route planners that generate routes for individual vehicles. During the LNAVSIM program, ORCA has researched alternative route planning methods for large groups to address the planning needs of "flocks" ("swarms") – large groups consisting of tens or hundreds of vehicles.

There has been a considerable amount of research into flocking behaviors, including Reynolds seminal work on "boids"[2]. In the paper "Flocking of Autonomous Unmanned Air Vehicles"[3], Crowther and Riviere apply the rules of flocking (cohesion, alignment, separation, and migration) as defined by Reynolds to the problem of managing the flight of a number of autonomous unmanned air vehicles. In their studies, they simulated the flight of a flock of 10 vehicles. It should be noted that this simulation did not include any

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[2] "Flocks, Herds, and Schools: A Distributed Behavioral Model", Computer Graphics, 21(4), July 1987, pp.25-34

[3] "Flocking of Autonomous Unmanned Air Vehicles", Bill Crowther, Lecturer, School of Engineering, University of Manchester, w.j.crowther@man.ac.uk; Xavier Rivier, Research Student, xavier.riviere@caramail.com

threats or military objectives. The focus of the paper was to demonstrate flocking behaviors and investigate the relationship between various flocking rules and behaviors. Below are their conclusions.

- “Flocking offers a potentially simple and efficient way of managing the flight paths of a large number of small autonomous UAVs such that the risk of collision and/or the need for evasive manoeuvers is reduced.”
- “The way in which flocking rules are implemented depends strongly on the nature of the flight control system available on the target flight vehicle.”
- “Basic flocking behaviour can be obtained as the result of application of just two rules: cohesion and alignment. However the effects of rules are not simply additive.”
- “The time taken to achieve coherent flocking behaviour is reduced by increasing the cohesion and alignment rule strengths. However increasing the strengths too far leads to oscillatory behaviour and increased flock convergence time.”
- “Flock behaviour over time can be characterised usefully by the time variation of two statistical parameters: the mean radius between flock members (flock density) and the heading angle standard deviation.”

These findings are similar to those ORCA documented in the briefing “Flocking Algorithms”, in June 2002.

ORCA developed a flocking capability, or “swarm management,” for LNAVSIM, during Phase II. This method uses a modified boids approach which insures that the physics of flight performance is maintained and creates the notion of a “virtual lead” vehicle around which other vehicles flock. Swarm management allows the user to group vehicles in swarms and generate routes for the swarms as opposed to generating routes independently for each vehicle. Swarm management provides an alternative to autorouting in an environment without threats and could be used to generate routes for missions such as surveillance in low threat areas.

2.3 Dynamic Tasking and Planning

These two functions make use of the existing capabilities to allocate targets, sequence the mission objectives, and generate new route plans. Time critical targets, changes in the battlefield, aircraft that take more than half a day to reach the target area, and uavs that are inherently re-programmable all create a demand for dynamic tasking and planning. The ability to replan quickly in face of changing conditions is the essence of having a short “observe, orient, decide, act”, or OODA, loop. Col. John Boyd showed that having a shorter OODA loop than your opponent is a key indicator of success in military operations.[4] Automated decision aids can be important tools in developing and assessing plans when responding dynamically and therefore shortening the OODA loop.

There are several levels of replanning of interest. The highest level involves changing strategic objectives leading to a change in objectives and their priorities. These changes can create the demand for a new allocation of objectives to force elements—the force

[4] “Boyd: The Fighter Pilot Who Changed the Art of War” Robert Coram, Little Brown & Company, 2002

allocation problem at the JFACC level. In current day planning, the JFACC's commands flow to wings and squadrons who would then have a smaller allocation problem. Each squadron or uav pod would also have to allocate targets and objectives to its members. Although the mathematics is the same, we have been referring to this as the target allocation problem.

At the lowest level is route replanning for each sortie. If there is a change in objectives, it is obvious that the route should change as well. The route might also change if there is a change in the threat laydown.

2.4 Analysis

LNAVSIM is an analysis tool to evaluate command, control, and operations concepts and strategies for large force structures involving a variety of aircraft types. OPUS provides a suite of analysis tools that can be accessed by LNAVSIM components through the OPUS API. Below is a list of available analysis features.

<u>Sortie Attrition</u>
The probability of survival for a sortie route is computed using a deterministic methodology. Additional route figures of merit are available including the number of SAM shots, amount of exposure to EW/GCI radars, amount of exposure to tracking radar, and track time by sites and networks.

<u>Interactive Simulation</u>
A discrete event simulation models the execution of one or more sorties against the threat laydown. SAM and AI launches are determined by the defense network using one of several decision criteria. SAM and AI engagement outcomes are sampled from probability distributions determined by vehicle geometry.

<u>Monte Carlo Simulation</u>
Multiple simulations may be executed to collect statistics for the average and standard deviation for all vehicle figures of merit.

<u>Exposure Reports</u>
Reports on exposure of sortie routes to any combination of threat types can be computed.

<u>Logistics</u>
Reports on fuel use are available by strike base, vehicle types, and time on target, as is information on takeoffs, landings, fuel throughput, and aircraft flying.

3 LNAVSIM Concepts of Operation

3.1 LNAV Analysis Environment

In the LNAVSIM concept, the one-vehicle, single-route notion is replaced with vehicle control paradigms for multiple types of vehicles in user-specified numbers, route optimization routines for multiple vehicles, and vehicle intradependent proximity behavior logic necessary to simulate coordinated vehicle movements involving multiple vehicles. In addition, simulated visuals from virtual terrain sensors onboard an unmanned vehicle could be used to present visual cues of the target airspace.

Imagine having the flexibility to model and simulate a wing of fully coordinated and intradynamically linked ucavs flying in formation until they break-off from each other to pursue individual mission objectives, and then later converge as they complete their mission to return home. System users of LNAVSIM will be able to model and simulate various battlespace conditions, and confront them with open and flexible user defined LNAV scenarios. This is the concept of operations provided by the LNAVSIM analysis environment.

3.2 UAV Command and Control

Command and control is entering a new era. There are several forces at work that will soon make the synchronous 24 - 72 hour process too unwieldy. One of those forces in the employment of unmanned aircraft whose control is inherently asynchronous. New tools will be required to address the new weapons systems being developed.

A key part of the LNAVSIM program is the LNAVGEN component, which provides software tools for target allocation, route planning, swarm management, evaluation, and analysis. The LNAVGEN tool is an example of the type of mission planning tool that can address the mission planning needs of uavs and ucavs. ORCA technology, accessed through the LNAVGEN, can provide the operator with automated target allocation, route planning, group planning for a pod of vehicles, and analysis and evaluation tools. These tools present the operator with actionable intelligence - information that is presented in a form that enables the operator to do something constructive - and the decision aids help to increase the operator's span of control. The SEM is a key ingredient of the allocation process.

3.2.1 Actionable Intelligence

A current important phrase for designing and evaluating C2 technology is "actionable intelligence." What it means is that information that is presented to an operator should be in a form that enables the operator to do something constructive. In general, we expect the tools we are designing to increase user situation awareness and to display data in such a way that it shows the situation and highlights potential actions. When a threat pops up or a new target presents itself, our goal is to quickly be able to present the operator with at least one choice of a response and provide quantitative data scoring for the various response options. For example, if a threat pops up, our tools can provide metrics, such as survivability and mission effectiveness, for the current route given the new threat. The operator can compare these metrics with the original route metrics and determine if replanning is necessary. After using the autorouter to replan the route, the operator can view the metrics for the new route and compare them with the metrics for the current route plan before assigning the new route to the vehicle. ORCA's automated tools can produce the metrics and plan the routes quickly, allowing the operator sufficient time to analyze the options.

3.2.2 Span of Control

The number of aircraft controlled by each operator is the span of control. Automated planning tools increase the operator's span of control by shifting much of the mission plan workload to the computer, thus freeing the operator to concentrate on other tasks, such as analyzing SAR images and other intelligence data. Increasing the span of control while maintaining effectiveness is a goal of several unmanned aircraft programs. Currently, some unmanned vehicles require more than one operator to control a single vehicle. One operator controls the aircraft while others are in charge of managing the sensors and analyzing sensor data. We envision a single operator controlling multiple aircraft using LNAVGEN. Increasing the capability of C2 decision aids and automating tasks such as target allocation and route planning can help increase the span of control.

3.2.3 Managing the SEM

The SEM is a key element of the allocation process and aids in coordinated group planning by modeling the synergetic effects produced by pairs of missions. It enhances the operator's ability to model objective values and enriches the allocation process, but requires an ongoing effort to manage and update the values for objectives and synergetic effects. ORCA is designing automated SEM population tools that will help lessen the burden on the operator. ORCA is also researching methods to generalize the SEM concept from pairs of tasks to groups of tasks. Such a generalization will offer more flexibility to decision makers and planners.

3.3 Pod Control Concepts

3.3.1 Pod Control

A group of uav/ucav needs to be controlled. When given an appropriate set of mission objectives for the aircraft and the threat laydown, LNAVGEN tools can be used to automatically allocate aircraft to objectives, generate route plans, analyze the proposed routes, and dynamically replan missions while the aircraft are in flight due to any changes in the planning problem. An LNAVGEN client application, such as the POPI, allows the operator to access LNAVGEN mission planning functionality for pod control and provides visualization of mission plans.

3.3.2 Multiple Operators

The LNAVSIM architecture allows multiple LNAVGEN clients to operate simultaneously. The JFACC has the responsibility of allotting aircraft and mission tasks to each operator. Each operator then develops detailed mission plans for his group of vehicles.

3.3.3 Dynamic Planning

The LNAVSIM researcher/analyst will have the capability to autonomously reallocate mission objectives and recalculate an optimal flight plan based on pop-up threats, a mission replan or an operator approved command redirect and provide the flexibility to update the current flight plan in near real-time.

4 LNAVSIM Software

During Phase II, ORCA developed LNAVSIM software that provides the Air Force with a state-of-the-art air war planning, modeling and simulation environment. Using a spiral development approach, ORCA designed four versions of the LNAVSIM software. Each version was shared with AFRL for input on the design and features. The ORCA-AFRL interactions helped shape the final version of the software. The final design of Phase II includes features and components that were not part of the original Phase II proposal but were identified during Phase II R&D. The culmination of this Phase II SBIR effort was the release of the LNAVSIM Version 1.0 software.

LNAVSIM 1.0 software is designed to offer flexibility to the user. Although LNAVSIM is designed as a distributed computing environment, all components could be hosted on one machine. Some components, such as the LNAVGEN mission planning component, can be used as stand-alone tools. LNAVSIM is a flexible plug-and-play environment that supports component swapping, including simulation environments. The components of LNAVSIM can be hosted on PC or Linux platforms.

4.1 LNAVSIM Architectural Design

The diagram below gives the high-level architecture of the LNAVSIM environment.

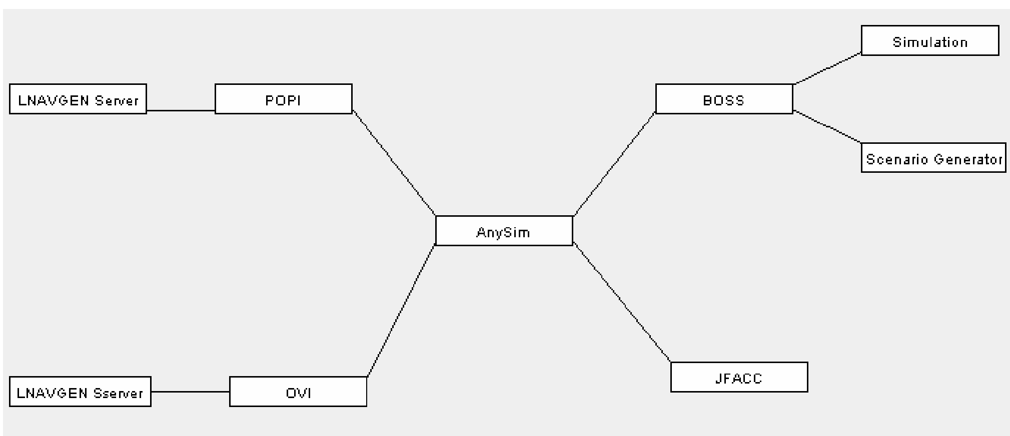

Figure 4 LNAVSIM Architecture

LNAVSIM consists of multiple components, which are discussed in detail in section 3.2. The AnySim component is the hub of the LNAVSIM environment. Its main function is to handle mail message traffic between the components. The Pod Operator Planning Interface (POPI), a prototype mission planning station developed by ORCA, and the Operator Vehicle Interface developed by AFRL are client applications that access the mission planning and analysis services of the LNAVGEN Server. The JFACC component is a basic planning tool for the commander. It provides tools for setting objective and synergetic values and assigning aircraft and objectives to pod operators. The BOSS component is used to set up and manage the scenario and the simulation environment. LNAVSIM 1.0 has interfaces with the OPUS 3, JIMM, and Supressor simulations.

The LNAVSIM components work together in a distributed computing environment. The components interact using the Remote Method Invocation (RMI) and the Simple Object Access Protocol (SOAP). This design gives LNAVSIM the ability to run across multiple machines using different operating systems. The main languages of LNAVSIM are Java and C++, which allows LNAVSIM components to be hosted on PC or Linux platforms. The diagram below shows the types of messages and data that are passed between components.

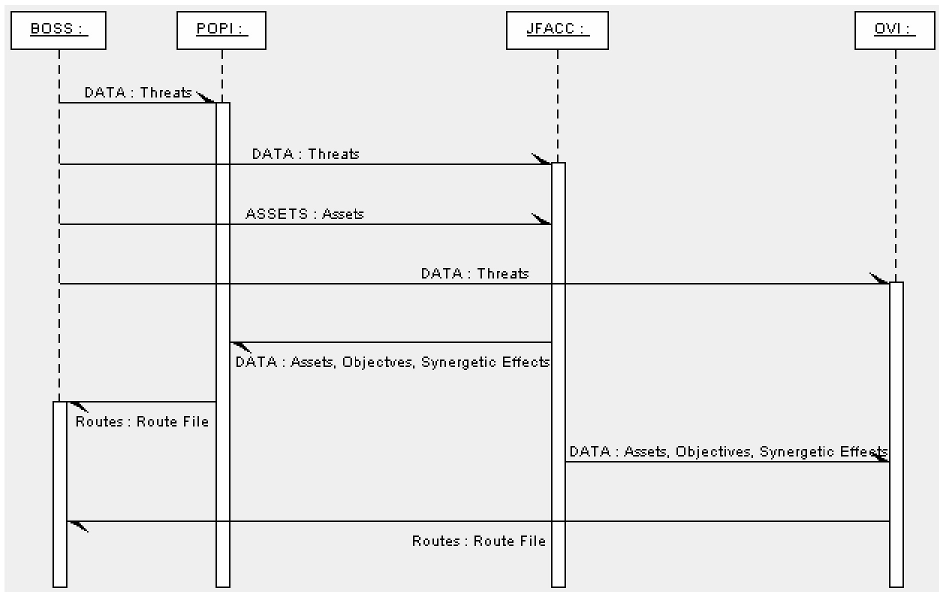

Figure 5 LNAVSIM Component Communications

4.2 Components

4.2.1 LNAVGEN

The Large Number of Air Vehicles Generator (LNAVGEN) is a stand-alone mission planning component that provides tools for an operator to control a group of vehicles. It consists of two sub-components, the LNAVGEN client and the LNAVGEN server. These components provide services for allocating aircraft to mission tasks, generating route plans, evaluating and analyzing mission plans, as well as visualization tools to display the threat laydown and view mission plans and sortie routes.

The LNAVSIM architecture supports the use of multiple LNAVGEN components. Each LNAVGEN could serve as the planning station for a wing or the control station for a pod of unmanned vehicles.

4.2.1.1 LNAVGEN Client

A client application is used to access the mission planning services of the LNAVGEN Server. ORCA has developed a client, called the Pod Operator Planning Interface (POPI), which is a prototype pod operator mission planning station. AFRL is developing the Operator Vehicle Interface (OVI), which can also serve as an LNAVGEN client. Other clients could be developed to use the services of the LNAVGEN Server.

4.2.1.2 Pod Operator Planning Interface (POPI)

The POPI is a sample client for the LNAVGEN Server. It represents a simple way in which one can take advantage of all the functionality bundled into LNAVGEN. The POPI represents one view of managing a group of assets.

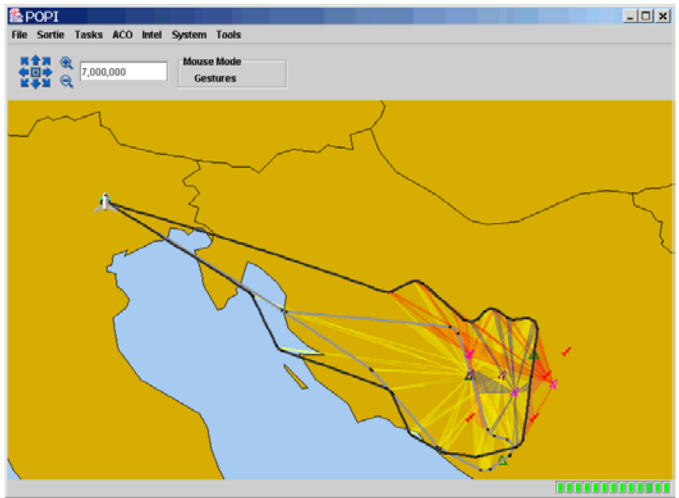

Figure 6 Pod Operator Planning Interface (POPI)

The POPI provides a variety of evaluation and analysis figures of merit to the operator, including probability of survival, number of shots by threat type, track time by radar type, exposures to radar, and radar probability of detection. When a new event is received from the simulation, FOMS are recalculated for the original route. If a new route is planned, FOMs for the original and new routes are displayed before the new route is accepted or rejected.

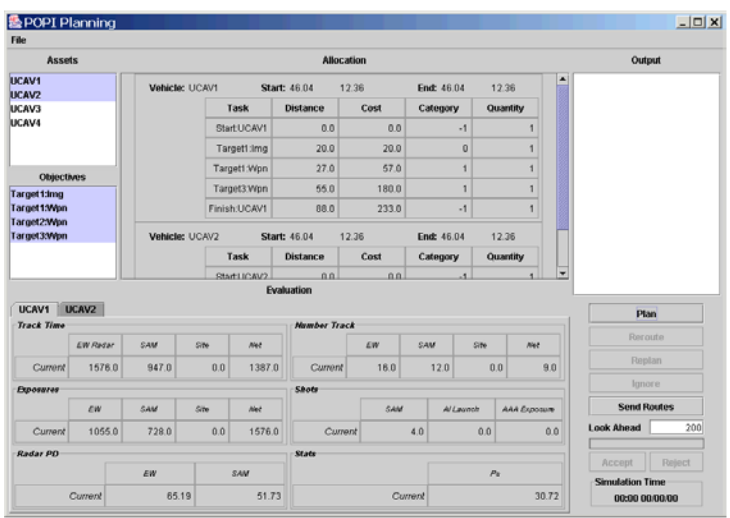

Figure 7 POPI Planning Dialog with Figures of Merit

4.2.1.3 LNAVGEN Server

The LNAVGEN server provides planning services to the LNAVGEN client by accessing OPUS 3 services for allocation, autorouting, evaluation, analysis, data management, and the Swarm Management component. The allocation service produces an ordered list of mission tasks, called a "tie-up," for each vehicle. The tie-ups serve as an input to the autorouter. Once routes are generated by the autorouting service, the client can call the evaluation and analysis services for route metrics. The flocking service, which is provided by the Swarm Management component, provides an alternative method for generating routes for groups of vehicles.

4.2.2 JFACC

The force commander uses the JFACC component to make high-level allotments of aircraft and mission tasks to pod operators, who then develop detailed mission plans using the LNAVGEN component. The JFACC component is also used to set values for mission tasks and synergetic values for pairs of tasks.

The diagram below shows the JFACC map display, dialogs for making assignments of assets and objectives, and the SEM tool, which is used to set task values.

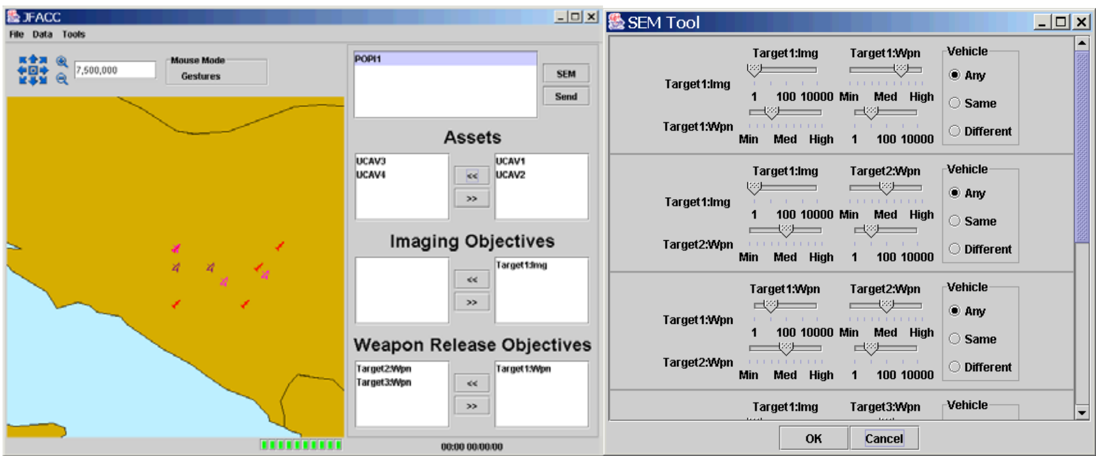

Figure 8 JFACC Component GUI and SEM Tool

The JFACC component was an idea that emerged during the LNAVSIM Phase II development process and was not part of the original design. In its current form, the JFACC component is limited to the manual allotment of aircraft and mission tasks to pod operators and assignment of values to mission tasks, as part of the POPI initialization process. The JFACC component could be outfitted with automated planning tools for force level allocation. In an IR&D effort, ORCA is investigating automated SEM population methods, which could be used by the JFACC component.

4.2.3 AnySim

The AnySim component is the hub of the LNAVSIM environment. The idea for AnySim was conceived in an ORCA-AFRL brainstorming session early in the LNAVSIM Phase II program and was envisioned to serve as a single, stable, well-defined interface to provide plug-and-play capability to *any sim*ulation (hence the name, AnySim). During Phase II design and development, the AnySim evolved into a component through which LNAVSIM components communicate.

As currently implemented, the AnySim is used to set permissions for components to participate in the LNAVSIM environment, register components, set rules for mail message traffic between components, assign transformations, control when the simulation starts and stops and its pace, and manage the mail message traffic between components.

4.2.3.1 GUI

The AnySim has a graphical user interface (GUI) through which its functions are controlled and some component activities can be monitored. The GUI has a window that displays information about the interaction between components and another that shows the registered components.

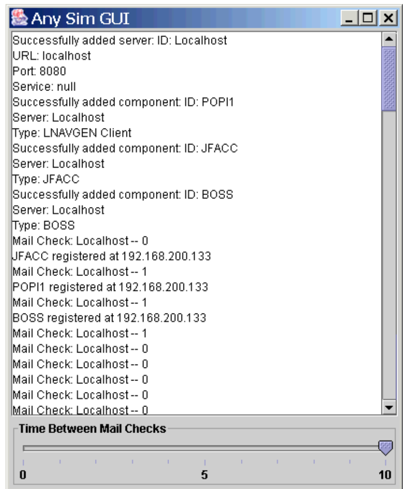

Figure 9 AnySim GUI

4.2.3.2 Interface

The components of LNAVSIM communicate via mail messages and the AnySim serves as the central post office for all mail message traffic. Each machine hosting LNAVSIM components will have an AnySim Interface, which serves as a local post office to handle all mail for the components on that machine. The AnySim checks periodically with each AnySim Interface for mail messages.

4.2.3.3 Mail Messages

The components of LNAVSIM communicate via mail messages using the Simple Object Access Protocol (SOAP) mail message protocol. SOAP allows applications to communicate using hypertext transfer protocol (HTTP), which is supported by all Internet browsers and servers. SOAP provides a platform-independent and language-independent method for applications to communicate. SOAP messages are formatted using the eXtensible Markup Language (XML). XML is similar to HTML in that it uses tags and attributes, but XML is fundamentally different than HTML: HTML is used to display data and XML is used to describe data.

To communicate using SOAP, a sender must package a message as a SOAP message and the receiver must have a way to identify the message as a SOAP message and direct it to the appropriate service. Tomcat and Axis are the enabling technologies for these processes. The sender uses Axis to package a message as a SOAP message. The receiver side has multiple services for processing the message: the Tomcat web server, the Axis

SOAP server, and the LNAVSIM services used by Axis such as the LNAVGEN Server and the Scenario Generator. Tomcat, unlike some other web servers, has the ability to recognize an XML message, which is necessary when using SOAP. Tomcat parses any XML messages it receives. If the message is a SOAP message, Tomcat will find a tag that will cue Tomcat to forward the message to Axis, the SOAP server. Axis forwards the request to the appropriate LNAVSIM service.

The diagram below gives details of the mail process.

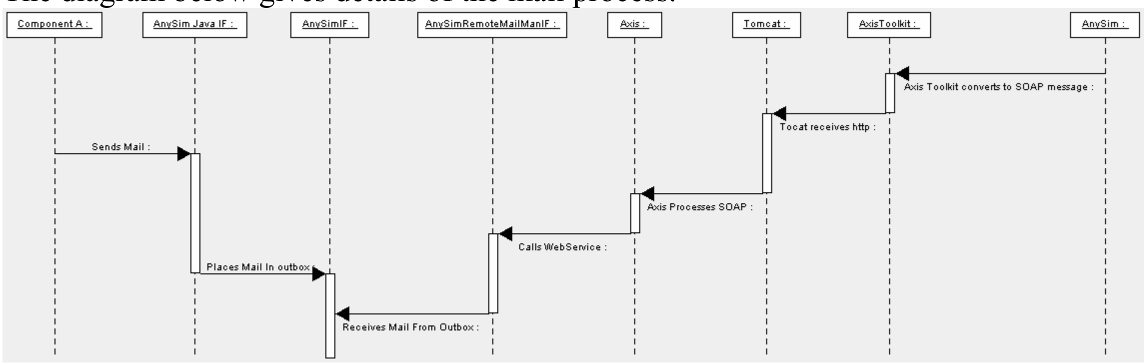

Figure 10 Mail Message Details

4.2.4 BOSS

The Broad Overseer of the Scenario and Simulation (BOSS) component is used to help set up the scenario and to make changes to the state of entities during the simulation. The subcomponents of the BOSS are the Scenario Generator and the Simulation Interface.

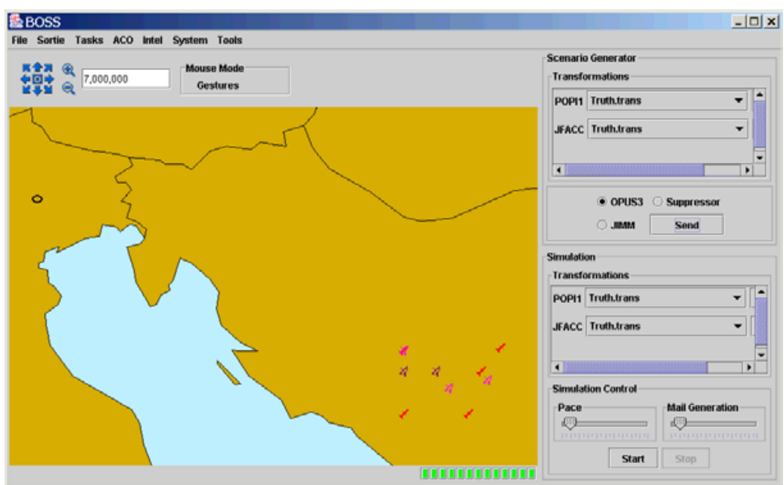

Figure 11 BOSS GUI

The BOSS has access to all scenario data and knows all LNAVSIM players. The BOSS can change the initial threat laydown and is responsible for setting transformations for each POPI. During the simulation, the BOSS is able to add or delete entities (vehicles, targets, etc.) in the simulation.

4.2.4.1 Scenario Generator

The Scenario Generator is a GUI-less server that provides initial target and threat location data to the LNAVGEN clients. The Scenario Generator imports scenario data from the simulation, prepares a data file for each LNAVGEN client by applying the transformations for that client to the ground truth data obtained from the simulation, and then sends data to the clients.

4.2.4.2 Simulation Interface

The plug-and-play nature of LNAVSIM allows any simulation to be used by LNAVSIM, provided the simulation has an interface with the AnySim component. The Interface Design Document (IDD) provides the simulation interface requirements. The final version of LNAVSIM developed in Phase II of this SBIR program can interface with the JIMM, Suppressor, and OPUS 3 simulation environments.

The simulation interface passes sortie routes from LNAVGEN clients to the simulation and sends back updates on sorties and changes in targets and threats. Update messages from the simulation are filtered and transformed according to transformation rules by the simulation interface and then sent to individual pod operators.

4.2.4.3 Transformations

Transformations are a device to filter and control the information provided to each LNAVGEN Client. Just as in a real combat situation, mission plans in LNAVSIM will be affected by an operator's perception of the battlefield. This perception is based on the intelligence information available to the operator and in most cases will differ from ground truth. For example, the aircraft under the control of an operator may not be capable of detecting threats of a certain type, in which case the operator would not know about these threats unless she had another intelligence source. Transformations are used in LNAVSIM to simulate these intelligence gaps.

Transformations are defined for each LNAVGEN Client in the BOSS component and implemented in the Scenario Generator and Simulation Interface.

4.2.5 Simulation

The simulation engine is the driving force behind the dynamic LNAVSIM air war environment. Without the simulation, the components of LNAVSIM are reduced to static planning and computing tools that solve single pre-mission planning problems. The simulation provides dynamic events such as pop-up threats, time-critical targets, and changes in aircraft status. The simulation could also model weapon and sensor effectiveness, and provide data about target damage and target/threat detection. The simulation is initialized with the ground truth. It executes sortie route plans as they are received and can change the status of threats and targets. It also provides the clock for the LNAVSIM environment. LNAVSIM Version 1.0 has interfaces with the OPUS 3, JIMM, and Suppressor simulation environments.

4.2.6 Route Export to VBMS

The Virtual Battlespace Management System (VBMS) supports visualization of large-scale tactical engagements. VBMS was originally developed at Wright Laboratories, Wright-Patterson Air Force Base. It was modified and then integrated with MIL-AASPEM by Charles River Analytics.

Any vehicle routes generated by the LNAVGEN server are written out in VBMS format, in addition to the OPUS format used by LNAVSIM components. The VBMS route files can then be opened and viewed with VBMS.

4.3 LNAVSIM and OPUS

LNAVSIM components use OPUS 3 services for mission planning, evaluation, analysis, simulation, and data management. These services can be accessed directly through the OPUS API or across the Internet as web services.

4.3.1 OPUS API

The OPUS API is a set of software libraries and interfaces that allows other programs to access the non-graphical mission analysis, vehicle allocation and autorouting functions of the interactive version. LxOPUS API is a version of OPUS that runs on the Linux operation system.

4.3.2 OPUS Services

4.3.2.1 Autorouting

The autorouter component produces threat-avoiding, goal-seeking, terrain-aware routes for aircraft with conventional or Low Observable (LO) Radar Cross Section (RCS) signatures. It contains threat analysis techniques that result in route generation speeds far faster than traditional time step / ray trace approaches.

4.3.2.2 Target Allocation

The target allocation component assigns vehicles to sets of target objectives to achieve force application goals. The assignment process considers vehicle resources such as fuel and available weapons and sensors, assignment costs such as vehicle value and probability of arrival, and target values.

4.3.2.3 Evaluation

The evaluation component provides information about how a route interacts with the theater battle space.

4.3.2.4 Analysis

The analysis component provides a variety of figures of merit for attrition analysis and mission effectiveness. A documented C^3I model that includes hierarchical defense command modeling, radar detection, and SAM engagement and AI end-game models are implemented.

4.3.2.5 Data Management

The data component provides a mechanism for managing all data needed by the other components.

4.4 HLA Compliance

The High Level Architecture (HLA) is a general-purpose architecture developed under the leadership of the Defense Modeling and Simulation Office (DMSO) to support reuse and interoperability across the large numbers of different types of simulations developed and maintained by the DoD.[5] The intent of this architecture is to encourage the interoperation of simulations and the reuse of simulation components. HLA provides standardization of models, templates, and interfaces to facilitate simulation interoperability.

LNAVSIM Version 1.0 uses a simulation to drive the dynamic environment. In the sense of HLA, LNAVSIM components are subcomponents of the simulation and provide data to the simulation. LNAVSIM does not directly interoperate with multiple simulations. The simulation being used by LNAVSIM may interact with other simulations. In that case, the HLA issues apply to the interoperability of those simulations.

5 LNAVSIM Studies

ORCA performed three studies during Phase II to demonstrate LNAVSIM tools and to provide blueprints for the types of mission planning studies that can be conducted using LNAVSIM. An important part of any study is setting up the data and these studies give insights into the type of data required by LNAVSIM components.

Below is a summary of each of the studies. It should be noted that the target, threat, aircraft, sensor, and weapon data used in the studies was not real data, and therefore not much weight should be put on the specific results. If the same study is performed with real data, the results may vary.

5.1 Study 1: Sensor, Jammer, Shooter

In this study, we used LNAVSIM tools to investigate the effects of jamming of threats on aircraft mission effectiveness and survivability. We considered how jamming can enhance missions and looked at the consequences of failing to execute jamming missions. If plans are generated assuming threats will be jammed and then the jamming is not performed, aircraft could be more vulnerable than if the planning were performed without the assumption of jamming being present. This type of study can help planners decide how best to incorporate plans for jamming into the overall planning process.

The results indicated that if routes are planned and evaluated, exposures to threats are identified, and those threats are jammed, then the quality of the mission is improved. However, if missions are planned with the assumption that jamming will be performed and it is not, the mission quality is diminished.

[5] DMSO website: https://www.dmso.mil/public/transition/hla/

5.2 Study 2: Hunter-Killer

The Hunter-Killer scenario involved searching for a target and releasing a weapon against it once its location has been determined. In the Hunter-Killer study, a target was located (imaged) and then a weapon was released against it. We investigated the influence of the aircraft's weapon and sensor configurations on route quality. We also compared the results of using one aircraft versus two aircraft to perform the mission. The results of the study indicated that the choice of weapon type influences mission quality.

5.3 Study 3: UCAV Command and Control

The LNAVSIM report "Command and Control Issues in UAV Operations" discussed a number of topics related to unmanned air vehicle operations. One important issue raised in the report was "span of control": the number of unmanned aircraft controlled by an operator. Automating mission planning tasks helps to increase the span of control by freeing the operator from some planning duties. It is important to investigate which tasks can be automated and which tasks should be left to the human operator.

ORCA has developed decision aids and automated tools to assist an operator controlling a group of aircraft. In this study we focused on the allocation service as a decision aid. ORCA's HEX target allocation tool can be used to generate assignments of aircraft to mission objectives, such as sensor imagining assignments and weapon release tasks. ORCA's SEM is a key ingredient of HEX and a useful decision aid for the operator. The SEM enhances the ability of the operator ability to model mission objective values and enriches the allocation process.

LNAVSIM components make use of the HEX tool and the SEM. The POPI is used to generate mission assignments and route plans for a group of aircraft. Values for the SEM can be set using the JFACC component. These values are sent by the JFACC to the POPI, which passes them along to the LNAVGEN server when the allocation service is called. The LNAVGEN server accesses the HEX tool through the OPUS API to generate the allocation for the POPI.

In this study, we used LNAVSIM to compare the results of allocating with and without using automated target allocation. To investigate the impact of the SEM, we compared results for various parameter settings. The study indicated that the SEM and automated allocation tools used in LNAVSIM would produce coordinated and cooperative assignments without degrading mission quality.

6 LNAVSIM: The Future

During Phase II, ORCA has designed and developed a number of components and tools that comprise the LNAVSIM air war modeling, planning and simulation environment. However, LNAVSIM is a work in progress and ORCA's vision of LNAVSIM, summarized in this document and presented in more detail in "Operational Concepts", extends beyond the current implementation. In this section, we give some possibilities for LNAVSIM enhancements. As we have done throughout Phase I and Phase II, we present these ideas as a way of stimulating discussions with AFRL about the possibilities for development in a Phase III effort.

6.1 Architecture and Design Assessment

The LNAVSIM Version 1.0 software represents one implementation of the LNAVSIM vision. The first step in designing an enhanced LNAVSIM environment will be to assess the strengths and weaknesses of the current architecture and individual components. This assessment has already begun at ORCA.

One important aspect of the design that is not apparent to LNAVSIM users is the middleware that allows communications between distributed components. ORCA has learned about middleware possibilities through this R&D effort. We have ideas about how to improve on the current implementation. A goal for next version of LNAVSIM will be to simplify the middleware and mail message handling. Possibilities include eliminating the use of RMI and using the Direct Internet Message Encapsulation (DIME) format to improve interoperability between Java and .NET.

6.2 Enhanced Tools

Experience from the LNAVSIM software development process and in-house OPUS 3 R&D have given us ideas for enhancements to current LNAVSIM tools and components.

6.2.1 Improved Set of FOMS

For OPUS 3, ORCA is considering several new analysis features, including an expanded set of FOMs, which will provide planners with more decision aids. In particular, ORCA is investigating force-level mission effectiveness metrics and allocation metrics, and temporal based metrics. New OPUS 3 metrics and analysis tools will be available for use in LNAVSIM components through the OPUS API or as a web service.

6.2.2 Flocking

The current flocking capability allows routes to be generated for groups of vehicles and is similar to the "boids" implementation of Reynolds. However, ORCA's flocking algorithm uses the notion of a virtual lead route – a route that the group tries to follow while obeying other flocking rules. The flocking algorithm generates the virtual lead's route. A possible change would be to design a graphical tool that would allow the operator to draw the virtual lead's route on the map display.

Another area to investigate is the concept of operations for groups of vehicles on the order of one hundred, or even one thousand, vehicles. The role of flocking will become more important if the notion of "large numbers" is increased one or two orders of magnitude.

6.2.3 Deconfliction Tools

Through OPUS R&D, ORCA has developed a prototype time-line viewer that provides a tool to identify and resolve route conflicts for a group of vehicles. The tool flags routes that fall within a safe buffer around other vehicles' routes and allows the user to change the start and/or end times of routes to remove these conflicts. An operator could use this automated planning aid during the route planning process for a pod of vehicles. It could also be used by the JFACC when evaluating force-level plans

6.2.4 Automated Tools for the JFACC

In the current implementation, the tools for the JFACC are all manual. ORCA is investigating automated methods for populating the SEM. ORCA is also researching alternative allocation methods, including automated tools for force-level allocation that are less detailed than those currently employed in the LNAVGEN component. With such a tool, the JFACC could make high-level allocations, and leave the detailed planning to the pod operator.

As mentioned above, the time-line viewer may be another automated tool that could be used by the JFACC.

6.3 New Features

In our on-going research effort, we recently come across research that has given us ideas for new features for LNAVSIM. Below we discuss two possibilities: vehicle communications models and the use of multiple simulations.

6.3.1 Vehicle Communications Models

In the paper "Minuteman: Forward Projection of Unmanned Agents Using the Airborne Internet"[6], written in support of the ONR's MINUTEMAN (Multimedia Intelligent Network of Unattended Mobile Agents) project, the authors frame the importance of autonomous agents such as unmanned ground and air vehicles ("agents") in the future battlefield. Agents will be grouped into clusters and efficient communication between agents (including agents from different clusters) will be critical to the success of missions. Missions need to be carefully scheduled, coordinated, equipped with adequate resources, and monitored. LNAVSIM provides a platform to accomplish many of these goals (e.g. monitoring or scheduling). The goal of the MINUTEMAN project is to work on the concept of an agile and dynamic "Internet in the Sky" that can support the demanding communication requirements of unmanned missions.

The description of the MINUTEMAN project lists some of the communication challenges that unmanned missions encounter, such as agent mobility, quality of service, and environment changes including losing key assets. LNAVSIM uses transformations to model the "Quality of Service" that a monitoring agent, like the POPI or OVI, receives.
The paper makes a clear argument that communication amongst a large number of air vehicles is a vital function and an important topic for research. There are many possible schemes to handle communication between air vehicles and controllers. A "plug and play" communication model would enhance the utility of LNAVSIM for communication studies in a simulated environment.

[6] "Minuteman: Forward Projection of Unmanned Agents Using the Airborne Internet", Mario Gerla, Kaixin Xu, Computer Science Department, University of California Los Angeles; Allen Moshfegh, Office of Naval Research

6.3.2 Incorporate Other Simulations

Incorporating a wider range of models and simulations would enhance LNAVSIM analysis and simulation possibilities. In the paper "A Case Study on Model Integration, Using Suppressor"[7], Gregory Douglas presents techniques to allow the integration of multiple models and simulations. An environment that supports the integration of external models and simulations should help increase the use of modeling and simulation technologies, a desire of the Department of Defense (DoD). Suppressor already provides rich analysis capabilities so it was chosen as the "glue" simulation that would hold everything together. It was modified to allow any piece of data to originate from an external simulation. This was accomplished by modifying the interface architecture to Suppressor so that a simulation that implemented the interface could be "plugged in". The user would be able to choose what model(s) or simulation(s) would control an entity's movement, the Command and Control system, sensors, and weapons.

The ability to integrate simulations and models should result in an increased use of simulations. LNAVSIM similarly allows an ability to use different simulations, with different model fidelities. By facilitating the ability of other simulations to "plug-in" to LNAVSIM, richer analysis will be possible because results from multiple models can be used to enhance algorithms.

7 Conclusion

This is the final report of the ORCA LNAVSIM SBIR Phase II effort. During Phase II, ORCA continued the research effort begun in Phase I and implemented a prototype LNAVSIM environment: LNAVSIM Version 1.0. During our research effort and development of LNAVSIM V1.0, we have gained valuable insight into the LNAV modeling, mission planning, and simulation problem and the challenges of developing a flexible distributed, open architecture in which software tools interact to form a dynamic LNAV simulation environment.

The LNAVSIM software designed during this effort represents state-of-the-art technology for mission planning, modeling, and simulation. ORCA is prepared to leverage the knowledge and experience gained through this program and our on-going in-house R&D efforts to enhance the LNAVSIM architecture, algorithms, and tools in a Phase III effort.

[7] "A Case Study on Model Integration, Using Suppressor", Gregory Douglas, L-3 Communications Corporation, Link Simulation and Training Division