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MIXED INITIATIVE CONTROL OF AUTOMA-TEAMS, OPEN EXPERIMENTATION PLATFORM

McDonnell Douglas Corp., The Boeing Co.

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13. ABSTRACT *(Maximum 200 Words)*
The MICA Open Experimentation Platform (OEP) successfully provided an integration framework for MICA controllers and experimentation platform for simulation, demonstration, assessment and transition of MICA research to operational systems. Accompanying Challenge Problems (CP) provided a challenging environment and C2 products representative of real world Intelligence Preparation of the Battlefield (IPB), Commander's Guidance and Rules of Engagement (ROE). The CPs also incorporated a red force controller that enabled intelligent adversarial reactions including an Integrated Air Defense System (IADS). The combined OEP/CP capabilities represented a challenging but manageable 3 to 5 day air campaign encompassing all elements of the Target Kill Chain. This report describes the OEP/CP capabilities and summarizes experimentation performed on MICA research artifacts using the OEP and CP.

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1 Summary

The MICA Open Experimentation Platform (OEP) successfully provided an integration framework for MICA controllers and experimentation platform for simulation, demonstration, assessment and transition of MICA research to operational systems. Accompanying Challenge Problems (CP) provided a challenging environment and C^2 products representative of real world Intelligence Preparation of the Battlefield (IPB), Commander's Guidance and Rules of Engagement (ROE). The CPs also incorporated a red force controller that enabled intelligent adversarial reactions including an Integrated Air Defense System (IADS). The combined OEP/CP capabilities represented a challenging but manageable 3 to 5 day air campaign encompassing all elements of the Target Kill Chain. The OEP and CP development strategy relied on early release of initial capabilities with frequent incremental upgrades prioritized to meet multiple research objectives. This strategy was successfully employed with the initial release of a substantial capability occurring within 60 days after contract award. This early release was crucial to enticing researchers to use the OEP rather than their in-house simulations. Subsequent OEP and CP releases consistently led researcher needs such that critical research was never hindered by a lack of OEP capability.

Boeing planned to conduct extensive experimentation as described in Appendix A. Unfortunately, MICA research was pre-maturely terminated due to evolving priorities within DARPA. Only two of the available controllers were submitted to Boeing for evaluation and both were less capable than would have been the case if planned research had been completed. Never the less certain conclusions can be drawn from the limited research. Both controllers exhibited a hierarchical decomposition of the challenge problem and allocated teams of assets to subsets of known targets. However, the construct of their team appears more to be a product of the logical partitioning of the challenge problem for planning simplification, rather than the grouping of assets that dynamically and purposefully cooperate. Both controllers provide capability to address the inherent uncertainty of knowledge of the battlespace such as Draper's Information Model and Iterativity's VII IPB interface. Both controllers have a broad Variable Initiative Interface (VII), albeit of varying levels of maturity and utility. Both controllers use Commander's Guidance and ROE to adjust target values but do not actively drive team composition, tasking or tactics based on guidance or ROE. Both controllers evidenced coordinated team tactics and planned asset flight paths in response to either team assignment or task allocation. Both rely on a centralized planning and control paradigm in which all replans are global and are executed when changes to the centralized database occur. Unfortunately, some of these replans were unnecessary (insignificant change to the centralized database) or should have been local rather than global. Furthermore, since each controller reacts to a limited subset of available events, many needed replans do not occur. For example, neither controller reacts to threat warning receiver events. The result is that all intra-team coordination is the consequence of *a priori* centralized scheduling or sequencing. There is no provision for rapid localized coordinated activities involving individual vehicles or groups of vehicles. Details of our experimentation results are provided in section 5.

The shortcomings of these controllers can best be appreciated through comparison with traditional air campaign C^2 approaches. In September 2003 MICA personnel visited to 133rd Iowa Air National Guard (ANG) to observe how they would prosecute the Challenge Problem. The intent of the visit was to develop a baseline to which MICA controllers could be compared. The 133rd ANG took a completely top-down approach to the problem. They allocated available resources into five primary teams, each composed to address their assigned objectives. The two largest teams were tasked to eliminate the enemy IADS by destroying their C^2 facilities. Two smaller teams were tasked with detecting and neutralizing enemy SSMs. The final team was held in reserve to protect the blue base, if necessary.

The 133rd ANG approach to problem decomposition was "solution centric" or effects based, i.e. "to defeat the enemy, we must do this, and this, and this…" and their solution started with a functional decomposition. In their effects-based approach they: 1) developed a hypothesis of the battle space based on available IPB, 2) selected specific actions to elicit responses from the uncertain enemy force structure to improve situational awareness, 3) chose major "high value" objective i.e. disable C2 facilities, 4) established an order to the battle, 5) task two separate simultaneous "waves" at C2 facilities, and 5) established a multi-pronged plan of attack that avoided sequential flight through layers Air Defenses to reach the chosen objective. The ensuing functional decomposition focused on team composition and task assignment. Two teams were composed to strike against the enemy center of gravity ~ C2 facilities. Wave one, tasked to find and locate SAMs included nine heterogeneous assets with mostly sensors and decoys. Wave two, tasked with clearing a path to and disabling command centers, included 12 heterogeneous assets with sensors, jammers, and shooters. Interdiction against Time Sensitive Targets tasking was given to 11 heterogeneous assets (sensors and shooters) that were split evenly by capability into two teams searching for TELs loosely located by IPB information. Blue base protection tasking was given to the six remaining assets (2 large sensors, 4 small weapons). These were allocated to CAP missions located between IPB indicated "red ground forces locations" and the Blue Base. The high endurance sensor platforms were tasked to stay on station while the low endurance small weapon platform divided with two on station and the remaining two as replacements remaining at the base. Although resource constraints prohibited subsequent execution of the 133rd ANG strategy, we are confident that their approach would result in an effective strategy for using the available assets.

A significant lesson learned is the importance of early experimentation. During the brief experimentation conducted we were able to work with the researchers to achieve significant improvement in their capabilities. We are confident that, if more time had been available, they would have achieved considerable success in executing the CP. The original MICA program plan called for experimentation in the 4th quarter of CY 02. This experimentation was replaced by a set of capabilities demonstrations. Although these demonstrations were deemed a success at the time, they eventually proved a detriment to the program when viewed in the context of premature termination. The end result is that because experimentation was delayed, researchers failed to receive valuable feedback that would have greatly improved their end products.

2 Introduction

Teams of unmanned platforms operating under guidance and management of a human operator can have a major impact on achieving battlefield success. The MICA program addressed fundamental technologies for control of teams of unmanned platforms. The MICA vision spans the waterfront of activities required for development and transition of these technologies to military forces. It includes: 1) Composing heterogeneous teams of heterogeneous unmanned platforms with mixed weapon and sensor packages to perform reconnaissance, strike, battle damage assessment and force protection activities; 2) Allocating tasks based on commanders guidance and ROEs; 3) Path planning activities for teams of platforms including collision avoidance and threat avoidance/engagement; 3) Defining effective team tactics to discover and attack enemy forces using real-time information; and, 4) Providing information to human operators / managers sufficient for effective control and decision making;

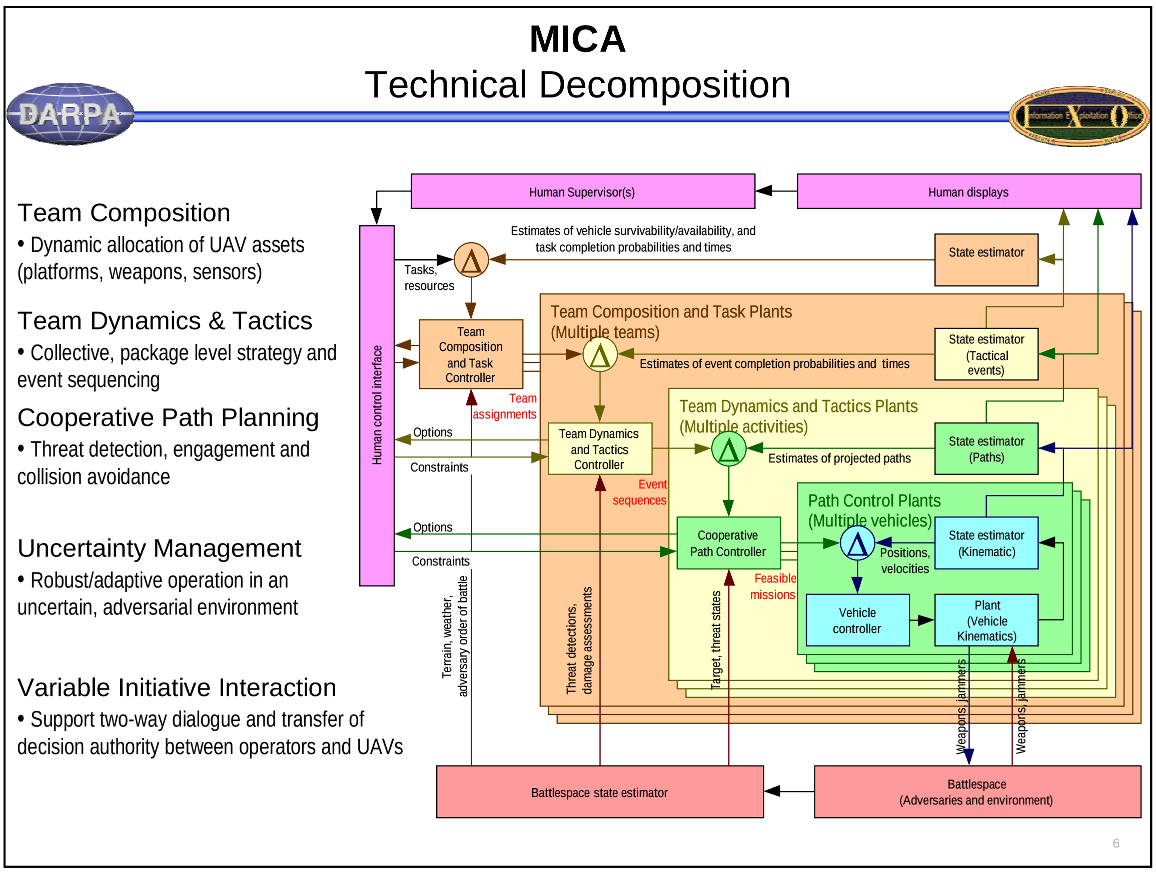

Figure 2-1 - MICA Functional Decomposition

To this end, the MICA Program focused effort in the following research areas, Figure 2-1:

a. Team Composition and Tasking (TCT)
b. Team Dynamics and Tactics (TDT)

c. Cooperative Path Planning (CPP)
d. Uncertainty Management (UM)
e. Variable Initiative Interaction (VII)

Specific Goals of MICA research included: 1) Achieve M operators << N vehicles (1:5 by 2003 and 1:30 by 2005), 2) Speed the sensor-to-shooter cycle, 3) Cooperatively couple sensing and strike, 4) Enable flexible self-reorganizing teams, and 5) Allow event-driven dynamic re-planning.

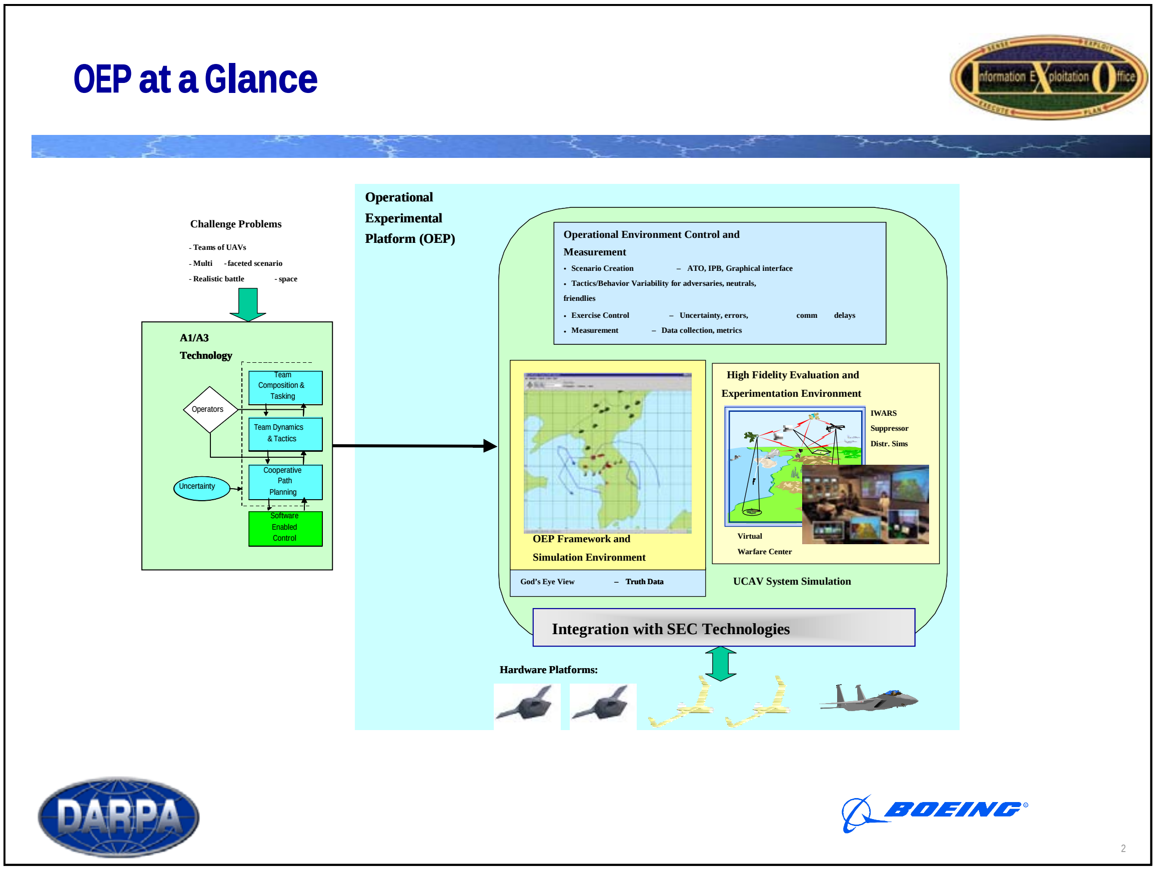

Figure 2-2 - OEP Overview

The MICA Open Experimentation Platform (OEP) was designed to provide an experimentation platform for simulation, demonstration, assessment and transition of MICA research to operational systems. The OEP also responded to the long-term need by incorporating capabilities to support the broader IXO vision. OEP requirements therefore cover a broad spectrum of modeling and simulation activities required for Finding, Fixing, Tracking, Targeting, Engaging and Assessing (F2T2EA) tactically significant enemy assets. The OEP is designed to provide modeling fidelity appropriate to MICA requirements. Because the OEP is not designed to evaluate lower level control schemes, it utilizes point mass rather than six-degree-of-freedom models. OEP models are effects based when feasible and provide higher fidelity in MICA critical areas of concern. Moreover, the OEP deliberately does not inherently model any existing or planned weapon system or platform. It is parameter driven and for MICA parameters were selected to stimulate controller development and ensure robustness in response to an intelligent adversary in a balanced scenario (one that is challenging but defeatable). Figure 2-2 shows an overview of the OEP application relationship to MICA research objectives.

3 Accomplishments and Achievements

The guiding principals behind our OEP Core development was to get a working product into the researcher's hands and to immediately and continuously improve this product in response to researcher feedback. In response to these needs we adopted a Spiral Development approach which yielded two major releases, Versions 0.0 and 1.0, and numerous incremental releases in the period from October 2001 through September 2003 when funding for the program was curtailed.

OEP Version 0.0 was released in December 2001, approximately 60 days after contract award. Version 0.0 provided early access to OEP capabilities in order to enable researchers to familiarize themselves with OEP operations and to initiate early feedback from researchers regarding desired changes and additional capabilities. Because the OEP is built upon the Boeing C4I Simulation, which has been under development and in use since 1994, Version 0.0 provided significant capability in all MICA requisite areas of modeling and simulation. An extensive presentation was presented at the MICA Kickoff Meeting to describe OEP Version 0.0 capabilities.

Subsequent to release of Version 0.0, Boeing actively sought feedback from researchers regarding their requirements. A TIM was held during the first quarter of 2002 to review and prioritize researcher requests. Highest priority researcher requests included:

- Terrain
- Separate locations for SAM site componentsSensor misidentification
- Additional API operations
- Command sensor spotlight
- Get target identification and signal properties
- Alter vehicle signature
- Max range for weapon
- Jamming
- Update OEP scripts dynamically
- Multiple engagements per SAM site
- Tracking and threat warning modes in sensor
- Push interface for sensor reports, events
- Generalize time step controller for use by all components / controllers
- For debugging, event playback from file
- Support embedding OpenMap window into researcher GUI
- Model SAM fly out and terminal maneuver

These requests were treated as candidate requirements which were prioritized by the MICA Government team and integrated into the OEP build plan.

OEP 0.0 was incrementally improved (six releases) over the period between December 2001 and May 2002. The culmination of theses incremental releases, OEP Version 1.0, was released in May 2002. OEP 1.0 responded to all but the last four of the researcher feedback items presented in the previous paragraph. Major OEP 1.0 capabilities included: 1) capability to locate objects over a terrain grid and execute inter-visibility analyses between airborne, space-based and ground objects, 2) capability to compose SAM sites from multiple, separated elements including search/acquisition radar, tracking (fire control) radar, controller and multiple launchers, 3) Sensor spotlight API call that causes a multi-mode sensor to interrupt search scan to perform a spotlight cycle at a specified geographic location. 4) Small arms model reflecting effect of shoulder fired SAMs, 5) Dynamic network configuration, 6) Sensor identification of targets, 7) position error in weapon aim point, 8) option to set and vary platform signature, and 9) platforms may be equipped with jammers that work against radar and passive RF sensors.

Subsequent to delivery of OEP 1.0, Boeing OEP core activities concentrated on additional capabilities desired by researchers to support the October 2002 Demonstrations. Seven incremental releases (OEP 1.0.1 through 1.0.7) added these capabilities including software hardening in Build 1.0.1. OEP capabilities incorporated into Build 1.0.1 included: (1) Event notification with buffered events; (2) GMTI sensor mode; (3) Imaging sensor mode; (4) Target classification; (5) Limitations on platform motion; (6) Scenario inputs; (7) Additional information query; and (8) Multiple buffered event subscription.

In the period between October 2002 and September 2003, Boeing produced three additional major OEP increments. The focus of build 1.1 was to incorporate additional modeling capabilities to support more realistic challenge problems and scenarios. Of primary interest was OEP support for cooperative path planning. OEP 1.1, released in Feb 2003, provided several new capabilities: (1) 3D platform signatures in several spectral bands; (2) An image interpreter can process multiple images concurrently; (3) Weapon guidance modes for seeker and RF seeker weapons were added; (4) Platforms may employ active signature enhancement; (5) Side lobe jamming may be employed; (6) Synthetic aperture radar imaging sensors are susceptible to jamming; (7) Air search radars and passive RF sensors now report jamming strobes; (8) Damage and destroy probabilities vary by distance and the cumulative number of damaging hits; (9) Terrain line of sight test uses nearest post rather than interpolation, reducing run time; (10) Terrain line of sight test was optimized to start at the lower point and stop when highest scenario altitude reached; (11) Platforms without emitters exit earlier from the passive RF sensor detection function, reducing run time; (12) Event subscription by CORBA objects in addition to XML; (13) Image events can be obtained by subscribing either to the image sensor platform or to the image interpreter platform; (14) Small arms threats may be limited to specific geographic areas ; (15) Additional buffered events were added; and (16) Additional OEP server calls were added. In addition a preprocessor was added, and the challenge problem was divided into modular files. The red controller will try to avoid engaging targets that appear to be decoys (the use of active signature).

The focus of OEP 1.2 was to support MICA controller development of team tactics. OEP 1.2, released April 2003, included: (1) The jammer model was revised to support team jamming by adding jammer power from all sources, (2) A multilateration model was added to support team position location of emitters, (3) Passive RF sensors can be connected to a multilateration component in a platform rather than to a track list, (4) Track list correlation permits miscorrelation, (5) A tracker was added to the location update function in track lists, (6) Weapon carrying load limits were implemented, and (7) the defense (SAM) model was changed to add more states and events for the red controller.

The focus of OEP 1.3 was to provide support of mid-term software and hardware experimentation. OEP 1.3, released in mid-August, provided several new capabilities: 1) The initial scoring and metrics interface, that enables clients to call the OEP server and obtain the current metrics that will be used in the experimentation phase to evaluate controllers, was added; 2) The TaskImagingSensor operation was changed to add priority and request id parameters; 3) The TaskGMTISensorList server operation, which enables tasking a GMTI sensor with a list of cells rather than with a rectangular region of contiguous cell, was added; 4) The GetGMTIProperties and GetImagingProperties server operations were added to retrieve sensor parameters that are useful for planning sensor tasks; 5) In platform types, the max_vertical_rate parameter was replaced by max_climb_rate and max_descent_rate, and a max_alt parameter was added for future use; 6) In the scenario/outputs/scenario/print_format section of the scenario input the show_zero parameter that was in the classification and damage parameter sections was changed to show_small_prob; 7) The OEP now throws an exception if there is a platform source conflict in a subscription; 8) The IADS model can now randomly choose to engage the target with the best side view (for higher signature) in addition to the previous tactic of selecting the closest target; 9) There is now a limit on the number of SAM sites that be moving at any one time; 10) Ground coverage sizes for imaging sensors may be set by inputs; 11) Support for time-varying commander's guidance and rules of engagement was added; 12) A scripted platform, such as the blue base, is allowed to broadcast messages to controller Proxies; 13) The obsolete sensor spotlight mode and the server operation AddSpotLightRequest were removed; and 14) The drop_age parameter was moved from platform type to track list, where values may be specified by motion hint.

In order to stimulate operationally relevance, a rolling series of challenge problems, formulated to stress research objectives, were developed in conjunction with the OEP core capabilities. The challenge problems posed formidable sensor management issues for finding and attacking targets and stressed the need for resource planning and team operations. The Challenge Problem scenario encompassed a representative Red Order of Battle including an Integrated Air Defense System and Time Critical Targets including both Surface-to-Surface Missiles and Armored Columns, which threatened Blue Assets. It also included both fixed and moving white objects that presented potential for collateral damage. Figure 3-1 shows an overview of the MICA Challenge Problem. The challenge problem is scalable to larger number of UAVs, dynamic in nature with changing objectives and incorporates random disturbances provide system shocks.

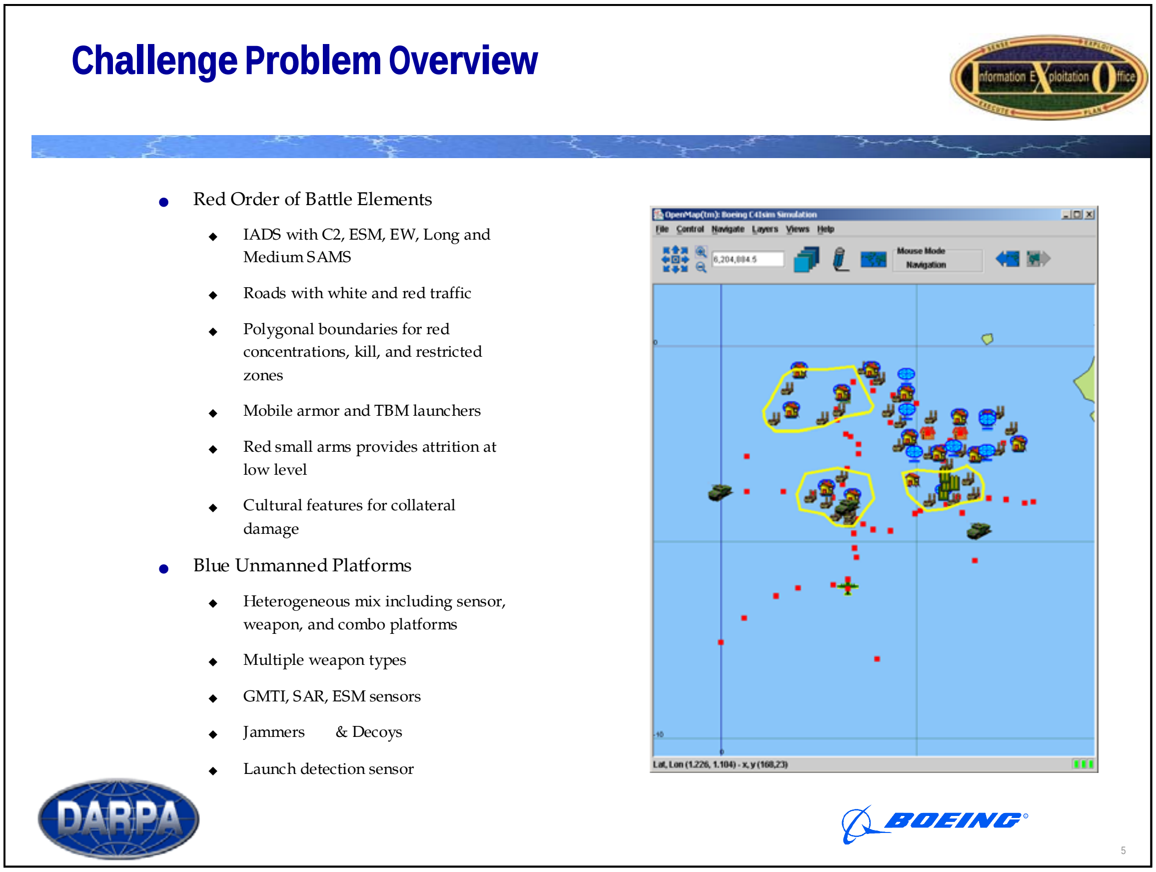

Figure 3-1 - Challenge Problem

4 Methods, Assumptions and Procedures

The MICA OEP is an effects-based, campaign-level simulation that produces two views of the battlespace: truth and perception (from multiple viewpoints). In order to model campaign-level effects, the OEP is designed to efficiently simulate large numbers of platforms and targets. By Effects Based, we mean that the effects of phenomena and actions are modeled rather than the detailed physics. The simulation normally utilizes a simple vehicle motion model but can also interface to higher fidelity third party motion models. It emphasizes fidelity in areas that are important to the MICA problem space. In particular, sensor errors and the propagation of errors from producer to consumer are treated in substantial detail, as are communication network delays and throughput. Sensor model fidelity is enhanced by a three-dimensional vehicular signature capability that can be tailored to each sensors spectral domain. The OEP is normally employed in a Monte Carlo fashion in order to achieve reasonable measures of performance. Users may specify random distributions or constant values for the random variables. Simulation entities are customizable and may represent a variety of air and ground vehicles, targets, and facilities.

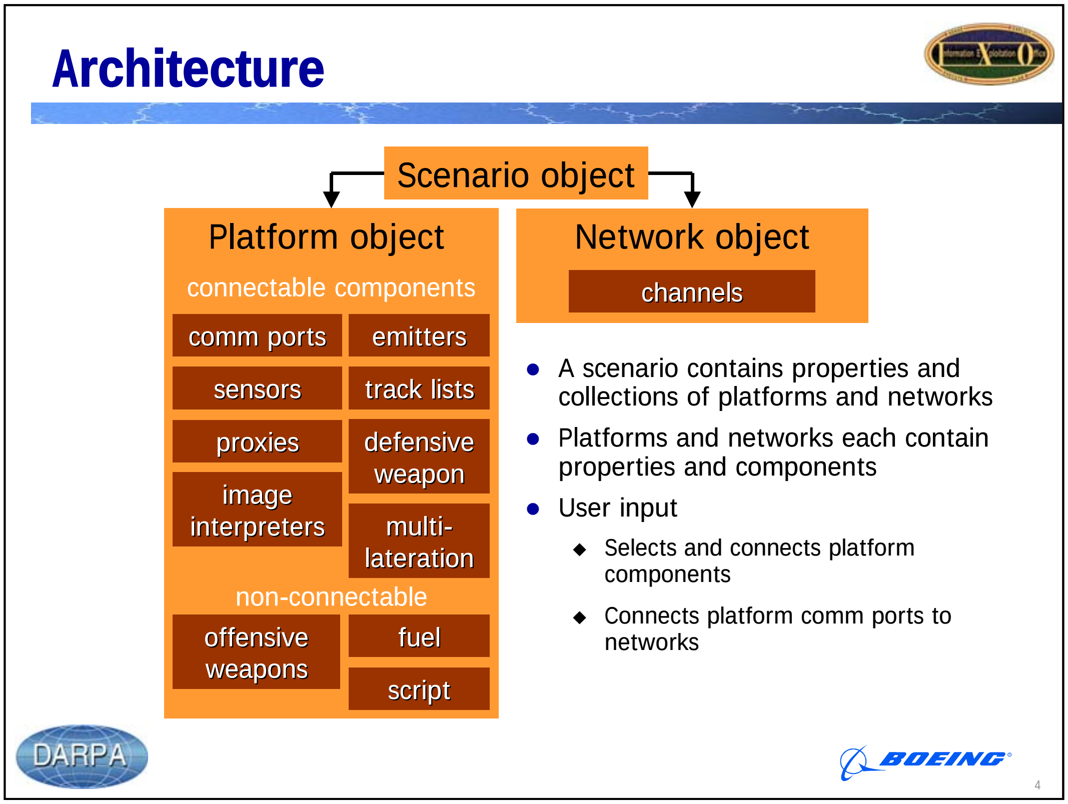

Figure 4.1-1 - OEP Architecture

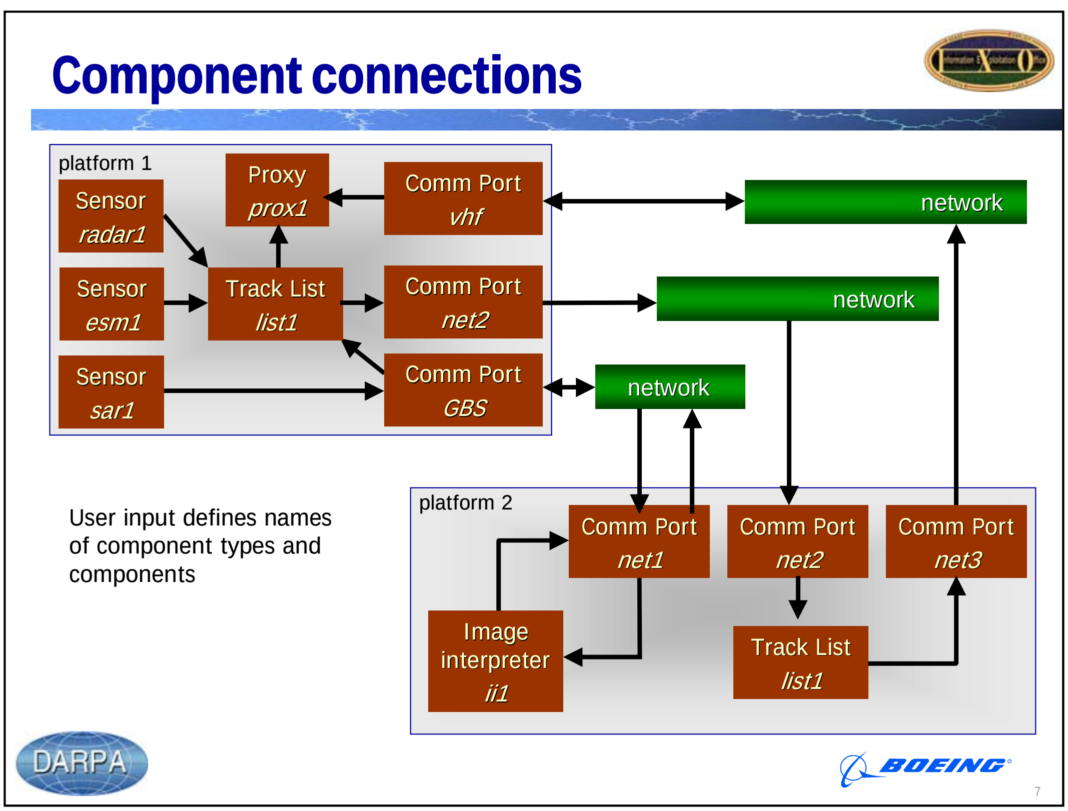

Figure 4.1-2 – OEP Component Connections

4.1 Architecture

The OEP Architecture, Figure 4.1-1, relies on two major simulation entities - platforms and networks. Platforms are constructed from parameterized building blocks, which are connected to each other by user input parameters. Connectible platform components include: 1) Communication Ports, 2) Emitters, 3) Sensors, 4) Track Lists, 5) Proxies, 6) Defensive Weapons, 7) Image Interpreters and 8) Multilateration Cells. Non-connectible components include: 1) Offensive Weapons, 2) Fuel and 3) Scripts. Networks may be customized to represent point-to-point, multi-point, half duplex, full duplex, broadcast, and time division multiple access networks. Network connections among platforms are specified by user input parameters. Figure 4.1-2 shows typical connectivity between platform elements using OEP Network Models. The OEP User's Manual provides details of all Platform and Network components.

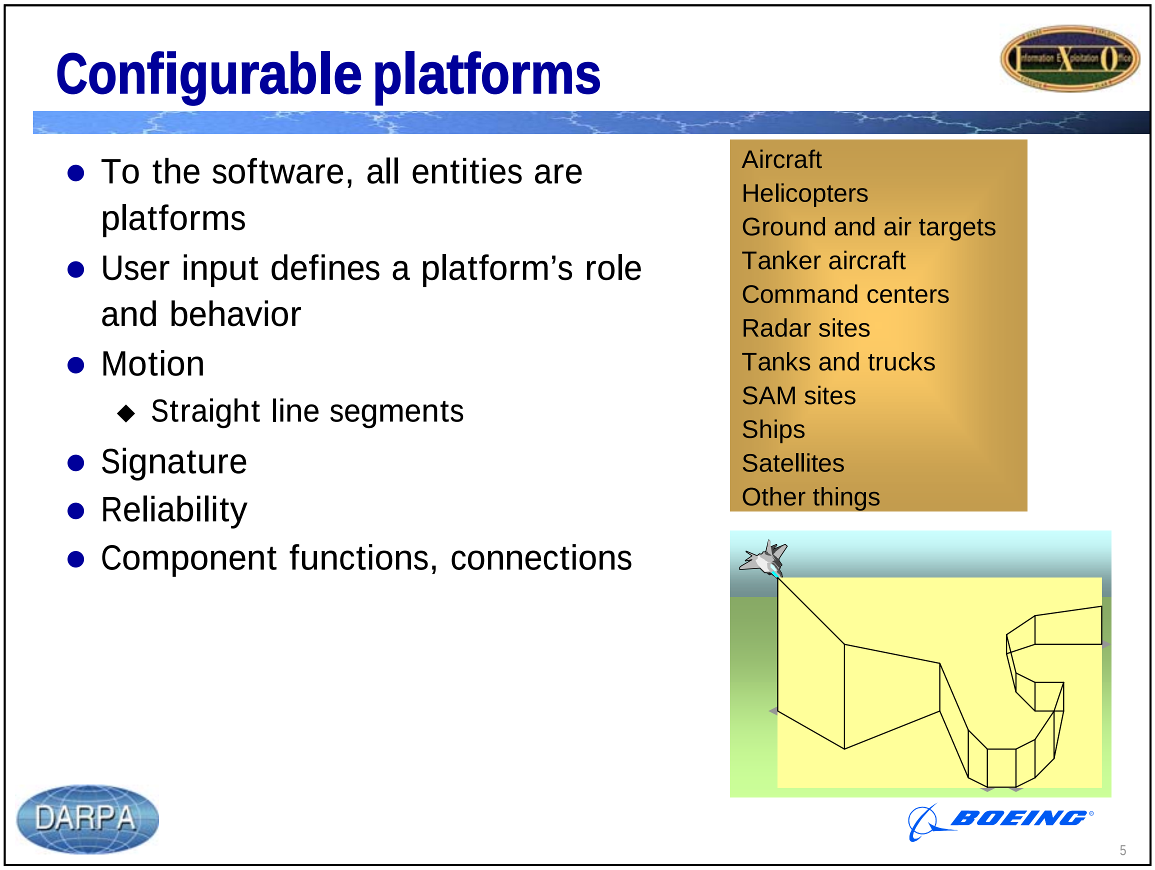

Figure 4.2-1 - Configurable Platforms

4.2 Platforms

Platform objects, Figure 4.2-1, can be used to model numerous battlefield entities including: Aircraft, Rotorcraft, Ground, naval and air targets, Tankers, Command and Control elements, Radar sites, Armored vehicles including tanks and Self Propelled Artillery (SPARTY), SAM sites, Satellites, etc.

4.2.1 Platform Motion

The OEP includes three basic models for platform motion: 1) Acceleration motion model; 2) Rotorcraft motion model; and 3) External 6-DOF. In the acceleration model we use a flight dynamics model with 3 degrees of freedom and a simple 3-channel autopilot that accepts commanded speed, acceleration limits, and either a destination location or commanded altitude and heading. Gains and limits are specified in the input. The autopilot feedback control loops calculate acceleration commands that are numerically integrated to get velocity and position. Body yaw angle and heading are set to the flight path azimuth angle. Bank angle is synthesized from lateral and vertical acceleration. A hold position command causes the vehicle to fly in a circle.

In the rotorcraft motion model we use a flight dynamics model with 3 degrees of freedom and a simple 3-channel autopilot that accepts commanded speed, acceleration limits, and either a destination location or commanded altitude and heading. Gains and limits are specified in the input. The autopilot feedback control loops calculate acceleration commands that are numerically integrated to get velocity and position. Bank angle is synthesized from lateral and vertical acceleration components. Pitch angle is synthesized to simulate the effect of the cyclic control. Body yaw angle can be commanded separately from heading. A hold position command causes the vehicle to hover.

The OEP also includes an interface to external six degree of freedom model. This enables OEP to utilize an external simulation to provide high fidelity vehicle dynamics. One instantiation of this is in the use of the Georgia Institute of Technology model for the Yamaha R-MAX. A software interface adapts the Georgia Tech code to the simulation pluggable motion interface.

4.2.2 Signature

For the 3D Signature Capability, platform signature can vary with azimuth and elevation angles. Signature determination can be performed using the nearest point in the Azimuth/Elevation Table or through linear interpolation. The signature is an arbitrary numeric value, which is associated with sensor performance through table lookups. Unique signatures can be associated with each spectral band (RF, visible, etc.). Separate signature tables can be provided for different platform states (damaged, bay doors open, etc). Azimuth values can be symmetric or asymmetric about body axis. For the purpose of determining signature, Azimuth = heading, Elevation = flight path angle and Bank = ±45 deg if turning, 0 otherwise.

4.3 Sensors

The sensor model provides general functions to simulate these kinds of sensors: radar, radar with ground moving target detection (GMTI), imaging (visible, infrared, synthetic aperture radar (SAR), and radio frequency signal measurement (ELINT or ESM). There are no specific sensor models in the software. Models of specific sensors are formed with input parameters. Figure 4.3-1 shows the general processing steps in sensors. The labels indicate the steps that apply only to certain types of sensors. Although the image interpreter is technically not a sensor or sensor mode in the software, it is shown in the diagram because it is closely related to the imaging sensor.

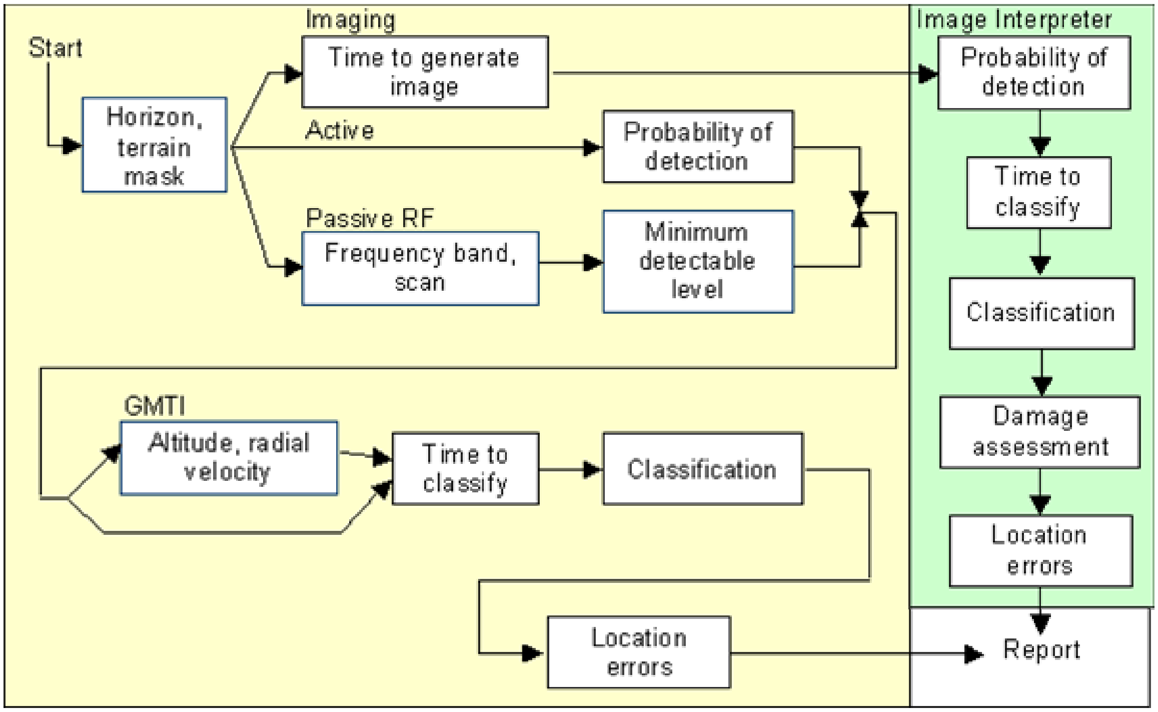

Figure 4.3-1 Sensor Processing

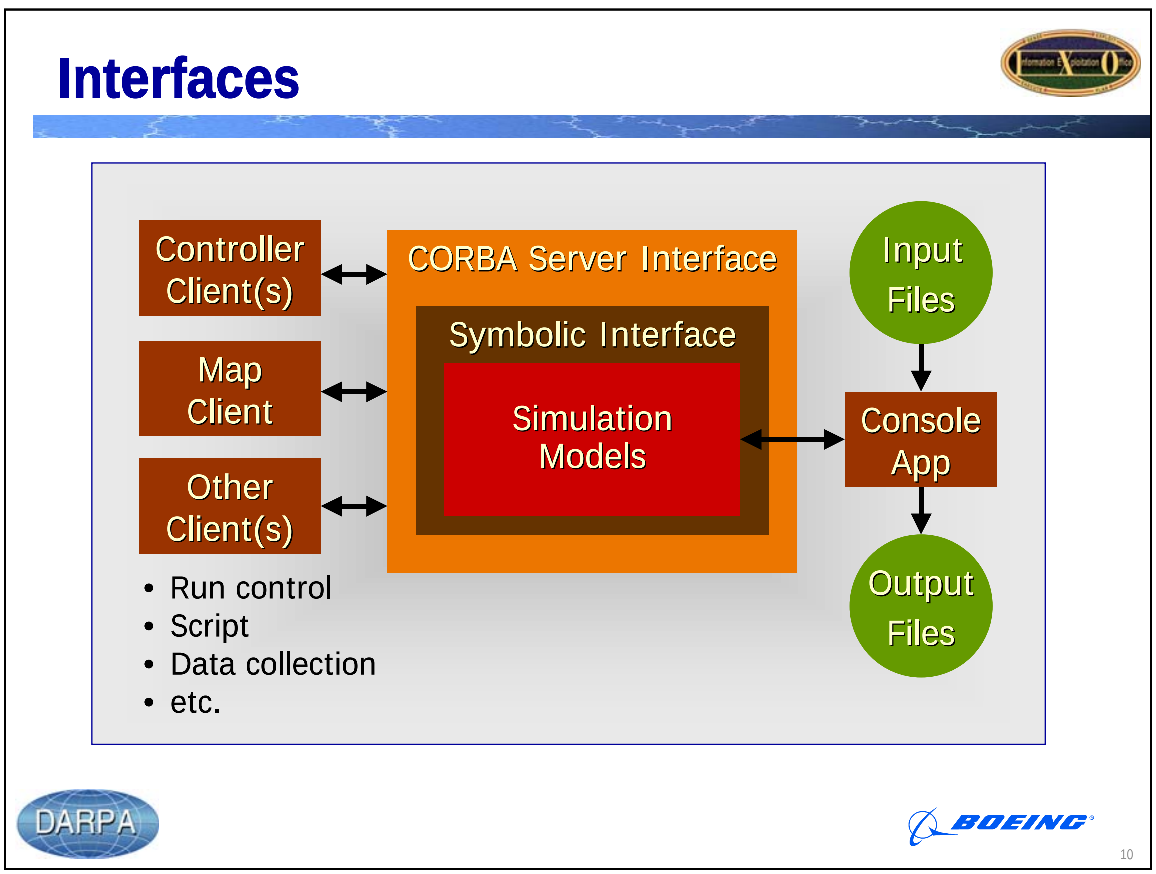

Figure 4.4-1 - OEP Interfaces

4.4 Interfaces

Figure 4.4-1 shows the MICA OEP Interfaces. The OEP Core Server, Simulation Models, provide a CORBA Application Program Interface (API) to multiple clients. The Challenge Problem models and scenario are executed using the Script Client. The Map Client provides a graphic interface (currently Open Map) to help visualize scenario progress. Researcher Blue Controllers, the Red Integrated Air Defense System (IADS) controller and the planned Red Reactive Ground controller use this interface along with other clients including Data Collection and Run Control. The Console Application allows the OEP to be run in a batch mode to assist in scenario development, debugging and test.

4.5 Red Controller Clients

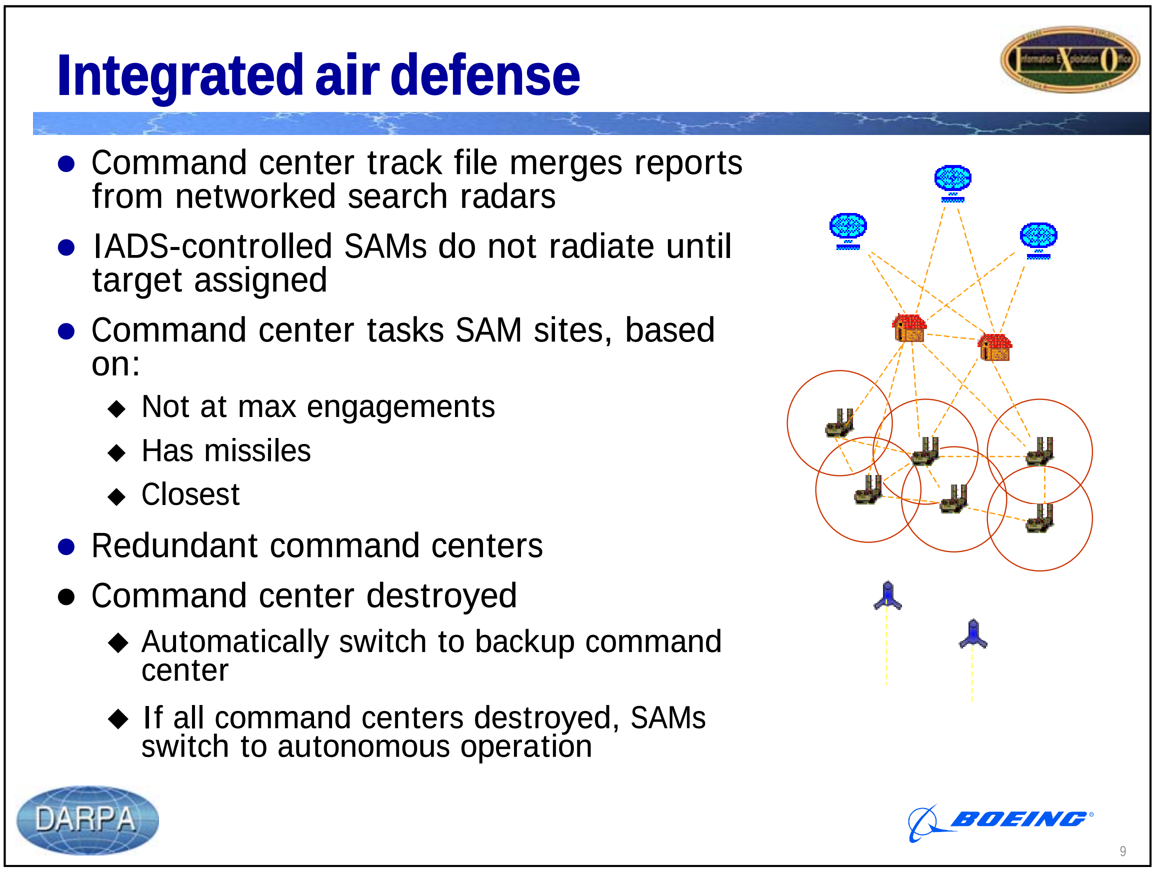

Figure 4.5-1 – Integrated Air Defense Capabilities

The MICA OEP also includes a Red Controller Client, which converts selected Red air defense elements into an Integrated Air Defense System (IADS). Within the IADS, designated EW Radars, SAM Search Radars and ESM sensors contribute to an integrated red intelligence database. The IADS controllers, Located at Red Command and Control (C^2) facilities control actions executed by the integrated red SAMs. If all red (C^2) facilities are destroyed the Red SAMs revert to independent operation. The IADS provides red defenses with the ability to radiate only after they are commanded to engage targets that are well within their lethal envelope. The engaging SAM is selected based on criteria including: Number of missiles remaining, Proximity to approaching blue asset, and blue geometry (signature) relative to SAM. The IADS also includes a “Shoot and Scoot” capability that relocates SAMs to alternative pre-planned locations after they have disclosed their location through emission. The “Shoot and Scoot” logic moves SAMs only when engagements are not imminent. The logic also controls the maximum number of SAMs in transit at any time. Figure 4.5-1 highlights OEP IADS capabilities.

5 Results and Discussion

MICA research was pre-maturely terminated due to evolving priorities within DARPA. Only a subset of the available controllers was submitted to Boeing for evaluation and those controllers submitted were less capable than would have been the case if planned research had been completed. Controllers submitted to Boeing were produced by Draper Laboratories and by the collaborative efforts of Ohio State University and Iterativity Inc. Two variants of the Iterativity-OSU controller were provided. One uses the Ultra planner and the other uses the Hierarchical planner. In general our discussion will treat the Iterativity-OSU controller as a single product. Where differences between the Ultra and Hierarchical planners are of note, they will be explicitly discussed. Evaluations of both controllers were performed at the Boeing St Louis facility during the fourth quarter of CY03 and the first quarter of CY04. Both research teams were provided feedback regarding observed behavior and were afforded multiple opportunities to explain and or correct deficiencies. Considerable progress and improvement occurred during the evaluation period. Unfortunately, neither controller was ultimately capable of demonstrating acceptable tactical utility when evaluated against the MICA challenge problem. This lack of comprehensive progress *may well be* attributed to the abrupt termination of the development cycle that left many algorithmic loose ends. It is also possible that a fundamental lack of maturity exists in one or more of the constituent technologies.

5.1 Summary of Results

Despite the early termination, much was accomplished. Both controllers exhibited a hierarchical decomposition of the challenge problem and allocated teams of assets to subsets of known targets. Both controllers evidenced coordinated team tactics and planned asset flight paths in response to either team assignment or task allocation. Provisions were put in place to address the inherent uncertainty of knowledge of the battlespace such as Draper's Information Model and Iterativity's VII IPB interface. Both controllers have a broad Variable Initiative Interface (VII), albeit of varying levels of maturity and utility. Unfortunately there was also much left undone. The following summarizes observed behavior in each of the research areas as well as certain functional categories. It is followed by a more detailed discussion organized by MICA research areas.

Team Composition and Tasking - The construct of team in the context of the MICA controllers appears more to be simply a product of the logical partitioning the challenge problem for planning simplification, rather than the grouping of assets that dynamically and purposefully cooperate. All intra-team coordination is the consequence of centralized a priori action scheduling or sequencing.

Team Dynamics and Tactics - All controllers have displayed some level of team tactics: cooperative jamming, bomb damage assessment, and the explicit coordination of actions performed by individual team assets. Unfortunately, the lack of an explicit logical communication activity functionally prevents any dynamic cooperation among teamed assets. There is no "active" cooperation, all coordinated activities are simply the product of a priori plan sequencing, and unless an existing plan is centrally altered, the planned tactical activities will be executed regardless of whether or not all constituent team members are present.

Cooperative Path Planning - Both global and local path planners were implemented, and all of the controllers did plan flight paths according to either team assignment or task allocation. Unfortunately, all of the path planners apparently reasoned primarily within a horizontal plane. That is, none of the controllers rigorously planned using the three dimensional platform signatures, which if exploited, would have significantly increased asset survivability while navigating a SAM engagement zone.

Uncertainty Management - The Draper Information Model provides a natural representation for both the 'certain' knowledge of the world, such as active target tracks, and the corresponding 'uncertain' awareness of expected but as of yet un-discovered targets. And in fact, both of these types of information are provided by the MICA IPB. Draper currently populates the Information Model with “truth" IPB data, extracted from the scenario XML file, rather than using the IPB provided.

Variable Initiative Interaction - The purpose of the VII is to provide the MICA Operator with sufficient information to develop the situational awareness necessary to interact with and control heterogeneous teams of UAVs. Even though the VIIs allowed the operator to see a god's eye view of the situation, input various planning parameters, and review the generated plans, there was no direct means to communicate new Strategic Objectives, Commander's Guidance, or Rules of Engagement. Moreover, none of the VIIs actually allowed the MICA Operator to directly interact with the planning process. No VII allowed the operator to edit a plan, either at the team composition level, or at the task allocation level. The operator could only initiate, accept, or reject a plan. Providing this ability, as well as a mean to visualize and implement higher-level strategies, would greatly enhance the utility of the VII.

Action Scheduling vs. Action Sequencing- There are two fundamental approaches to structuring the "actionable" plans, action scheduling or action sequencing. The Draper controller planned for asset-level cooperation by deterministically scheduling all activities, whether coordinated or not, in a global timetable. Alternatively, the Iterativity-OSU controllers planned for cooperation by establishing precedence and concurrence relationships among only those activities that are to be coordinated, thus placing fewer constraints upon the final plan that can be broken by an un-anticipated turn of events.

Thus the Draper controller is schedule driven and not event driven. An asset will simply perform an action for what has been determined is the appropriate amount of time, and then wait until it is time to begin the next scheduled action. A benign example of this is planned path execution. Rather than an asset simply flying until receipt of a waypoint arrival event, the controller will "fly" for the pre-determined time interval, and then query the OEP for platform location to determine arrival status. A less benign example is when the controller performs a BDA imaging action. After the execution of a sensor imaging action, rather than wait for receipt of an "image interpreter report event", the controller waits for a predetermined amount of time under the assumption that the new image data will have been "analyzed by the image interpreters" and incorporated into the central Information Model. While this approach will work much of the time, it cannot account for indeterminate image interpreter delays that may result from network congestion or from processing an unknown number of images generated by other assets.

Alternatively, the Iterativity-OSU controllers simply sequence the planned activities, and then repeatedly test for activity completion. This allows for 'less-brittle' plans since fewer constraints need to be established which might later be violated. For example, perturbing a "FlyTo" activity to avoid a discovered threat does not necessarily invalidate the larger plan. Since the next action is minimally constrained to begin upon completion of the prior action, it will simply begin a bit later than it otherwise would.

In general, it appears that action scheduling tends toward more brittle plans that can more easily be broken when events do not occur as anticipated. Alternatively, action sequencing appears to be more flexible by logically allowing for unanticipated delays from an uncertain adversarial environment.

Event Handling- There is 15 event types available to the controllers from the MICA OEP. Thirteen of these event types directly represent either state information of the platform or state of the world, or are the results of platform actions. OEP event types available for registration are

received communication	sensor collection start
	sensor collection done
platform condition	sensor collection reported
sensor report	waypoint arrival
image interpreter report	
multilateration report	weapon release
track report	weapon arrival
threat warning	

Of the 15 available event types, the MICA controllers have registered for the following subset of events, and appear to actively "consume" even less …

SENSOR_COLLECTION_START	OSU	
SENSOR_COLLECTION_DONE	OSU	Draper
THREAT_WARNING		Draper

TRACK_REPORT	OSU	Draper

The only event type determined with certainty to be consumed by the controllers and thereafter used for planning is the track report. This artificial limit on the type of events consumed will arguably limit how the controllers represent this "knowable" yet ignored state of the word. And moreover, this will limit with what and how the controllers react in the world. For example, it is the threat waning event that conveys perhaps the most urgent information about the state of the world and immediate intent of the enemy, that a SAM is actively engaging a blue asset with the intent of destroying it. Unfortunately, the Iterativity-OSU controllers did not register for threat warning events, and even though the Draper controller did, there was no evidence that they made use of the threat warning reports in their planning or world model.

Events are retrievable from the MICA OEP in both a "batch" mode or upon specific event occurrence, but in both cases, event retrieval must be initiated by the OEP client. In the beginning of experimentation, the Draper controller only retrieved events at the end of a 'planning increment', which could be on the order of several hundred seconds simulation time. In order for a controller to react to the dynamic adversarial environment, the event query period should be less than the expect threat episode, which for a medium SAM is about 25 seconds. Additionally, these extended retrieval periods would often lead to event queues containing several thousand events to be processed. By the end of the experimentation phase, all controllers were querying for events on the order of every 10 seconds, but no controller was yet making use of the threat warning events.

In general, controller performance could be fundamentally improved by more frequent consumption of a larger set of event types that would provide a richer representation of the dynamic and adversarial state of the world.

5.2 Detailed Discussion

MICA experimentation was designed to assess research artifacts (controllers) to quantify their capability in each of the five research areas:

1) Team Composition and Tasking,
2) Team Dynamics and Tactics,
3) Cooperative Path Planning,
4) Uncertainty Management,
5) Variable Initiative Interaction,

and to measure their robustness in adapting to a variety of tactical situations:

a. SEAD against individual SAM sites,
b. SEAD against an Integrated Air Defense System,
c. Interdiction against fixed and moving targets,
d. Intelligence, Surveillance, and Reconnaissance (ISR),
e. Employment of a variety of weapons, sensors, and countermeasures,

f. Adherence/adaptability to the Commander's Guidance and Rules of Engagement.

The remainder of this section further discusses experimentation results categorized in each of the five research areas.

5.2.1 Team Composition and Tasking

The MICA operational vision entails "teams of heterogeneous UAVs with mixed weapon and sensor packages performing reconnaissance, strike, BDA and force protection activities" under the supervision of a few (ultimately 1 operator per 40 vehicles) human operators. All of the controllers evaluated exhibited a hierarchical decomposition of the challenge problem and allocated teams of assets to subsets of known targets. The optimality, responsiveness and sophistication of this allocation are discussed below.

5.2.1.1 Team Composition

The construct of teams by the evaluated controllers appears to be a partitioning of assets for planning simplification rather than a grouping of assets that purposefully cooperate to achieve tactical objectives IAW Commander’s Guidance. The coordination of assets is achieved by a central planner rather than through dynamic distributed or centralized logic. Specifically assigned tasks are pre-arranged in time either by sequence or by schedule. The planners either establish an ordering or precedence constraints for all tasks, or assign a start time and duration for each task.

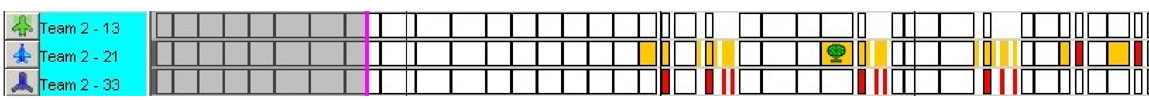

Figure 5.2.1.1-1 – Sample Draper Team Composition

In most cases, teams were constructed as a mix of heterogeneous platform types having complementary sensing, strike, and defensive capabilities. The Draper controller would often plan around small teams composed of different platform types, such as the team below, Figure 5.2.1.1-1, composed of one sensor platform, one weapon platform, and one combo platform.

The Iterativity-OSU controller composed fewer, but larger more stable teams. As with the Draper controller, these teams were composed of a mix of weapon and sensor platform

Icon	Icon Name	Class Type
	Attack	Activity
	Locate	Activity
	FlyTo	Activity
	Identify	Activity
	Jam	Activity
	Protect	Activity
	Refuel	Activity

Figure 5.2.1.2-1 – Iterativity-OSU Planning Activities

types, as is illustrated below with a snippet from an OSU TCT planner log file. Neither controller exhibited a strong coupling between the tactical situation/objectives and the composition of assigned teams.

stagesUavNamesInTeamsTable[0][0][0] = small_weapon_1
stagesUavNamesInTeamsTable[0][0][1] = small_weapon_2
stagesUavNamesInTeamsTable[0][0][2] = small_weapon_3
stagesUavNamesInTeamsTable[0][0][3] = small_weapon_4
stagesUavNamesInTeamsTable[0][0][4] = small_sensor_2
stagesUavNamesInTeamsTable[0][0][5] = small_sensor_1
stagesUavNamesInTeamsTable[0][0][6] = small_combo_1

5.2.1.2 Activities Planned

Iterativity-OSU defined seven distinct activity types that can be reasoned over and planned with as illustrated in Figure 5.2.1.2-1. The seven activity types represent all fundamental platform capabilities *except* communication and controlled network connection required for multilateration team formation. Figure 5.2.1.2-2 is a plan sequence illustrating five of the logical activities. No OSU-Iterativity plans have been observed which contained either the 'refueling' or force 'protection' activities.

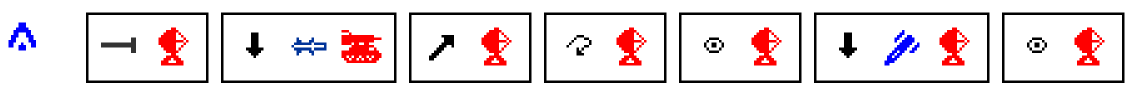

Figure 5.2.1.2-2 – Iterativity-OSU Plan Composition

The Draper controller plans were constructed with 10 distinct activity types, six of which are illustrated in Figure 5.2.1.2-3. Again these activity types represent the fundamental platform capabilities *except* communication and controlled network connection.

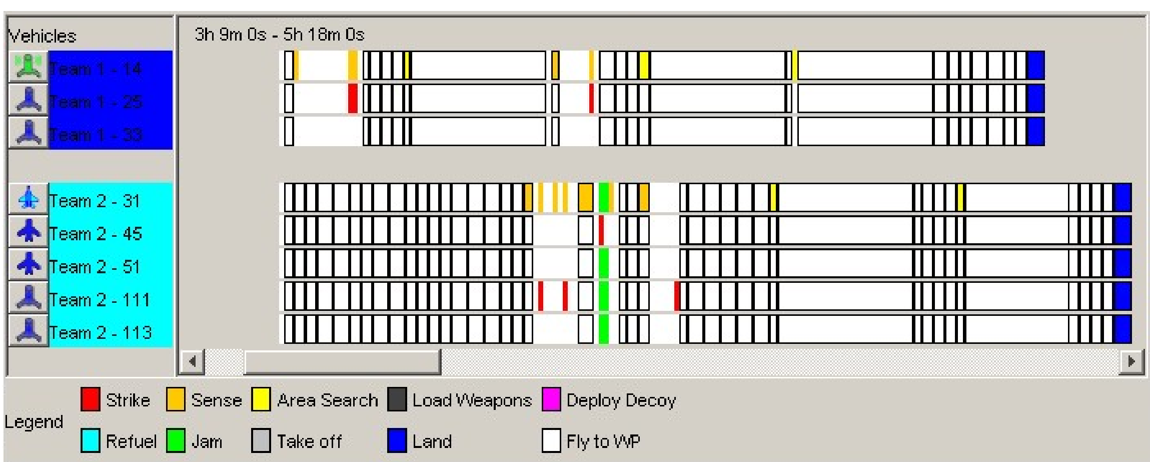

Figure 5.2.1.2-3 – Draper Plan Composition

This lack of a logical communication activity type to reason upon prevents a plan from containing dynamic synchronization events, e.g. "call me when you're ready", and dictates that any coordinated actions among team participants are deterministically pre-planned and scheduled prior to plan execution. This is a critical shortfall of both controllers because the MICA vision entails dynamic responsiveness to evolving guidance, constraints and tactical needs and emphasizes cooperation between heterogeneous elements. Current controller designs are limited to centralized control and rely primarily on pre-planned activities. Furthermore, neither controller accurately modeled the tactical communication environment and limitations that will dramatically affect real life employment.

5.2.1.3 Are multi-team composition and activities coordinated?

The construct of teams within the current controllers appear to be a simple partitioning of assets and targets arising from the 'decomposition' of the challenge problem into smaller sub-problems that can be planned for more easily. In this regard, the teams do not appear to be cognizant of each other, and any intra-team coordination is simply the product of the original problem decomposition.

5.2.1.4 Do assets employ full spectrum of weapons?

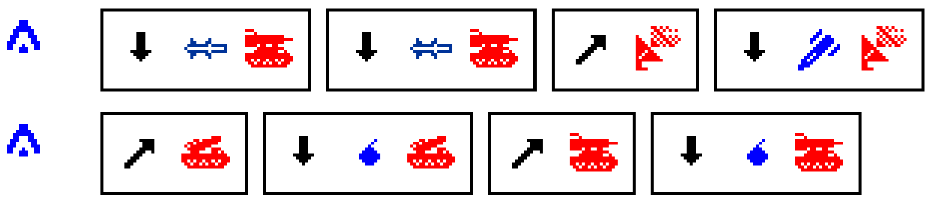

Figure 5.2.1.4-1 – Iterativity-OSU Planned Weapon Utilization

The controllers did plan to use a variety of weapons as illustrated in the plan sequences below, Figure 5.2.1.4-1, but the favored weapon by far was the seeker missile which maximized per asset weapon carriage, minimized the probability of collateral damage, and minimized useless expenditure of weapons by requiring a target lock prior to weapon release.

The first plan sequence shows a small weapon UAV launching two decoys against two separate long SAM launchers, flying to an EW radar site, and launching a seeker missile against the EW radar. The second plan sequence shows another small weapon UAV flying to a medium SAM site, dropping a GPS bomb, flying to another medium SAM site and dropping another GPS bomb.

5.2.1.5 Commanders Guidance and the Rules of Engagement

The Commander's Guidance and Rules of Engagement represent objectives that must be satisfied and planning constraints that must be adhered to while executing a military campaign. These planning objectives and constraint sets were initially provided to the MICA developers as a PowerPoint presentation along with the Challenge Problem documentation. They have since been translated to an XML representation as part of a "planning language" that is distributable to the platforms within the MICA OEP via the communication networks.

The Draper controller requires that the MICA operator translate Commander's Guidance and Rules of Engagement into target valuation tables, Figure 5.2.1.5-1. These valuation tables assign relative awareness, kill, and BDA values to the target types within a designated area. The burden lies with the operator to select values that produce the desired effect and unfortunately the system provides no assistance to the operator for executing this essential task. For example, if a target type is not to be prosecuted outside of a designated 'Kill Zone', the operator must manually set its relative kill value to zero in all other areas. Or if a localized target set must be destroyed within a given time frame, its associated target type kill value may initially be set high to promote a higher probability of early prosecution task assignment. Then as the objective is approached, the kill value may be iteratively, and manually, reduced. It is these target-task values that are then used in the planning process to assign asset-missions to targets by maximizing a global utility function. For example, discovering and destroying high value targets add more to the global utility than prosecuting low value targets.

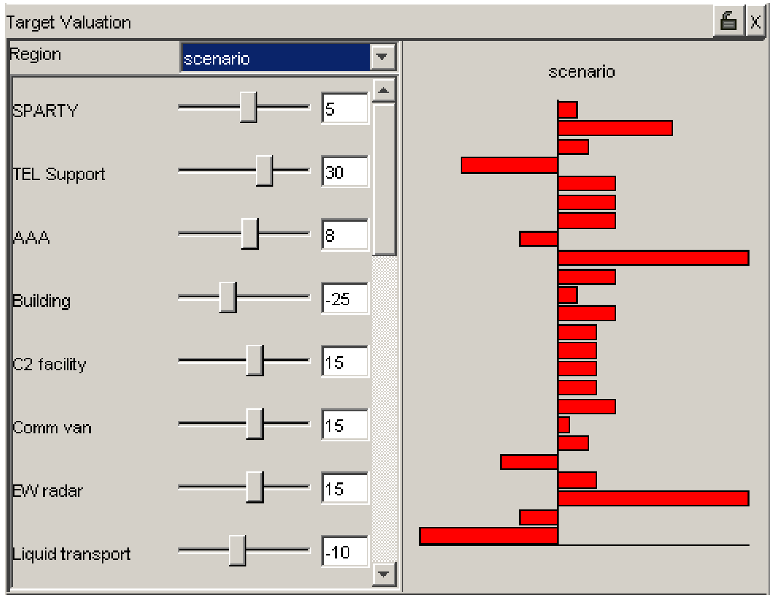

Figure 5.2.1.5-1 – Draper Target Valuation Table

The Iterativity VII does allow for the assignment of one of four predefined Rules of Engagement (kill zone, time critical, hostilities, or no strike) to each of the predefined mission types (SEAD, Interdiction, or CAS) in each of the Red Areas, Figure 5.2.1.5-2. However, there is no automated means of responding to changes in Commander's Guidance or ROE. With both of the controllers, it remains the MICA Operator's responsibility to manually reflect any guidance and ROE changes.

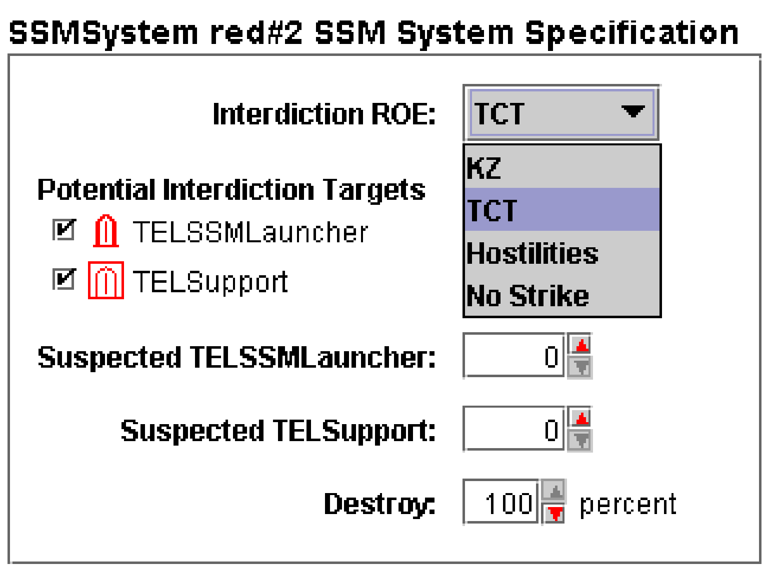

Figure 5.2.1.5-2 – Iterativity VII ROE Selection

Both controllers were 'unstable' and could not progress sufficiently against the challenge problem to enable a statistical assessment of adherence to CG and ROE. With respect to the Draper controller, collateral damage against white occurred even in the limited experimentation sample. There was no behavioral demonstration, for either controller, that the Rules of Engagement were actively constraining either the planning process or weapon release. Both controllers were 'unstable' and could not progress sufficiently against the challenge problem to enable a statistical assessment of adherence to CG and ROE. With respect to the Draper controller, collateral damage against white occurred even in the limited experimentation sample. It was not apparent that the Rules of Engagement were translated to logical rules or targeting constraints that were assessed during the planning process or prior to weapon release.

5.2.2 Team Dynamics and Tactics

Both controllers have displayed evidence of some team tactics: 1) cooperative jamming, where one asset strikes a target while another asset jams; 2) cooperative bomb damage assessment, where different assets are allocated for weapon release and subsequent target imaging; and 3) pre-planned mission execution, the explicit sequencing of actions performed by different assets toward a single target. Unfortunately, effective end-game team (or individual) tactics have not been demonstrated.

5.2.2.1 Jamming Tactics

The OEP's integrated jammer and radar models predict both main-lobe and side-lobe jamming effects including the 'additive' contributions of multiple, dispersed emitters. All SAM tracking radars have a "guide-on-jammer" capability allowing the SAM sites to acquire, track, and engage any platform that is jamming within its engagement zone. The simple tactic of continuously self jamming a SAM site during an engagement will lead to a high probability self destruction. Effective jamming tactics against a SAM site therefore requires combinations of multiple participants having more complex flight plan geometries inside and outside of the effective SAM engagement envelope and employing time-varying techniques that take advantage of SAM lock on and tracking peculiarities.

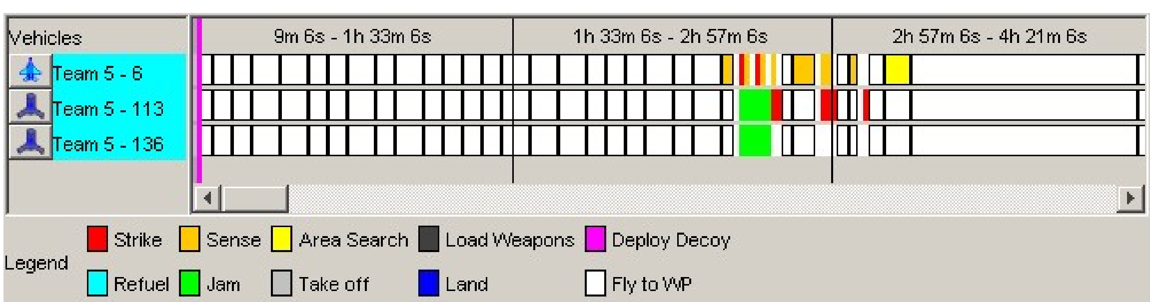

Figure 5.2.2.1-1 – Draper Cooperative Jamming Plan

The Draper controller performed cooperative stand-off jamming as is illustrated in the team plan scheduled below, Figure 5.2.2.1-1. In this plan, two members of the team are stand-off jamming while a small combo effectively locates, strikes, and performs BDA on the target. These tactics were effective within the limitations of pre-planning and re-planning, i.e. all mission elements were pre-planned and in many cases changes in the tactical situation initiated replans that removed needed elements from these cooperative scenarios. In re-planning the controller failed to recognize the critical inter-relationship between cooperative elements and would re-allocate one or more jamming contributors leaving the remaining attack asset(s) vulnerable to the red defenses.

The Iterativity-OSU Ultra planner made extensive use of jamming. Unfortunately there is no indication of cooperative multi-platform jamming tactics. The Ultra planner simply attempts to intermittently self jam targeted SAM sites. An example of this unsuccessful self-jamming technique is indicated on the following Ultra plan sequence of a small combo UAV SEAD mission against a long SAM launcher, Figure 5.2.2.1-2. The sequence of planned actions are: Jam, FlyTo, Locate, Identify, Attack, and Assess. The OSU-Hierarchical planner made no use of the jamming.

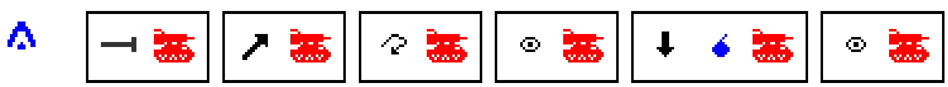

Figure 5.2.2.1-2 – Iterativity-OSU Self Jam Plan

5.2.2.2 Cooperative Engagement Tactics

The majority of blue asset types provided by the MICA challenge problem do not have sufficient native capabilities to independently perform all of the target kill chain activities, Figure 5.2.2.2-1. For example, the weapon platforms do not have sensors sufficient to precisely locate or assess a target's damage state, and the sensor platforms have no weapons with which to strike a target. Even the combo platforms are limited in their capability to operate alone. Thus cooperative tactics for target engagement are imperative.

Figure 5.2.2.2-1 – Target Kill Chain

All of the controllers planned for cooperative target prosecution by sharing the various activities of the kill chain among the members of a heterogeneous strike team. Task dependencies are strongly indicated with the Iterativity-OSU Hierarchical and Ultra planners by graphically representing activity precedence and concurrence as connecting lines in the partially ordered plan sequences. The plan snippet below, Figure 5.2.2.2-2 shows concurrent decoy and seeker missile launches by a weapon platform against a large SAM tracking radar and the enforced precedence ordering of the following imaging task.

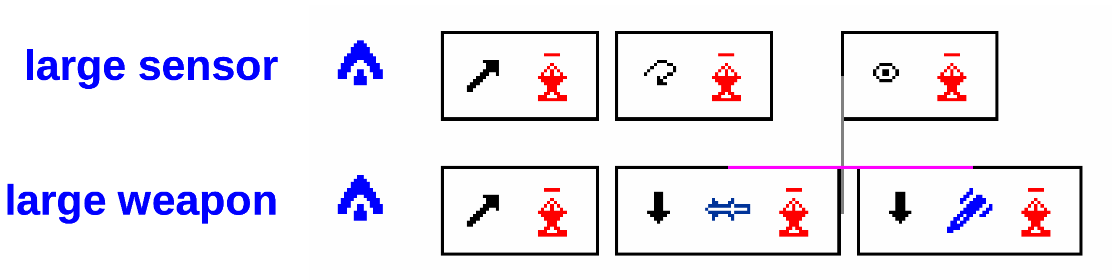

Figure 5.2.2.2-2 – Iterativity-OSU Inter-plan Task Dependencies

Planned coordination of team activities in the Draper controller can be illustrated with the "Team Synchronization Matrix" shown in Figure 5.2.2.2-3. This plan segment shows the distribution of activities across a heterogeneous team of UAVs engaging a long SAM tracking radar. The initial target location and identification tasks and the final bomb damage assessment has been allocated to one of the two large sensor platforms. The weapon release has been assigned to the weapon platform having the smallest signature. And all other team members perform stand-off jamming against the long SAM tracking radar.

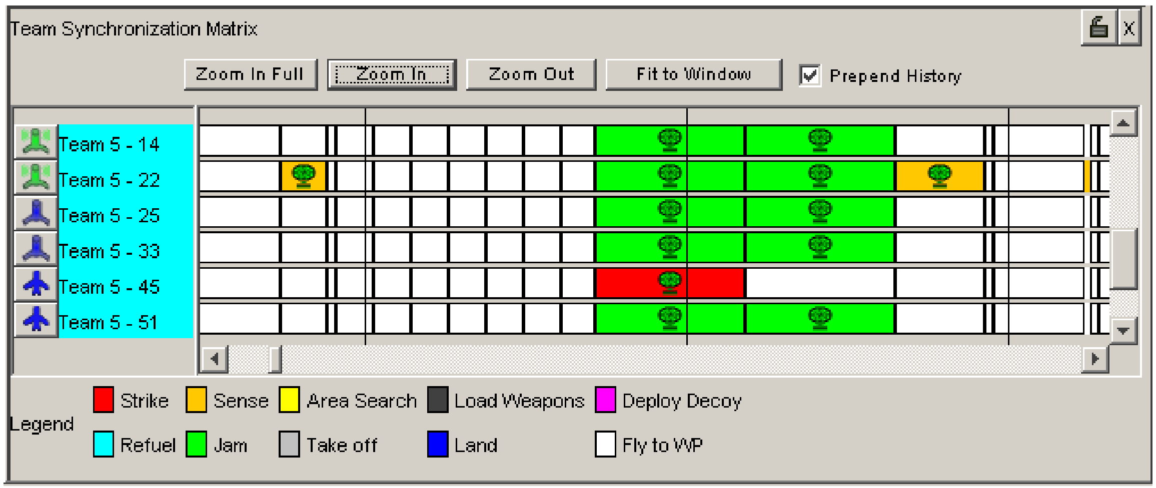

Figure 5.2.2.2-3 – Draper Synchronization Matrix

5.2.2.3 Multilateration Teams

Multilateration, Figure 5.2.2.3-1, is the most effective tactic for locating and identifying emitting targets. Additionally, multilateration is necessarily a team tactic requiring the connection of team participants to a shared data network. Neither of the controllers fundamentally planned for

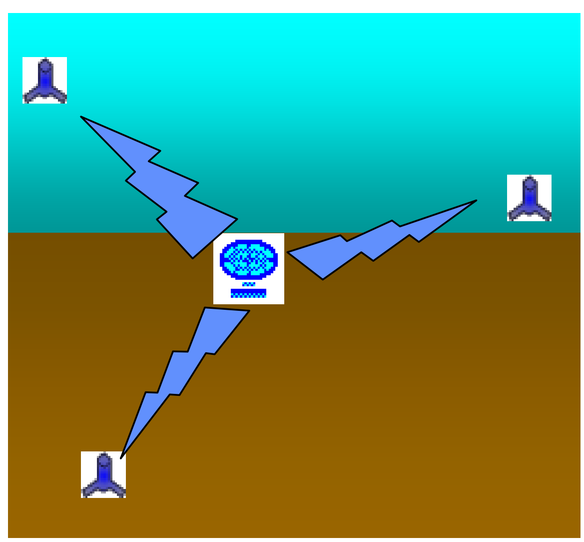

Figure 5.2.2.3-1 - Multilateration

use of multilateration teams.

Changes to the passive ranging model were made in OEP version 1.2 formally available in May 2003. The original single ship passive ranging model was replaced with a multi-ship model requiring team formation for precise location and identification of RF emitters. For ESM sensors to generate tracks, they must first be connected to 'networked' multilateration components, rather than directly to the tracklists in the platforms. A multilateration team is then established by three or more platforms connecting to a common network and sharing ESM sensor reports. The accuracy of resultant reports can be extremely high if proper geometry between platforms and the observed emitter is maintained. Because of this geometric sensitivity, multilateration teams should be constituted and their geometric spacing planned as part of an overall system solution.

During the initial experimentation, it was discovered that the Draper controller made no use of multilateration for target location and identification. Multilateration teams were subsequently added, though this was done without a logical "network connection action". The resultant ad-hoc multilateration teams are not a driver in the development of mission plans, but are created after other tasks have been allocated and the routs have been planned. Multilateration team geometry thus arises accidentally from other path planning considerations. Frequently, multilateration team participants have minimal geometric separation relative to their targets. Occasionally, one member of a three ship multilateration team would still be located at the blue base on the ground, and therefore would not be able to generate multilateration reports. In any case, these conditions essentially made multilateration ineffective.

It was also determined during experimentation that neither Iterativity-OSU planner used multilateration. No 'reasonable' network-connection activity was defined and no platforms were connected to the multilateration networks.

The simple addition of multilateration would have greatly improved the information gathering performance of both the Draper and Iterativity-OSU controllers. By having the UAVs in a local area publish their locations, they could then determine locally optimal team geometries and form ad-hoc multilateration teams. This would have allowed for accurate discovery, localization, and identification of every emitting platform in a covered region.

5.2.2.4 Planning Triggers

Planning triggers are critical elements of MICA controller design. A balance must be struck between committing to existing plans, in order to complete tactical objectives and replanning to achieve a more optimal overall solution. Effective controller design supports automated local and global triggers, subject to operator concurrence, coupled with the cap ability for the operator to initiate similar partial or global replans. Each of the evaluated controllers offer elements of the desired capability but neither affords all desired features.

The Iterativity-OSU controller allow user selection of planning triggers including New Target discovery, Asset Loss, and Time Based replanning, Figure 5.2.2.4-1. Additionally the Variable Initiative Interface allows for MICA operator initiation of a team level re-plan, see below. However, the operator is not afforded the opportunity to concur with the replan nor is the operator able to initiate a global replan.

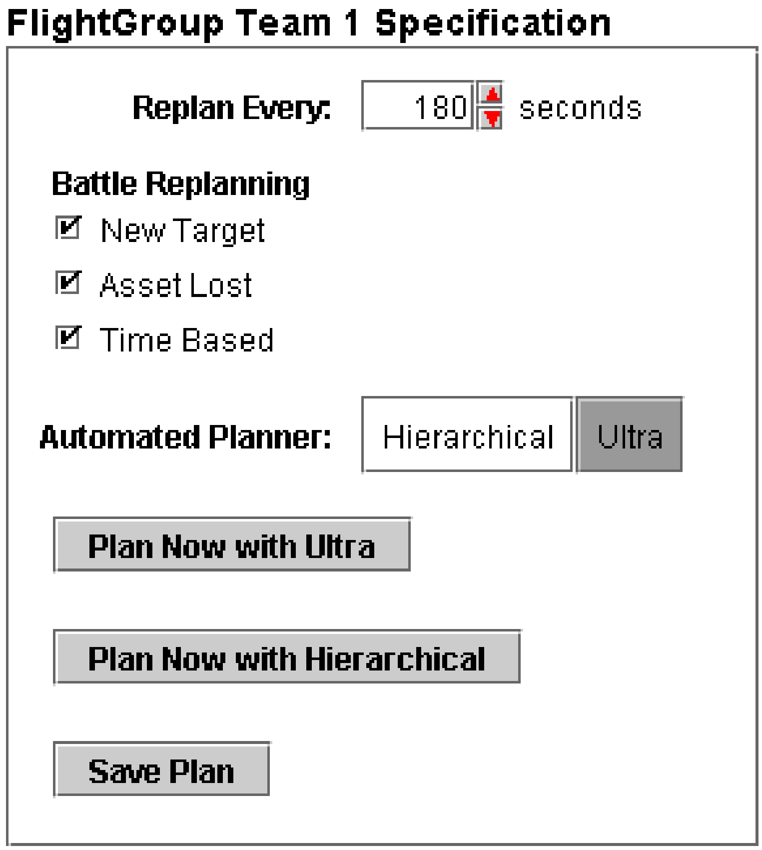

Figure 5.2.2.4-1 – Iterativity-OSU Trigger Selection

The primary planning trigger for the Draper controller appears to be cumulative changes to the Information Model, i.e. discovery of new targets, movement of known targets, or changes to the target probability distributions. Additionally the Draper controller re-plans at both the TCT (Team Composition and Tasking) and TDT (Team Dynamics and Tactics) levels on a predefined time interval. TCT globally re-plans every hour and the TDT re-plans on a shorter time interval. It was not evident that re-planning is initiated by asset loss, and there is no user interface to dynamically influence re-plan criteria or to initiate a replan. Below is a 'message log' illustrating initiation of a top level TCT re-plan request due to cumulative changes to the Information Model which have apparently altered the calculated utility of the current plans.

```
[Fri 14:18:07]      Updating aircraft/tracks/gridcells.
[Fri 14:18:08]      Update complete.
[Fri 14:18:10]      Updating aircraft/tracks/gridcells.
[Fri 14:18:10]      Update complete.
[Fri 14:18:11]      Updating aircraft/tracks/gridcells.
[Fri 14:18:12]      Update complete.
[Fri 14:18:13]      Updating aircraft/tracks/gridcells.
[Fri 14:18:13]      Update complete.
[Fri 14:18:14]      Updating aircraft/tracks/gridcells.
[Fri 14:18:14]      Update complete.
[Fri 14:18:16]      Updating aircraft/tracks/gridcells.
[Fri 14:18:16]      Update complete.
[Fri 14:18:16]      Approval needed for controller replan.Reason:
Situation changed
       Objective value has increased.
```

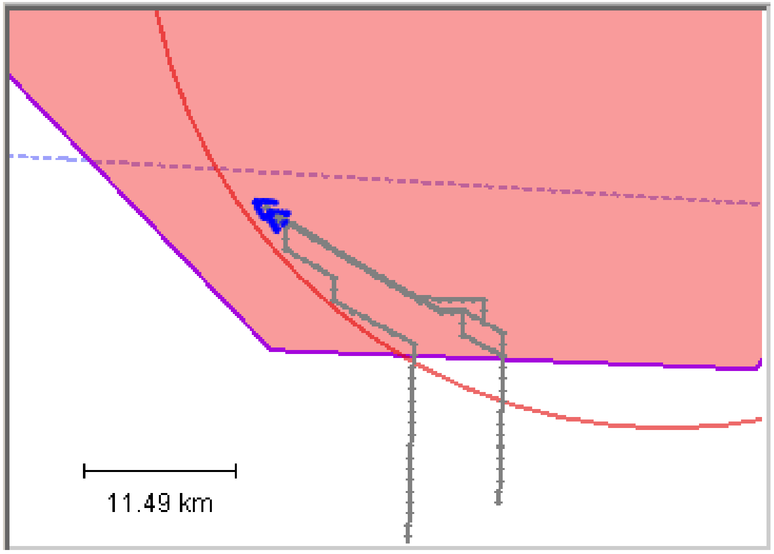

Figure 5.2.3-1 – Iterativity-OSU “Gradient Descent” Planner

The net result is that the Draper plans are reset excessively, inhibiting any significant progress toward achieving the campaign level goals. Assets initially allocated to one team will often get re-assigned to new a team or sent back to base without accomplishing any assigned tasks. Additionally, many of the new 'teams' are composed of very few assets. A better balance needs to be achieved on commitment to existing plans and the extent and frequency initiating re-plans. Allowing for customization and control of planning triggers by a MICA Operator would be a powerful tool to enable better control of the replan cycle in real-time.

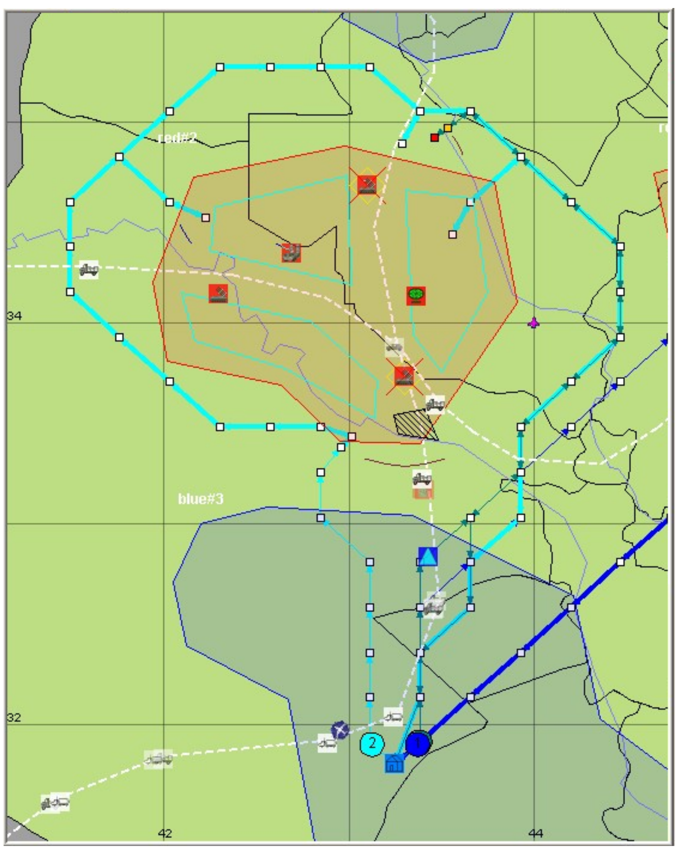

Figure 5.2.3-2 – Draper Global Search Planner

5.2.3 Cooperative Path Planning

Both controllers exhibited evidence of coordinated team tactics and planned asset flight paths in response to either team assignment or task allocation.
Both controllers currently plan and fly in a horizontal plane, i.e. the path planners are two-dimensional. The Draper controller flies at 4000m while the OSU-Iterativity controller files at 5000m.. The planned flight paths of the Draper controller deviate from the plane but only for an asset to takeoff and land.

This implies that neither of the controllers are rigorously applying or taking advantage of the three-dimensional aircraft signatures in their path planning. Signature management, when engaging a long SAM, can greatly increase the probability of UAV survival.

The OSU-Iterativity controller has implemented a potential based "gradient descent" local path planner, Figure 5.2.3-1. The potential is based upon known threats. Escape from local potential minima is handled by uniformly lowering the calculated threat potential. While this will guarantee UAV progress toward its goal, the path planner is not likely to find the lowest risk path. The benefit is that the planner will inherently react to discovered threats by adding them to the composite threat potential.

Draper seems to have implemented an entirely global, graph search based path planner, Figure 5.2.3-2. Additionally Draper seems to have tightly coupled the task allocation and path planning in their TDT/CPP planner. A significant drawback of this approach is that they have not demonstrated a capability to perturb a planned path segment to avoid a discovered threat without initiating some level of TDT/CPP re-planning. A 25 Km rectilinear grid is used for global path planning. Initially, paths appeared to be constrained to the grid, deviating only when necessary to engage (sensor or weapon) a target. With later releases, the planned paths have deviated more significantly from the course grid. This allows for more survivable routs when traversing a complex threat environment. The Draper results would have been even less promising if they had not taken advantage of “perfect IPB, discussed below.

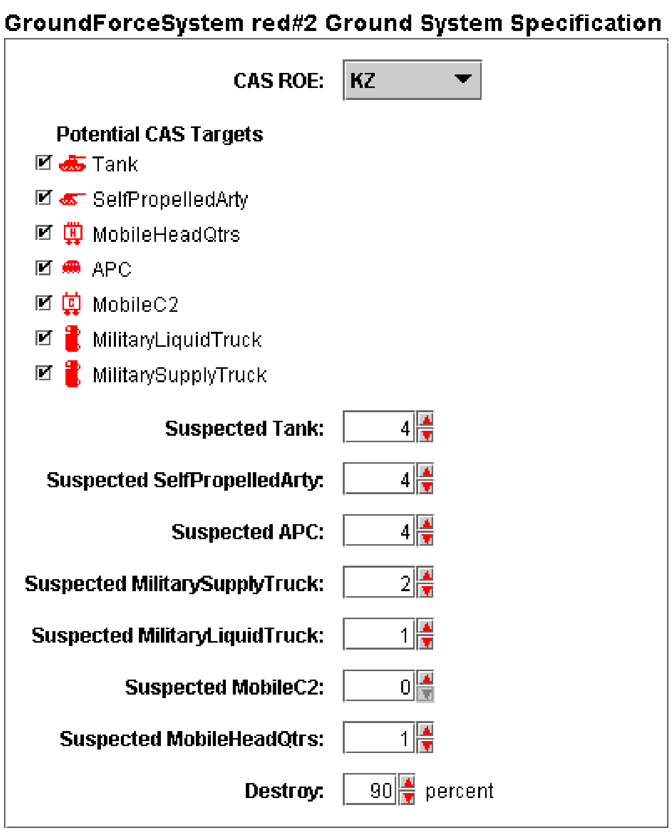

Figure 5.2.4.1-1 – Iterativity IPB Entry

Because Iterativity-OSU enables localized replanning, they are able to account for discovered threats without abandoning a plan in progress. As would be expected, these localized reactions appear to improve controller performance. In contrast, the Draper controller does not support localized replanning, is unable to make these surgical adjustments, and thus suffer additional attrition and loss of progress due to excessive global replanning.

5.2.4 Uncertainty Management

The MICA IPB (Intelligence Preparation of the Battlefield) was designed to realistically reflect the uncertainty of information available to the planning process prior to initiation of a campaign. The ability of the controllers to manage varying amounts of uncertainty was to be evaluated primarily by varying the completeness and accuracy of the provided IPB. Proper use of this IPB was deemed essential to controller performance as not all targets and threats would be precisely known prior to beginning an operation. Unfortunately, the limited performance of the controllers against the MICA challenge problem, even with a "perfect IPB", limited the value of a detailed assessment.

5.2.4.1 Initial Preparation of the Battlefield

The MICA Challenge Problem and OEP provided both qualitative and quantitative IPB content. Quantitative IPB information was accessible to the controllers via initial data in the various platform tracklists available upon scenario startup, and all controllers have made use of this. Qualitative IPB information was initially available to the MICA "UAV Team" Operators as a PowerPoint presentation, much as it is handled in the field today. In response to a request from Draper during early experimentation, a preliminary XML representation of this qualitative information has been developed and is accessible via the GetProperty("IPB") API call.

Prior to provision of the XML representation, Draper had been generating a "perfect qualitative IPB" which was used to initialize their Information Model, discussed below. It was discovered during experimentation that the Draper controller was consuming the Challenge Problem XML and storing red and white platform quantity and type as a probability mass function across the scenario area. This PMF, based on truth data, was then used to deterministically plan flight paths around known but as of yet 'undiscovered' threats, and to initiate sensor missions to establish tracks for targets that were known to exist, but had not yet been discovered.

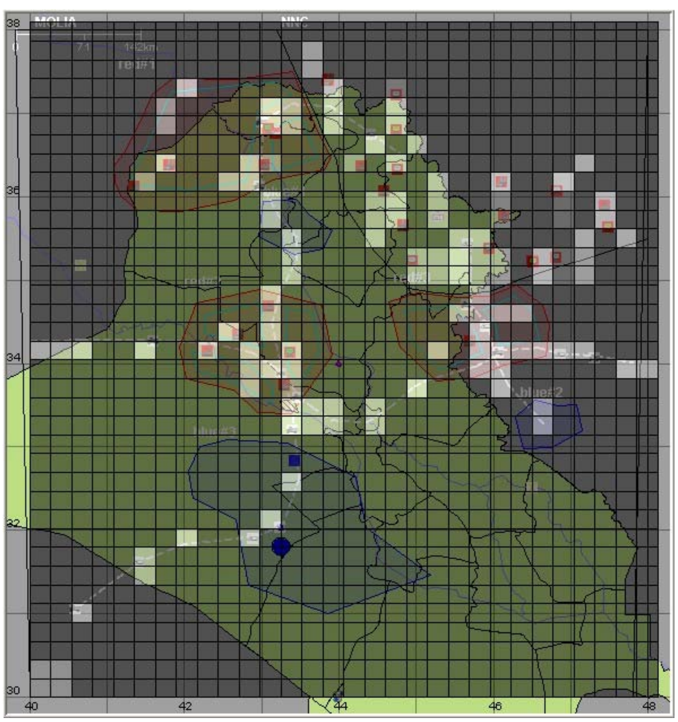

Figure 5.2.4.2-1 – Draper Information Model

Alternatively, the Iterativity VII provides an intuitive USI for input of the qualitative IPB data provided in the PowerPoint File, Figure 5.2.4.1-1. A set of potential target types, associated quantities, and Rules of Engagement for each geographic area is presented to the MICA Operator for selection and data input. Corresponding symbols are then placed in each of the geographic areas allowing for subjective placement of the targets and assignment of their location errors.

5.2.4.2 Draper Information Model or Probability Mass Function

Draper has created a target Information Model that maintains estimations of target type, location, and state across the geographic region of interest. Figure 5.2.4.2-1. In principle, this two dimensional target distribution, or probability mass function, is initialized from both the Intelligence Preparation of the Battlefield and the targets known a priori, i.e. the Initial Track List. OEP Track Events are then used to update and maintain this model.

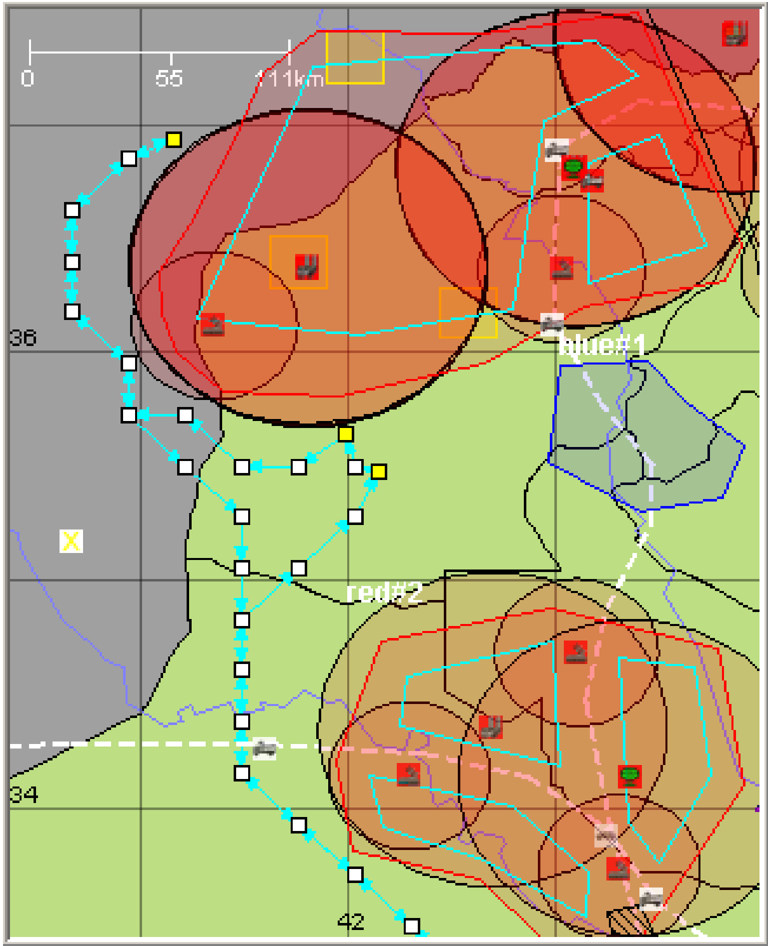

Figure 5.2.4.2-2 – Draper ISR Mission Plan

This information model maintains a representation of both uncertain targets, targets that are expected to be found in a general area but for which a track does not yet exist, and 'certain targets' for which do tracks exist and are being maintained.

It is this naturally complementary representation of target information that is then used to support task selection, allocation and path planning. For example, the expectation of several uncertain targets within in a local area may be used to initiate and plan ISR missions, Figure 6.2.4.2-2. Or the existence of 'certain tracks' of known type and state may be used to initiate strike missions and the existence tracks of uncertain type or state may be used to initiate ID or BDA missions. Also the presence of both certain and expected threats may be used for path planning and threat avoidance.

Figure 5.2.4.2-2 represents an ISR mission planned accordingly. As can be seen, the path has been planned to avoid the known threats, and the search areas □ correspond to PMF cells with large target expectation highlighted above.

In light of the Information Model structure, and its initialization by parsing of the Challenge Problem XML, it can be understood why the Draper controller does not respond to threat warning reports and only rarely retrieves OEP Events. The various planners reason upon the Information Model, and are triggered by changes to the modeled state. First, since any change to the represented state *might* be significant, the controller re-plans with every state change, no matter how in-significant, i.e. a small change in target location or perhaps a change in target classification probability triggers a full replan. Second, even though the Information Model can represent a target as a SAM, including its location and damage state, there does not appear to be a means of representing that it is actively engaging a blue UAV. Because of this limitation, the planners cannot reason upon this un-represented state and determine that the engaged UAV needs to take immediate evasive maneuvers. With the Information Model, Draper has constructed an elegant vehicle for representing the uncertain nature of knowledge of the battlefield. Unfortunately,, because of the incomplete state representation, or perhaps because of the way it is integrated with the planners, it is not well suited for driving local reactive planning such as the exemplified evasive-maneuver. These problems may be mitigated by expanding the modeled state space and by 'tuning' the algorithm used to initiate team level re-planning.

5.2.5 Variable Initiative

The Variable Initiative Interface is intended to provide the MICA operator information sufficient to assess both the global situation and the appropriateness and soundness of the proposed team plans. Additionally, it is intended to allow the operator to interact with the decision process, and in the extreme, control the various MICA assets.

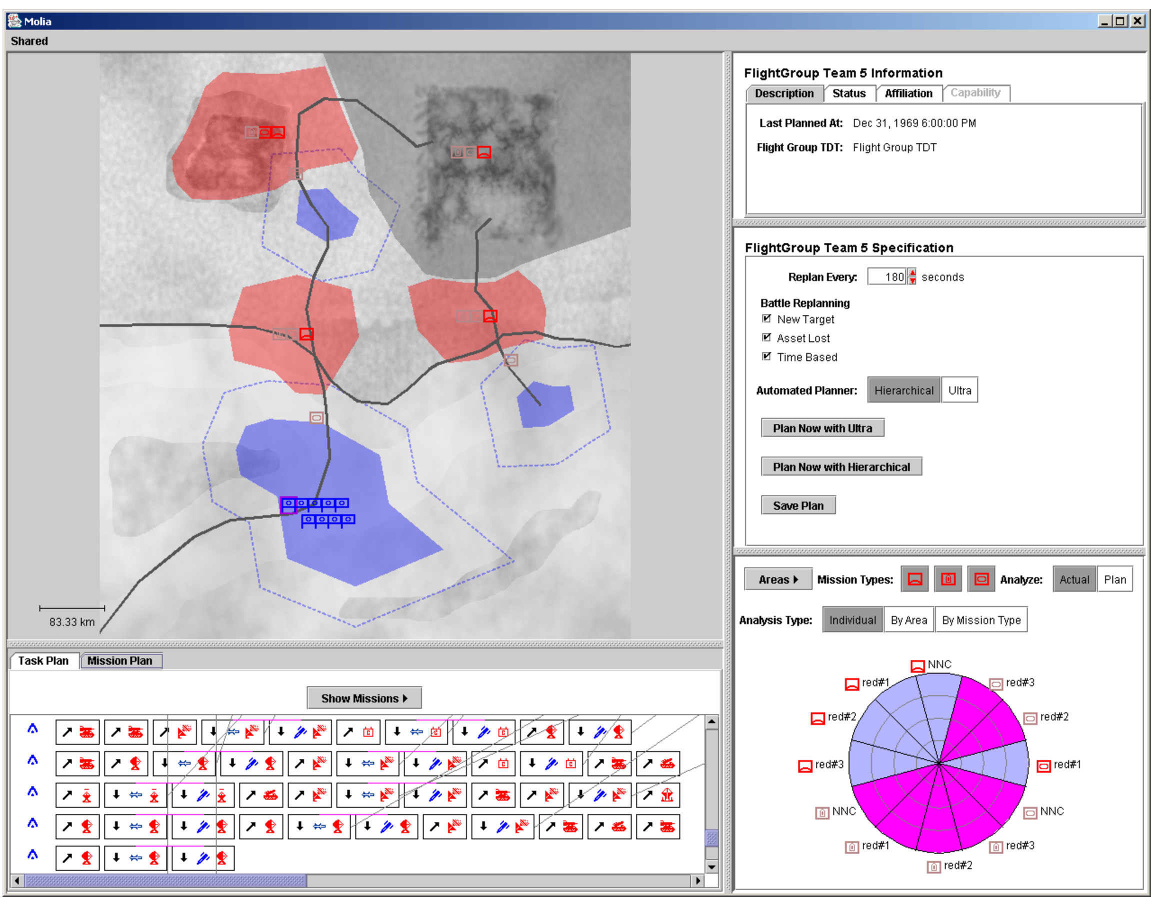

Figure 5..2.5.1-1 – Iterativity VII Display

5.2.5.1 The Iterativity Variable Initiative Interface

There are at least two outstanding features of the Iterativity VII, Figure 5.2.5.1-1. First, the graphical representation of the partially ordered plan sequence with "activity tiles" proved to be an effective approach to intuitively conveying what activities are being planned and when (with respect to order) they will occur. Time is not explicitly represented, but this may be a strength since the critical element in planning is the sequence of events rather than maintaining a rigid schedule.

A further improvement would allow the MICA Operator to use this "activity tile" plan representation as means for interacting with the planning process. The operator might explicitly assign a platform to a specific target, or restrict the weapon type to be used against a target. Or perhaps the operator could enter coordination events to impose a sequencing on the Order of Battle. Additionally, it would be beneficial to have a corresponding "target centric" representation of this plan interaction interface.

The Iterativity VII allowed for intuitive input of additional information to be used by the planning process. As discussed previously, the Iterativity VII allowed for intuitive input of qualitative battlefield intelligence, i.e. approximate quantities of targets in approximate locations. Additionally the VII allowed for intuitive assignment of Rules of Engagement to pre-defined target clusters as well as ranking of the various Commander's Guidance Objectives to be used in the planning process. What would have made this even better would be to be able to define "new" Rules of Engagement, Commanders Guidance, and target clusters.

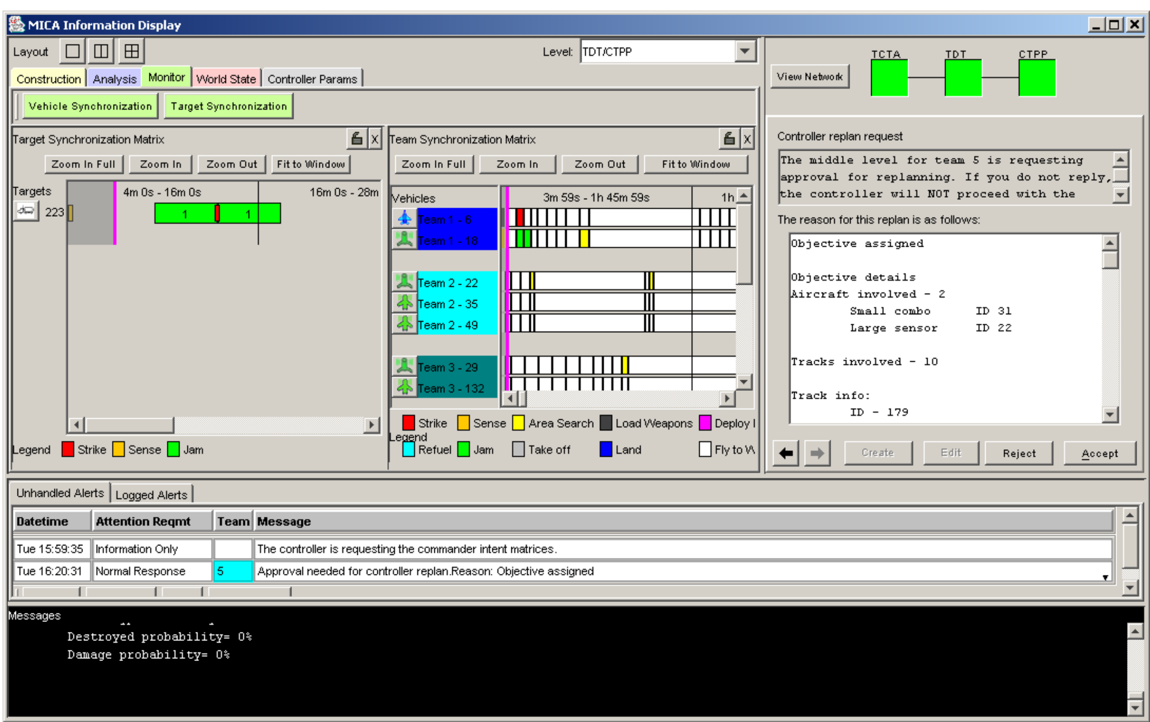

Figure 5.2.5.2-1 – Draper-Charles River VII Display

Two drawbacks of the Iterativity VII were the lack of visualization of planned paths, and a lack of means to edit a generated plan sequence or directly interact with the planning processes, though this was a shortcoming of all of the controllers.

5.2.5.2 The Draper - Charles River Variable Initiative Interface

The Draper VII was separated into a planning and control MICA Information Display, and a situational awareness Human-System Interface visualization display, Figures 5.2.5.2-1 and 5.2.5.2-2. This separation naturally reflects the main purposes of the VII, the monitor and control of MICA teams.

The MICA Information Display, Figure 5.2.5.2-1, allowed for both asset centric and target centric viewing of generated plans, but as with the Iterativity-OSU controller, there were no means of direct interaction during plan formation nor of subsequently editing the generated plans. Interaction with the planning process was largely limited to adjusting

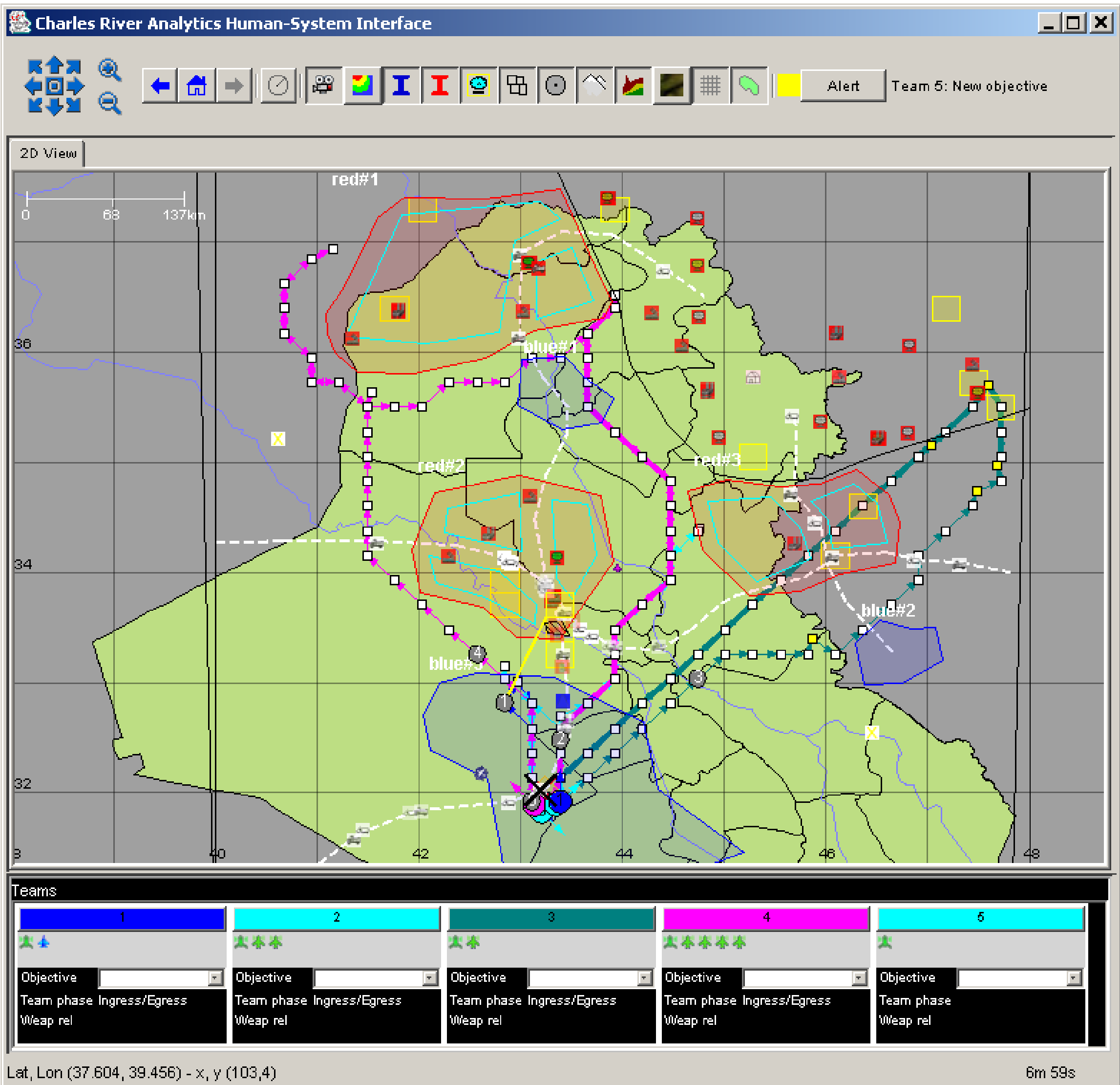

Figure 5.2.5.2-2 – Draper-Charles River HSI

target table valuations prior to plan auto-generation, and the subsequent acceptance or rejection of the plan in its entirety.

Furthermore, there were no means for entering additional information such as qualitative battlefield intelligence, new strategic objectives, or changes to the rules of engagement - other than tuning of the target valuation tables. This approach appears to be more algorithm oriented than operator oriented. For example, this forces the MICA Operator to discover how to translate a strategic objective into a specific target value distribution, rather than simply entering a symbolic (logic) representation of the strategic objective.

The Draper HSI display provides several intuitive plan visualization tools such as a planar graph representation of planned paths with selectable activity symbols such as search, strike, and sense. The HSI could be decluttered, if beneficial, by displaying only selected assets and teams. Additionally, the HSI provides a "Plan Animation" feature allowing a "preview" of the current plans as they are anticipated to play out.

5.2.5.3 Variable Initiative Interface Summary

As discussed above, no VII actually allowed the MICA Operator to directly interact with the planning process. No VII allowed the operator to edit a subsequent plan, either at the team composition level, or at the task allocation level. Providing these capabilities, as well as a mean to visualize and implement higher level strategies, would greatly enhance the utility of the MICA Variable Initiative Interface.

5.3 Challenge Problem Tractability

Several researchers have contended that their lack of progress against the MICA Challenge Problem is reflective of an impossible degree of difficulty in terms of IADS capability vs. blue assets. This issue can be partially addressed through comparison with the Boeing BlueController, whose quantitative performance exceeded that of the heavyweight MICA Controllers in terms of the kill ratio between red and blue assets, but whose algorithms were lightweight in comparison.

The Boeing Blue Controller evolved over the final 18 months of the MICA program. It was initially developed as a tool for robustly debugging the new models and APIs that were added to the OEP. Its capabilities grew under the influence of other programs (AFRL REAC) and research efforts, and under the MICA need to stimulate and challenge the IADS Red Controller. Perhaps the most notable distinction of the Blue Controller from the heavyweight MICA Controllers, other than algorithm complexity, was that the Blue Controller consumes a larger subset of OEP events, most notably the Threat Warning Event. This, and a short event handling cycle of 5 seconds, allowed the Blue Controller to rapidly perceive and react to the changing adversarial environment, and particularly to engagements by red SAM threats.

Briefly, the Blue Controller was built around an auction based task allocation protocol and a centralized KnowledgeObject, Figure 5.3-1. Auction based task allocation allowed algorithms to be located where requisite data was naturally resident, thus minimizing communication requirements among the various platforms. Examples of distributed algorithms are Cost and Merit calculation used for Utility calculation and the reactive threat avoidance algorithm. In contrast, the KnowledgeObject defines the "universe of discourse" and allows specialized algorithms to operate upon a shared representation of the battlespace. Examples of specialized algorithms would be the application of ROE constraints to target selection, or the greedy task-asset selection algorithm, which combines the cost and merit reported by each asset into a communal utility, which is then maximized to determine the optimal asset for each task assignment.

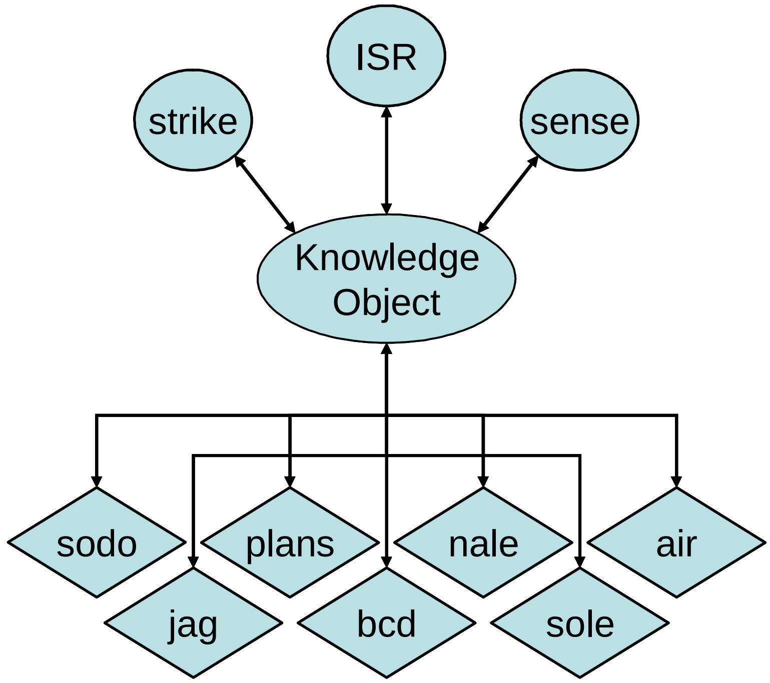

Figure 5.3-1 KnowledgeObject

Even with these relatively lightweight algorithms, BlueController performance often exceeded that of the evaluated MICA Controllers. While these would lose most if not all of their assets while destroying 2-3 SAM sites (a ratio of 1 red asset destroyed for every 12 to 18 blue assets lost), the light-weight BlueController tended to destroy 3 red assets for every 5 blue assets lost, demonstrating consistent progress against the full MICA Challenge Problem. More importantly because the BlueController was focused to the primary Blue objective of eliminating the IADS by destroying the redundant red C^2 facilities, it was often able to accomplish this task. Once the IADS is eliminated, the BlueController consistently demonstrates a significant tactical advantage over the red SAMs that must operate individually. Neither of the heavyweight controllers was ever able to destroy either of the C^2 facilities. Furthermore, the BlueController achieved these results without employing jamming. The Challenge Problem is designed to require cooperative jamming for IADS penetration with minimal blue asset loss. We are confident that the BlueController could successfully eliminate the IADS, by destroying the C^2 facilities, while suffering minimal loss of blue assets once cooperative jamming techniques are integrated into the controller. Unfortunately this planned BlueController enhancement could not be completed during the shortened research period.

Regarding Challenge Problem tractability, we would also reference the UCSB research results. UCSB developed a controller that focused on managing blue vehicle orientation relative to red defenses coupled with cooperative jamming. Their results confirmed our Challenge Problem design expectations and demonstrated a significant tactical advantage for blue over red. Based on our experience with the BlueController and the UCSB demonstrated results, we are confident that the Challenge Problem is tractable and is representative of real world challenges.

6 Conclusions

Although much was accomplished significant research is still needed due to the premature termination of the program. OEP research needing to be completed relates to completion of the planned experimentation. This involves more than execution of the experiments. There are additional OEP capabilities required to execute each phase of experimentation as well as additional controller capabilities. Most importantly, early experimentation has confirmed the extreme value of the integration process in improving controllers and focusing them ob tactical utility. The remainder of this section will address requisite activities and capabilities associated with each experimentation hypothesis.

6.1 H1 Experimentation

The original objective of H1 testing was to quantify the benefit of MICA research by comparing execution of the MICA Challenge Problem by USAF domain experts using currently available technology against the performance of MICA controllers. Towards this end a top-level battle plan for the MICA CP was developed by the 133rd Air National Guard (ANG). The original intent was to eventually involve representatives of the 133rd ANG in execution of the full challenge problem scenario. This execution would have provided a benchmark for absolute evaluation of controller performance. This benchmark will be required if any absolute measure of controller performance is to be derived.

It is worth mentioning that the H1 Experimentation that was performed has proven extremely valuable during our limited H2 and H3 testing discussed above. The H1 experimentation has highlighted the absence of a top level battle strategy in the controllers evaluated and has led us to the conclusion that future automated controllers need to incorporate such a strategy. Clearly automated controllers need to integrate the lessons learned through years of battle management experience if they are to be successful. This experience dictates that a sound overall battle plan and strategy are the first element of a successful campaign.

We believe that complete execution of the H1 Experimentation would yield many additional lessons that should be integrated into a successful controller design. As the old adage says, “No battle plan last beyond the first shot.” It would be enlightening to see if automated controllers are as successful at adjusting as are competent domain experts. Expansion of the OEP visualization capability would greatly assist in execution of this expanded Hi Experimentation. Visualization is essential to integrating additional human in the loop control into MICA execution and would facilitate qualitative evaluation of both human and automated controller performance.

6.2 H2 Experimentation

Completion of H2 experimentation would greatly enhance the overall capability of MICA controllers. Significant improvements in the Draper controller were effected in the short time available. Much greater progress would have been made if time were available to complete testing for all factors and most importantly for Draper to respond to experimentation feedback by incorporating additional features and logic. Unfortunately Draper was the only research organization that afforded Boeing the opportunity to both perform experimentation and to engage in a dialogue with controller designers. It is clear that if time and resources had permitted, continued H2 experimentation would have benefited each controller and would have resulted in far more tactical utility from the MICA research.

An OEP capability that would have greatly enhanced this expanded H2 Experimentation if the Red Cell. The envisioned Red Cell capability would have added to the current automated red IADS by adding capability for closed loop control of red ground assets and by introducing the capability to integrate human decision making into the red control. This type of experimentation would be of great value as the automated blue controllers began to mature. It would have generated additional avenues of research for the blue side and would have resulted in a much more robust and useful set of MICA research artifacts. Expanded visualization capability would have been critical to the human in the loop red cell capability because it would enable the red commander to effectively employ his assets.

6.3 H3 Experimentation

Our limited experimentation with the Draper and Steinmetz/OSU controller confirmed the importance of the variable element to MICA. We were strongly impressed with the human interface of the Steinmetz/OSU controller and believe that additional innovation in this area is critical. In particular giving tools to the commander to monitor and adjust the battle plan as well as the tempo and extent of replanning appears to be powerful. Again, expansion of the OEP visualization capability would aid in this area.

6.4 H4 Experimentation

This area is critical if MICA controllers are to gain credibility as transitionable products. Little beyond planning has been accomplished in this area. An additional capability required to execute H4 Experimentation is the interface between the OEP and the vehicle controllers. Improved visualization would greatly enhance the impact and effectiveness of H4 Experimentation.

6.5 Summary of Additional Research

In addition to complete execution of the MICA Experimentation Plan, three additional OEP capabilities are required to complete the research. Additional effort in the visualization interface would benefit all phases of experimentation. The Red Cell capability would enhance the quality and extent of H2 Experimentation and would yield more robust and tactically significant controllers. An OEP to Mission Control Station interface would enable H4 Experimentation and would facilitate transition of MICA research artifacts to operational employment.

Appendix A - Planned Experimentation

At the time that MICA Program funding was terminated, Boeing was nearly finished planning the Experimentation phase of the program. The following sections detail the planned experimentation. Results of the limited experimentation that Boeing was able to accomplish are discussed in section 5.

A.1 Statement of MICA Experimentation Objectives

The objective of MICA experimentation is to assess MICA research products to: 1) Ensure that they represent a step increase in operational capability over currently planned approaches to battle management, 2) Determine the extent to which they respond to each of the five research areas, and their robustness in adapting to a myriad of tactical situations, and 3) Ensure that they are transitionable to currently planned tactical and C^2 Systems. The sequential nature of this experimentation is designed to ensure efficient expenditure of research and experimentation resources. The latter phases of experimentation will be performed only if the initial phase substantiates that MICA research artifacts demonstrate a significant increase in operational capability over current planned tools and processes. The second phase will be applied only to the extent that each controller shows promise in a specific area. To this end controllers will be pre-screened to ascertain the extent to which their design accommodates specific areas of experimentation. The final phase of experimentation, which involves a mixed environment with hardware operating in conjunction with a synthetic environment, will only be applied to those controllers that demonstrate the most operational utility and robustness during the first two phases.

A.2 Experimentation Hypotheses

Accomplishing these objectives entails evaluation of four hypotheses. The first directly relates to Phase 1 of the experimentation. The second and third will be evaluated during the second phase and the fourth relates to the third phase.

H1 – Teams of unmanned vehicles formed and controlled by MICA automated controllers combined with variable initiative technology does significantly better than current methodologies and tools applied to unmanned vehicles.

This hypothesis relates to the core justification for MICA research and addresses the question “Why should the Government buy MICA?“ Further investment in MICA research and experimentation is warranted if and only if this hypothesis cannot be refuted through experimentation. For this reason, the first phase of MICA experimentation is designed to evaluate this hypothesis and must be successfully performed before additional experimentation will be conducted.

H2 – MICA controllers provide an integrated solution spanning each of the four task areas for a realistic range of tactical situations.

The four task areas are: 1) Team Composition and Tasking 2) Team Dynamics and Tactics, 3) Cooperative Path Planning and 4) Uncertainty Management. The range of tactical situations shall include SEAD against Third World opponents as well as state-of-the-art Integrated Air Defense Systems, Interdiction against fixed and moving targets including designated Time Critical Targets, Intelligence, Surveillance and Reconnaissance, employment of a variety of weapons, sensors and countermeasures and adherence to representative Commander's Guidance and Rules of Engagement. Validation against this hypothesis ensures the robustness and attendant operational utility of the MICA research artifacts.

H3 – MICA controllers provide efficient operator integration enabling safe and robust human control of automa-teams consisting of 5 to 30 heterogeneous unmanned vehicles.

This hypothesis addresses human involvement in the battlespace management and control process. Status and recommendations provided by decision support systems must be of interest to and naturally understandable by a human, who must also be able to provide guidance to automata in a natural form.

H4 – MICA research artifacts can be transitioned to near-term (2 to 4 years) operational employment.

The critical issue regarding validation of this hypothesis is early introduction on hardware experimentation. Validation of the transition potential of MICA research requires that mixes of heterogeneous hardware platforms be controlled using MICA algorithms in a synthetic battlespace.

A.2.1 Hypothesis H1

The goal of H1 experimentation is to gauge the value of MICA technology for controlling teams of unmanned platforms against the current technology. The value of MICA technology will be evaluated against two hypotheses: H1-1) Development and execution of unmanned vehicle battle plans using MICA controllers utilizes significantly fewer resources than current tools and processes to accomplish the same job; and H1-2) MICA controllers provide superior battle plans and execution compared to current tools and processes. Figure A.1.1-1 depicts the process to be used for H1 Experimentation.

To evaluate the first hypothesis (H1-1), we will conduct a paper experiment at the 133^{rd} Air National Guard – Fort Dodge to determine manning and technology needs. This experiment will be conducted over the course of a single day and will draw upon domain experts at the 133^{rd} to identify resource requirements. The 133^{rd} detachment has expertise in air operations planning for manned platforms. They will provide insight into personnel needs to accomplish the detailed planning and coordination tasks that are handled autonomously by MICA controllers. H1-1 represents a gate that will determine whether additional H1 testing is required to quantify the benefit of MICA technology. The results of H1-1 testing will be an estimate of people requirements to perform this function including the logistics train required to support this number.

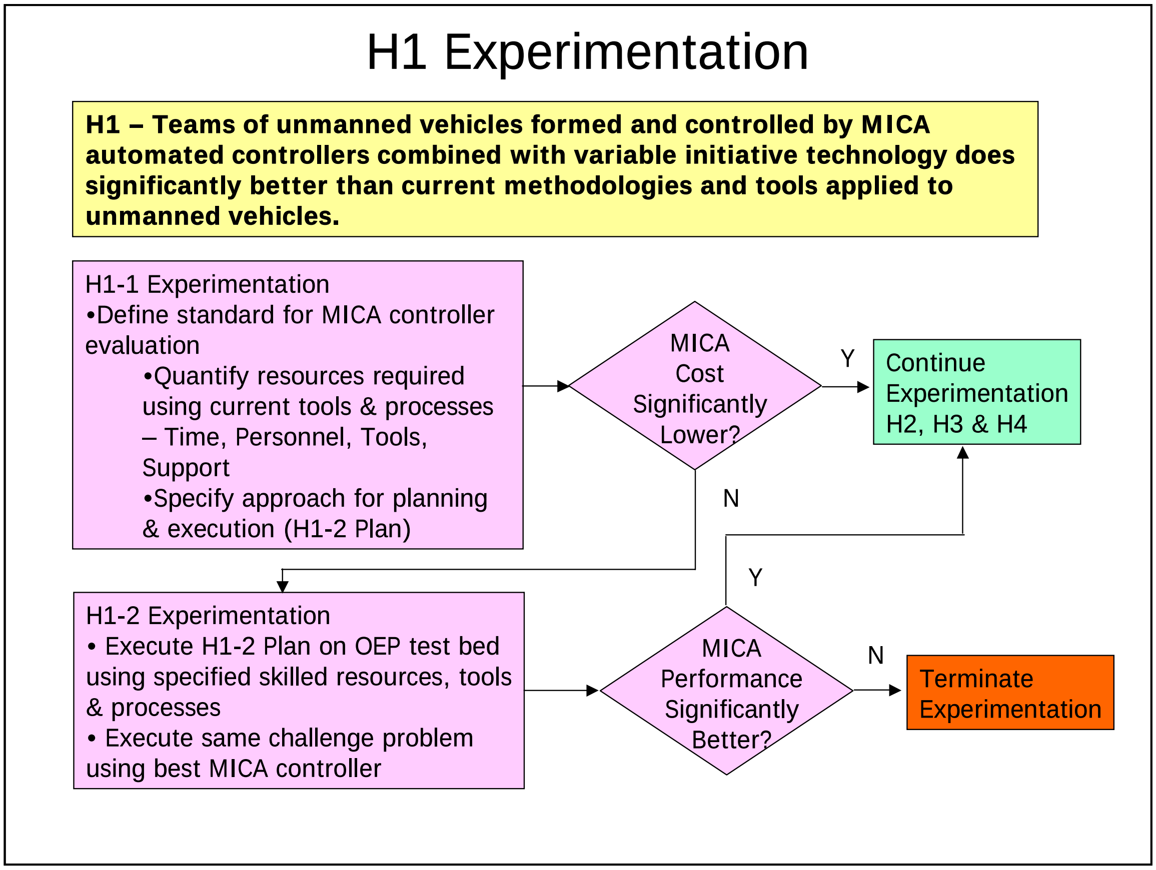

Figure A.1.1-1 – H1 Experimentation

In H1-2 experimentation, the set of domain experts identified in H1-1 would be utilized to plan, coordinate, and execute the MICA challenge problem using currently available tools and technologies. The same challenge problem would be executed using MICA controller(s). The experimentation for H1-2 would utilize the MICA OEP to simulate the dynamic battlefield environment including generation of representative sensor reports and for conflict resolution and the gathering of performance metrics. An apples-to-apples comparison between MICA controllers and current tools would be available through development of the same set of performance metrics. We currently envision this testing to be performed using one or both industrial prime controllers. H1-2 testing would be performed on the nominal factors with a single iteration. The hypothesis H1 indicates that MICA controllers should be significantly superior – thus the need for multiple iterations to generate statistically significant results is diminished.

H1-2 experimentation would require significant effort from a set of domain experts in order to develop and execute a responsive battle plan. Therefore it will be performed only if the results of H1-1 are not conclusive regarding MICA potential for a significant reduction in required resources. In this case the decisive criterion regarding MICA research value is the quality of resultant planning, coordination and execution relative to the current means identified in H1-1. To put this in simple terms, it is expected that H1-1 will indicate that significantly more resources, personnel, air vehicles, planning and execution time and logistic support, will be required to execute the challenge problem using current tools and processes. Given this result, there is no need to perform H1-2 testing since the only remaining question revolves around MICA controller performance. Are MICA controllers capable of planning, coordinating and executing the challenge problem to the standards defined below for H2 and H3 experimentation? If they demonstrate this capability, they are clearly superior to current tools and processes given that H1-1 shows significant cost savings. However, if H1-1 indicates that MICA controllers do not offer clear advantage in terms of resource consumption, it may be necessary to execute H1-2 to quantify the relative performance of MICA controllers against the current tools and processes and to compare MICA controllers against this standard. In order to formulate a clear decision regarding H2-2 experimentation, Boeing will formulate a formal recommendation for Government review subsequent to completion of the H1-1 experiment.

A.2.2 Hypothesis H2

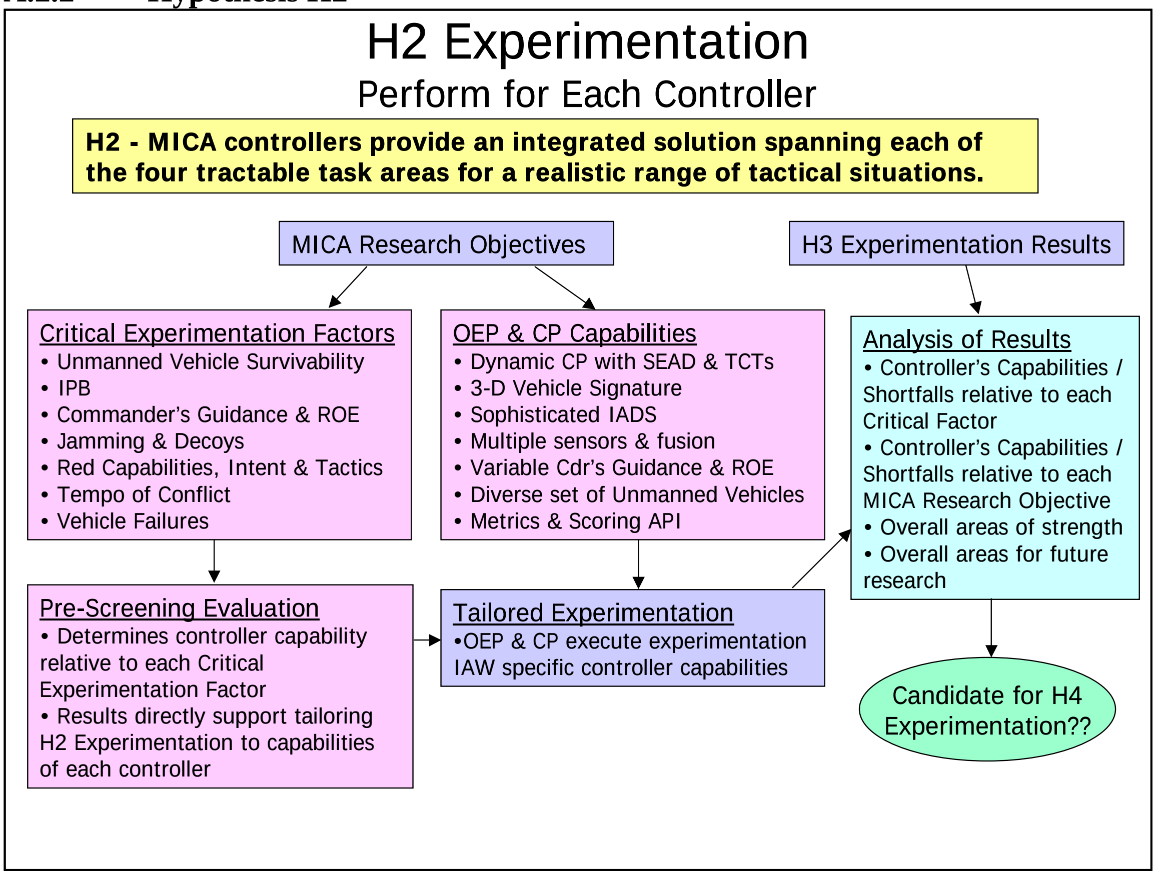

Figure A.1.2-1– H2 Experimentation

The intent of H2 experimentation is to examine the capability and robustness of each MICA controllers across the full spectrum of MICA requirements and war fighting situations. This is an enormous challenge involving an extensive number of combinations of experiment factors and values. There is obviously a physical limit to number of experiments that can be conducted in a reasonable time frame.

A typical challenge problem lasts 24 –72 hours and the combined OEP and controller execute 3 – 5 times real-time. Although extreme performance measure accuracy (with attendant large number of Monte Carl Iterations) is not needed, 3 to 5 Monte Carlo runs will be executed for each data point. Additionally, there are a large numbers of candidate metrics providing both technical MOP and operationally relevant MOEs. It is therefore critical that an efficient approach to H2 experimentation be adopted.

Figure A.1.2-1 captures the H2 Experimentation Process. OEP 2.0 and CP 2.0, developed in response to this prioritization, will provide the basis H2 experimentation. The Challenge Problem (Version 2.0) will be reformulated, with the same areas of emphasis, to ensure that researchers have not tuned their controllers to CP challenges and red tactics. In addition, a series of experimentation factors, described below, will be incorporated through variations in the CP models and scripts and red controller capabilities and tactics. Importantly, H2 experimentation for each controller will be tailored to the capabilities of the controller. A pre-screening process will be used to ascertain the capabilities of each controller relative to the experimentation factors. The experimentation will then be executed only to the extent that the controller is capable. Results of H2 experimentation will be combined with H3 results and analyzed for completeness relative to experimentation factors and MICA research objectives. An experimentation report will be produced which highlights each controller's strengths and areas for further research. Theses experimentation results will be used to select the best candidates for H4 Experimentation.

The H2 approach chosen applies Design of Experiments (DOE) methodologies to reduce the number of experiments to manageable level. The requisite experimentation will be executed at Boeing using the MICA OEP to exercise each candidate controller in an automated execution of a limited ensemble of Monte Carlo runs. To the extent feasible parallel experimentation will be executed on multiple processors to hasten the process. The limited duration Monte Carlo approach is warranted because we are interested in gross measures of performance rather than a precise measure. Boeing has worked with the Government and researchers to limit the number of factors to be considered. Because executing even this limited set of factors for each controller will be time (and resource) consuming, a pre-screening process will be used to provide a first order gate to determine completeness of the controller with respect to the MICA challenge problem. Based on the results of this pre-screen, a more limited set of factors, tailored to the specific capabilities of each controller, will be run.

H2 testing will rely upon the capabilities, features, and war-fighting challenges provided by the OEP and Challenge problem. Early in the MICA Program, Boeing analyzed candidate OEP and Challenge Problem (CP) features against the MICA BAA specification of desired controller capabilities. OEP/CP features considered included: Variations in Commander's Guidance and Rule of Engagement, Diversity of UAV, weapon and sensor types, Dynamic CP with multiple TCT excursions, Diurnal and Weather effects, Logistic and Battle Damage Effects and Delays, 3-D Air Vehicle Signature, Integrated Air Defense System (IADS) depth and sophistication, Enforcement of Deconfliction and No-Fly Zones, Extent of white vehicular traffic and white fixed assets, Accurate modeling of Blue Weapon Damage to Red Assets, Terrain, Multilateration of Blue ESM, Blue Cooperative Jamming, Accurate model of sensors and sensor report fusion and Reactive Red Ground Controller. Analysis of the influence of each of these factors on MICA research objectives yielded four areas of extreme importance: 1) Dynamic CP with multiple TCT excursions, 2) 3-D Air Vehicle Signature, 3) Integrated Air Defense System (IADS) depth and sophistication and 4) Accurate model of sensors and sensor report fusion. These four areas have been give maximum emphasis in the OEP/CP development. Seven additional areas score as moderately important: 1) Variations in Commander's Guidance and Rule of Engagement, 2) Diversity of UAV, weapon and sensor types, 3) Logistic and Battle Damage Effects and Delays, 4) Enforcement of Deconfliction and No-Fly Zones, 5) Multilateration of Blue ESM, 6) Blue Cooperative Jamming, and 7) Reactive Red Ground Controller. These capabilities have also been emphasized but less than the first four. Finally four areas show considerably less influence: 1) Diurnal and Weather effects, 2) and 3) Extent of white vehicular traffic and white fixed assets, and 4) Accurate modeling of Blue Weapon Damage to Red Assets. These have been given the least emphasis.

A.2.2.1 Design of Experiments Methodology

Boeing will tailor the classic Design of Experiments (DOE) process to MICA H2 experimentation. DOE provides a methodology designed to reduces the number of experiments required to characterize complex systems and processes. This methodology applies to the selection of high leverage experimentation factors (independent variables), reducing requisite number of test points required for each selected factor and analysis of results to characterize the effects of each factor considered. Appendix A outlines the DOE process that provides the basic design of our H2 Experimentation approach.

A.2.2.2 Experimentation Factors

In conjunction with the Government and other researchers, Boeing has identified a set of candidate factors for consideration in H2 experimentation. These factors represent the set of independent variables that exert the greatest influence on MICA controller performance. They may be separated into five general categories: 1) Variations in the balance of power between red and blue, 2) Variations in the quality of intelligence prior to initiation of hostilities, 3) Variations in Command and Control including Commander's Guidance and Rules of Engagement (ROE), 4) Weather and 5) Variations in rate of system and sub-system failures. Within each of these categories, multiple candidate factors were evaluated.

When operational, MICA controllers will need to operate in future battle spaces ranging from Major Regional Conflicts against state-of-the-art defenses through third-world interventions with less sophisticated defensive systems. In all situations they will be required to control a heterogeneous array of unmanned vehicles that have varying capabilities including their ability to penetrate enemy air defenses. It is important, therefore, that the controllers be able to adjust to these situations that can be characterized as variations in the balance of power between blue and red. For this reason, MICA H2 experimentation will include a set of factors that adjust this balance. Balance of power factors considered for H2 experimentation include: 1) Level of Blue UAV signatures, 2) Red SAM capabilities (Search Radar, FC Radar, missile), 3) Concentration of assets in the IADS, 4) Shape of the Blue UAV signature envelope, 5) Blue jamming capability, 6) Availability and capability of blue weapons, 7) Availability of decoys, 8) Extent armor and SSM activity in heavily defended areas, 9) Red air defense and ground control tactics and aggressiveness, and 10) Capability of red air defenses to detect decoys. After extensive discussion it was decided that varying the level (not shape) of the blue UAV signatures was the most effective way of representing variations in UAV penetration capability and SAM defensive capability. This means that item 1) will be included and items 2), and 4) will not. Regarding item 3), the IADS composition for the experimentation will be made more robust than that used to date. Item 5) (Blue jamming capability) will be included as a factor. Item 6) and 7) will be included to the extent that researchers will be given a fixed (limited) set of weapons and decoys for use throughout the experimentation Challenge Problem scenario. These will be chosen to allow sufficient response to the planned variations in Commander's Guidance and ROE. Similarly, the experimentation Challenge Problem will incorporate items 8) and 9) and will include a Red Cell capability in which human-in-the-loop control can be exercised on red air defense and ground assets. Item 10) was deemed of interest and will be included in the experiments as a factor, which varies the red capability to discern decoys.

Suggested Factors

Factor	Expected Benefit	Variations	Primary Applicable MICA Technology
•Estimate of overall Red strength & Tactics	•Controller Robustness in presence of Intel shortfalls	•Accurate Estimate, 50% over and 50% under estimate	•Uncertainty Management
• Time Varying Guidance and ROE	•Determine responsiveness of controllers as the goals and constraints evolve	•None (SEAD, TCT, etc) • Random time for change in ROE and CG	•Team Composition •Team Dynamics •Cooperative Path Planning
•Vary time available to achieve Commander's Objective	•Inject different tactics as required by Commander's Guidance	•Nominal • 12 hours to eliminate C2 Facilities	•Team Composition •Team Dynamics •Cooperative Path Planning
•UAV Signature (Variation Known)	•Examine controller robustness in MRC vs 3rd World Scenario	•10 db above Nominal •Nominal	•Team Dynamics •Cooperative Path Planning
•Jammer Effectiveness	•Controller Robustness	•Side lobe at 30 db below main lobe •Side lobe at 20 db below main lobe	•Team Dynamics •Cooperative Path Planning
•Vary ability of IADS to discern decoys	•Controller Robustness in presence on realistic battlefield limitations	•Nominal •Only 50% of decoys discerned	•Team Composition •Team Dynamics •Cooperative Path Planning
•Random Vehicle Failures	•Controller Robustness in presence of realistic tactical environment	•No failures •MTBF of 10 hours	•Team Composition •Uncertainty Management

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Figure A.1.2.2-1 – Recommended ExperimentationFactors

In order to accommodate operational realities MICA controllers must be able to adjust to varying levels of intelligence ranging from almost complete knowledge of enemy capabilities and deployment down to relatively little known. Factors, relating to intelligence, consider for inclusion are: 1) Percentage of red assets know a priori, 2) Accuracy to which red assets are known, 3) Percentage correct ID of known red assets, 4) Accuracy of overall strength of red forces, and 5) Accuracy of prediction of red tactics and intent. It was decided that the first three items would be varied in tandem and the latter two would be constant for H2 experimentation.
Operationally MICA controllers will be required to offer closed loop control of assets in response to guidance provided by Command and Control elements. Factors considered for inclusion in this area were: 1) Separate static cases which emphasize SEAD or TCT suppression (assume manned aircraft and cruise missiles responsible for SEAD and UAVs perform suicide missions against TCTs), 2) Time variant Guidance and ROE, 3) Inject real-time intelligence divulging impending SSM attack, and 4) Vary time available to achieve objective (example 5 days to eliminate C2 Facilities vice 6 hours). It was decided that H2 experimentation would include time varying Commander's Guidance and ROE that emphasizes different warfare areas. In addition, item 3) will be incorporated into the scenario. Item 4 will also be treated as a factor with two levels evaluated in the experimentation.
Since MICA controllers must operate in any weather for which the vehicles are capable, weather was considered as a factor. It was decided that controller ability to function in inclement weather will be verified but weather will not be included as a factor in the H2 experimentation.

The ability of controllers to react to and compensate for vehicle failures is considered critical. Vehicle failure rate will be included as an H2 experimentation factor. Figure A.1.2.2-1 above lists those factors chosen for inclusion in H2 experimentation along with the variations planned.

A.2.2.3 Pre-Screening Criteria

The following questions will be used to pre-screen controllers to determine the extent of experimentation to be performed.

Team Composition – Discuss degree to which controller does the following:

Responds to static Commander's Guidance and ROE

- What is the mechanism of linking CG and ROE to controller performance and tactics?

Responds to dynamic XML representation of Commander's Guidance and ROE.

Composes team from multiple heterogeneous UAV and sensor variants

- What criteria and logic are used to select team members and assign roles?

Employs full spectrum of weapons modeled

- What criteria and logic are used to select weapons against targets

- How is collateral damage considered, is there a cost mechanism?

Coordinates multi-team composition and activities

- Are teams autonomous or do they collaborate?

Te**am Dynamics & Cooperative Path Planning** – Discuss degree to which the controller does the following:

Incorporates dynamic information into real-time plan development

Develops survivable penetrating and / or threat avoidance routes in three dimensions against fixed and mobile threats

- What cost function or other criteria are used

Discovers threat laydowns that are imprecisely located and accurately fixes

- How are paths planned to ensure proper geometry to geolocate emitting platforms

Employs jamming and other countermeasures including decoys

- How are routes planned to ensure proper positioning and timing of jamming support
- What cooperative multi-platform jamming techniques used

Employs multiple sensors and platforms to find, fix, and identify objects of interest

- How are assets synchronized to provide multiple looks from different geometries
- How is logic linked to meet ROE requirements for identification

Responds to real-time intelligence divulging an impending TCT attack against blue or other high priority tasking or re-tasking

Varies tactics based on balance of power between red and blue and urgency in achieving tactical objectives conveyed in Commander's Guidance

Uncertainty Management - Discuss degree to which the controller does the following:

Behaves with varying levels of IPB extent and quality

- How is the IPB discovered?
- Are unique tactics to stimulate defenses employed?
- How is this reflected in team composition and tactics

Responds to vehicle failures including communications outages and battle damage

- How are failures discovered
- How are failures reflected in team composition and tactics

Adapt to different weather, predicted and unpredicted

Variable Initiative

Are there situations where an operator is required for basic execution of the controller --- is autonomous operation infeasible

What information does the controller provide the system operator?

What decisions and actions does the controller require from the operator?

- How do these change with ROE and CG updates?
- Is the amount of automation adjustable by the operator?

How does the HCI monitor battle progress?

- Is there an indication on the degree to which objectives are being achieved?
- Is the HCI extensible to support larger and smaller teams?

What is the skill set required for the operator?

How does the MICA HCI complement / conflict with the vehicle controller

Does the design envision a separate controller function or does the HCI incorporate vehicle control functions?

Does the controller provide all information required by your HMI? If not list information that will be required from the OEP.

Assumptions

List any assumptions, regarding platforms, sensors, weapons and red capabilities used in the development of your controller.

A.2.2.4 Measures of Performance

For MICA experimentation metrics will focus on operational values that show how MICA technology improves war fighting and can be related to specific technical objectives and over-arching technical performance measures. Examples include: 1) Number of vehicles per operator, 2) Mission / tasks complete, 3) Targets detected, identified, and damaged / destroyed, 4) Blue platforms damaged / destroyed, 5) ROE violations, collateral damage.

Primary metrics for each experiment and each iteration will be **Operational Utility** in terms of Total System of System score (includes value of targets destroyed, ROE violations, and damage sustained), 2) **System Performance** in terms of Targets destroyed of each type, Blue platform losses, ROE violations (No-hit" targets hit, etc), Number and type of red attacks against blue assets, Collateral damage, and 3) **Plan Efficiency** which includes consideration of Time and number of sorties to achieve objectives from commanders guidance (N %, 100 %), and Blue platform weapons used by type, 4) **How well is the battlefield "discovered" by the controllers** which considers Targets (fixed and mobile) detected, identified, attacked, BDA, Targets not detected / misidentified / not BDA'd, Time to detect, id, attack, and BDA, TCT's detected, identified, and attacked, Time to detect, id, attack, and BDA, Time attack to BDA, How comprehensive are the plans , % of target set covered, Span and efficiency of controllers, Number of platforms controlled per controller, and Amount of "real-time" used by controller.

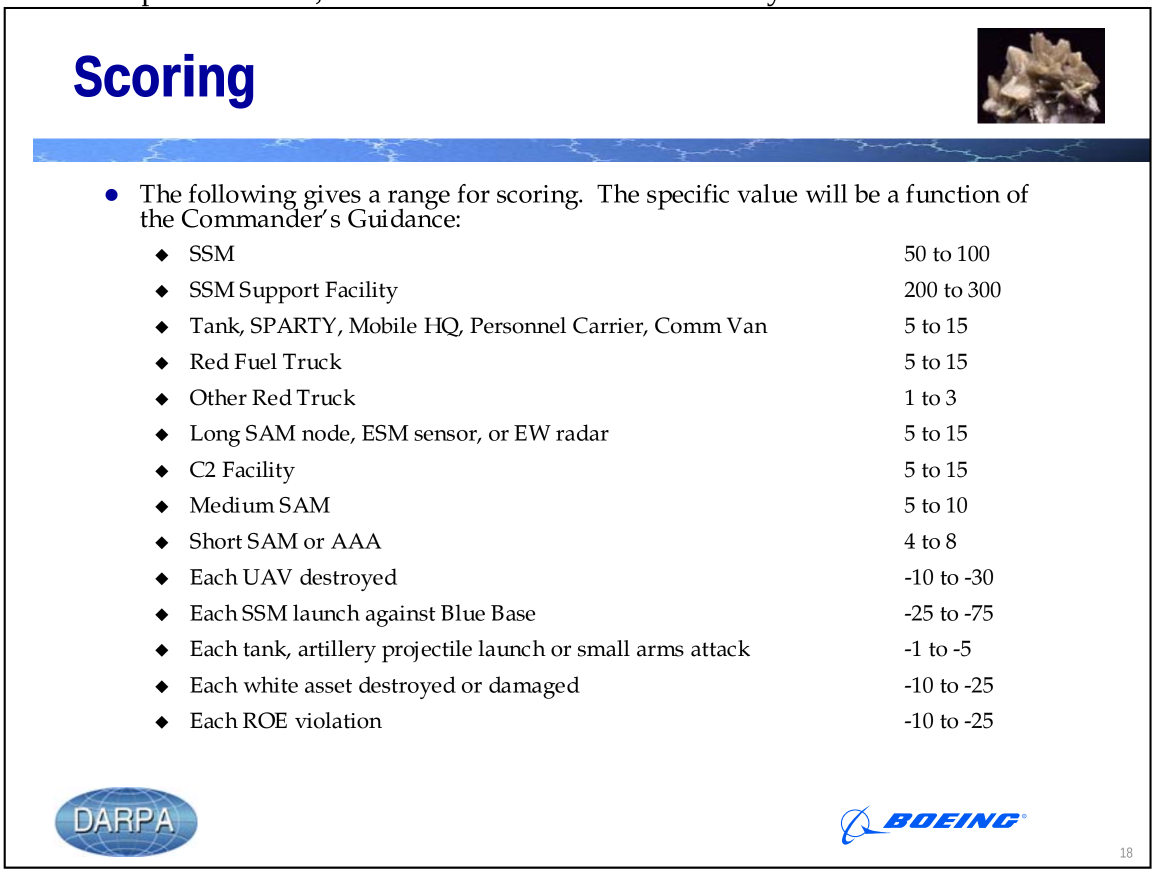


Figure A.1.2.4-1 – Range of Scoring Values

Scores will be associated with each metric and a composite score will be generated for each controller. The composite score will also be broken down into subsets such as platforms of each type detected, identified, damaged and destroyed, ROE violations, enemy attacks on blue forces, etc. Scoring will be adjusted to reflect changes in guidance and Roe. An example score for red platforms destroyed might be 100 points for SSM, 5 for a tank that is not threatening blue assets but 15 for a tank within attack range of blue. Points may be subtracted for violating ROE or inflicting collateral damage. Figure A.1.2.4-1 shows currently planned scoring values. The range of values reflects variations in Commander's Guidance.

A.2.3 Hypothesis H3

H3 addresses human involvement in the battlespace management and control process. Status and recommendations provided by decision support systems must be of interest to and naturally understandable by a human, who must also be able to provide guidance to automata in a natural form. Most importantly, a major goal of MICA research is to extend the operator span of control to 5 vehicles per operator by 2003 and 30 vehicles by 2005. Since initial H3 experimentation will occur in 2003, we will focus on a span of control of 5 vehicles.

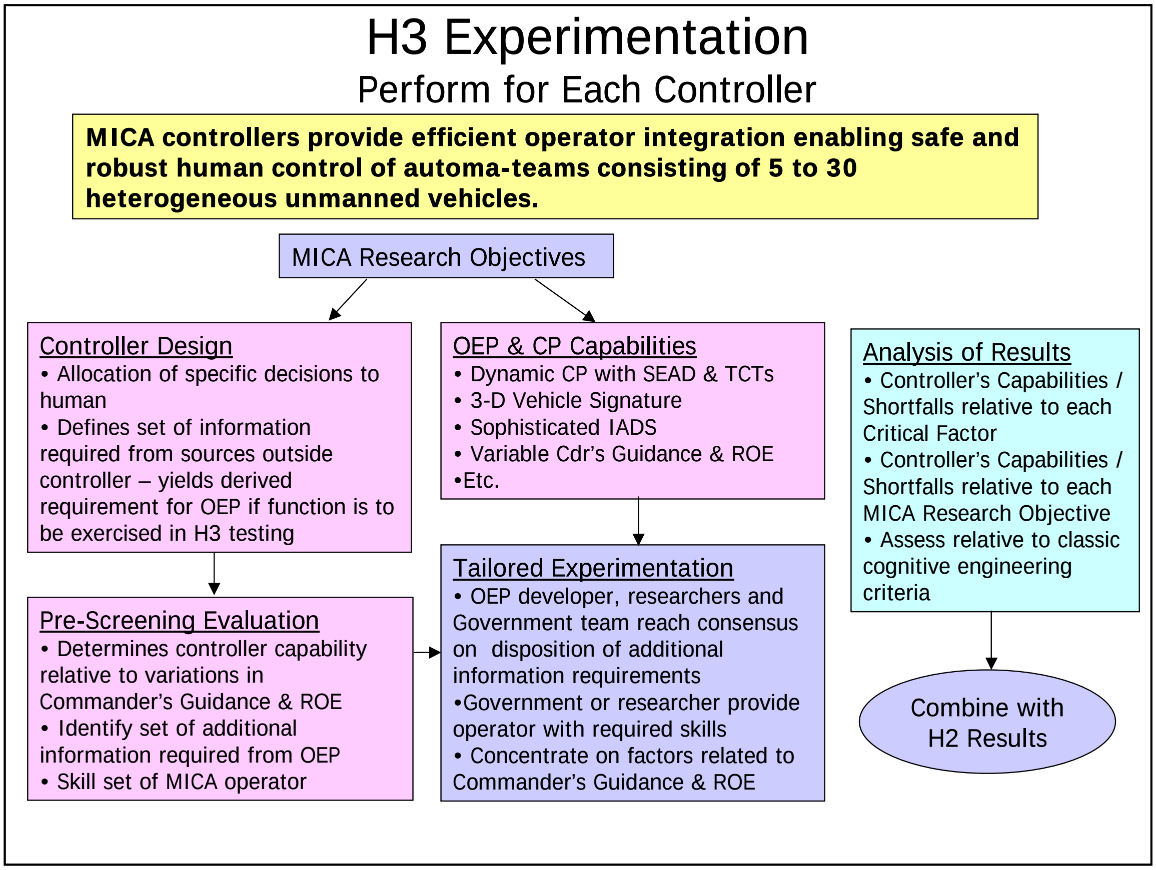


Figure A.1.3-1 – H3 Experimentation

H3 experimentation will be performed in a limited set of experiments. Figure A.1.3-1 depicts the process for H3 experimentation that will be executed for each candidate MICA controller. For all H3 experimentation, the controllers provide all requisite inputs to the operator; that is there is no direct interface from the OEP to the controller HCI. However, the HCI design may assume that in a warfighting situation, Essential Elements of Information will be received by the controller HCI from operational Intelligence systems and or platform sensors. As part of the pre-screening process, researchers will identify any Elements of Information required from the OEP to satisfy requirements of their HCI. Boeing, in conjunction with the Government team, will determine the extent to which these needs can be accommodated. Because the focus of H3 experimentation deals with the quality of the human interaction, there is no need to conduct a series of Monte Carlo iterations. By its nature H3 experimentation must be performed in real-time. We will concentrate on the subset of H2 experimentation in which variations in

Commander's Guidance and ROE is emphasized. In the H3 testing, one team of 5 air vehicles will be selected for operator control. All other teams will operate in the automatic control mode used to execute H2 testing. A single one-day scenario will be executed with operators transitioning as required. In addition to the system level metrics and scoring used for H2 experimentation, additional cognitive engineering measures such as number of false negatives, number of false positives, and time delay in generating operator decisions will be collected. The specific set of cognitive engineering measures, for each controller, will be generated in collaboration with the appropriate researchers and the MICA Variable Initiative Engineering Team.

A.2.4 Hypothesis H4

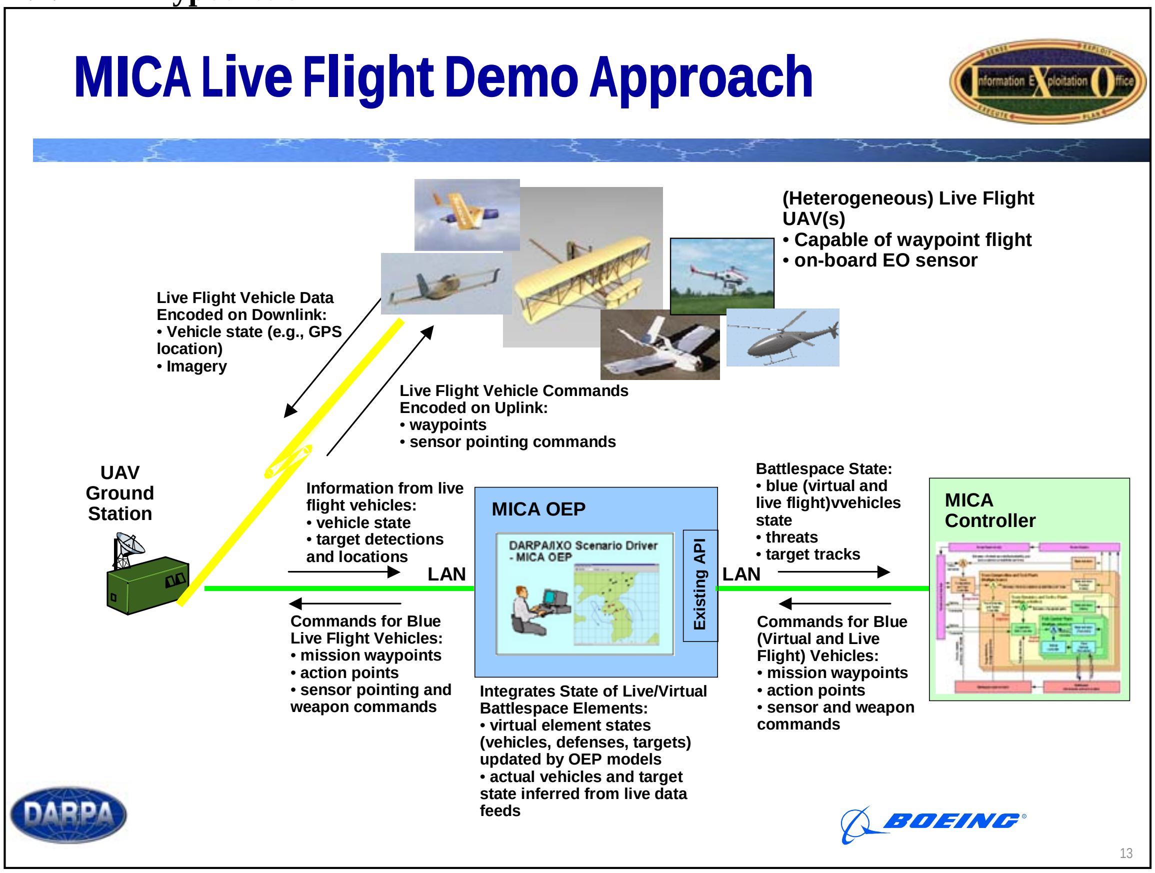


Figure A.1.4-1 - H4 Experimentation

H4 experimentation is designed to validate the transition potential of MICA research. No amount of simulation, regardless of the fidelity, can totally convince end users of MICA controller capability. Furthermore, hardware experimentation is the essential first step in productizing MICA research. It initiates the process of integrating MICA controllers to hardware platform using off-the-shelf Mission Control Stations as the interface. Only through hardware experimentation can questions be completely resolved regarding the interrelationship between real world effects and MICA controller performance. These real world effects include: 1) Inexactness in vehicle trajectory control due to real world navigation inaccuracies, wind and gusts enroute; 2) Effects of terrain, landscape, vegetation and cultural features, 3) Discriminating real world fixed and moving white objects from candidate targets (it is impossible to simulate the preponderance of white objects); 4) Representative vehicle system and sub-system failures, 5) Realistic communications delays, bottlenecks and obstructions and 6) Realism in converting MICA controller outputs into executable vehicle commands.

Executing meaningful H4 experimentation requires that mixes of heterogeneous hardware platforms be controlled using MICA algorithms in a synthetic battlespace. H4 experimentation will be performed in a series of experiments of increasing complexity and fidelity. As the experimentation progresses, the number and varieties of included hardware platforms will increase, the time duration of the experiments will increase, the complexity of the scenario and of the tasking assigned to hardware platforms will increase and MICA operators (variable initiative) will be included for some experiments. The specific platforms, scenarios and experiments will be identified as the experimentation progresses. However, regardless of these experimentation factors, the basic approach will remain constant and is shown in Figure A.1.4-1.

Key elements of the H4 experimentation approach are: 1) the OEP simulates the entire battlespace other than the dynamics of the hardware platforms, 2) The OEP integrates hardware platform state into the synthetic battlespace and generates appropriate synthetic sensor measurements on the hardware platform (egg synthetic SAM radar tracking hardware platform), 3) Controllers determine all air vehicle activities (synthetic and real) and communicate vehicle commands to the OEP through the same API used for H2 and H3 experimentation, 4) OEP controls synthetic platforms IAW controller commands, 5) The OEP interfaces to specific hardware platform Mission Control Stations to command vehicle activities and receive sensor outputs, 6) For variable initiative testing controllers will provide all information for their operator interface including display of hardware platform sensor outputs, and 7) As required operators will interface with Mission Control Platforms to extract information from sensor outputs. The following table addresses how each OEP function will be modeled for hardware platforms.

Function	**Approach for Hardware Platform Experimentation**
Synthetic Battlespace	Flight range for hardware platforms will be embedded as area within Challenge Problem gaming area. Objects of interest within range (buildings, vehicles, SAMs, etc.) will be represented in synthetic space. Additional objects that are included in the Challenge Problem but not available, as physical entities within the range will also be modeled in the simulated space. Range terrain data will be seamlessly integrated into the synthetic model. Hardware platforms will be modeled at their true (reported GPS) positions.
Blue engagement by Red SAM	OEP uses true position, velocity and attitude of hardware platform in conjunction with simulated 3-D signature, SAM location, and SAM capabilities. SAM tactics will be controlled by Red Cell using automated IADS. Human Red command may be included.

Function	Approach for Hardware Platform Experimentation
Multilateration	Since OEP models effects but does not solve TDOA equations OEP will perform multilateration for groups containing hardware platforms based on their true position using simulated ESM reports and the current multilateration model.
Imaging Sensor	For hardware platforms with simulated imaging sensors, OEP will use its current models applied about the true platform position and pointing commands. For hardware platforms with imaging capability operating against physical entities within the range, a human at the MCS will generate appropriate imaging reports for use by OEP and controllers. The received image will also be available for Variable Initiative experimentation, if desired. For hardware platforms with imaging capability operating against simulated entities within the range, current OEP models will be applied about the true platform position and pointing commands.
Multi-Mode Radar	It is not envisioned that any of the hardware platforms will have an active radar sensor. OEP will use its current models applied about the true platform position and pointing commands for all simulated and real items within the simulated field of view.
Blue Ordnance Delivery	All blue ordnance delivery by hardware platforms will be simulated using current models with true position as the launch point and aim point delivered from the controller to the hardware platform.
Jamming	Jamming by hardware platforms will be simulated in response to controller commands using their true position and current OEP models. Effects of third party (hardware or simulated platform) jammers, intended to support hardware platforms, will be modeled in their simulated engagement by Red SAMs.
Collisions	Collisions between hardware platforms and simulated platforms will be modeled to the extent supported by OEP.
Fratricide	Fratricide by hardware platforms against simulated platforms and by simulated platforms against hardware platforms will be modeled to the extent supported by OEP.
Communications	It is not expected that the hardware platforms will have communications capabilities equivalent to those expected in a war-fighting environment. Therefore the OEP will model higher fidelity, higher bandwidth tactical communications for hardware platforms. Obviously, physical communications media will be used for the actual uplink and downlink.

B Appendix B – Design of Experiments Methodology

MICA DOE Process Flow

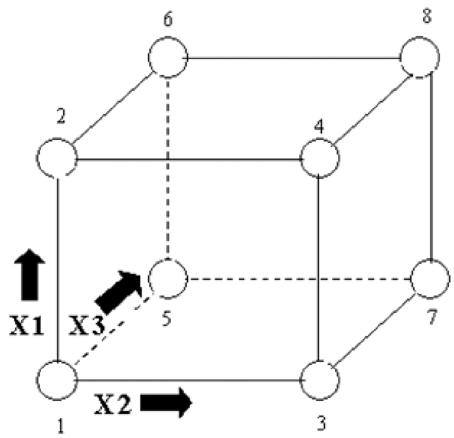
1. **Objective definition**
    a. Evaluation: Stated in MICA Hypotheses
    b. Comparative designs
        i. Choose between alternatives, with narrow scope, suitable for an initial comparison
        ii. Choose between alternatives, with broad scope, suitable for a confirmatory comparison
        iii. If you have one or several factors under investigation, but the primary goal of your experiment is to make a conclusion about one a-priori important factor
    c. Screening designs to identify which factors/effects are important
        i. When you have 2 - 4 factors and can perform a full factorial
        ii. When you have more than 3 factors and want to begin with as small a design as possible
        iii. When you have some qualitative factors, or you have some quantitative factors that are known to have a non-monotonic effect.
    d. Response Surface modeling to achieve one or more of the following
        i. Hit a target objective
        ii. Maximize or minimize a response
        iii. Reduce variation by locating a region where the process is easier to manage.
        iv. Robustness
    e. Regression modeling
        i. To estimate a precise model, quantifying the dependence of response variable(s) on process inputs.
2. **Selecting Process variables**
    a. Process variables include both *inputs* and *outputs* - i.e., *factors* and *responses*.
    b. Include all important factors (based on MICA experts)
    c. Check the factor settings for impractical or impossible combinations.
    d. Include all relevant responses.
    e. Avoid using only responses that combine two or more measurements of the process.
3. **Selecting design approach**
    a. Pre-screen process utilizes fractional factorial design matrices
        i. Mixed level Fractional design matrices support MICA hypotheses which maximum observable information through a minimum number of runs.

1. 2^(k-p)
2. Plackett-Burman

ii. Calculate factor effects and identify insignificant factors and factor interactions

iii. Refine design matrix (full/fractional orthogonal design matrix)

iv. Perform Fold-Over if necessary.



	X1	*X2*	*X3*
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1

Figure B-1 – Two-Level, Three-Factor Diagram

b. Full factorial design to evaluate main effects
   i. Two/Three level designs requiring 2,3^factors experiments
   ii. Replication: For each corner of the box (run), calculate the average response and observe dispersion.
   iii. Determine if variance is homogeneous (uniform) across the factor space.
   iv. Two level, three factor diagram shown in Figure B-1.

4. Data Analysis

Figure B-2 shows the flow of the data analysis process

a. Analysis Steps
   i. Graphical construction
      1. Histogram: Graphically summarize the distribution of a univariate data set.
      2. Box: Conveying location and variation information in data sets, particularly for detecting and illustrating location and variation changes between different groups of data.

3. Dex Scatter: What are the most important factors - What is the best setting for each of these important factors - What data points are outliers.

ii. Create a model from the data

1. $\hat{y} = \bar{y} + (\bar{A}_{high} - \bar{A}_{low}) + (\bar{B}_{high} - \bar{B}_{low}) + ...$

iii. Use results to answer the questions in MICA objectives

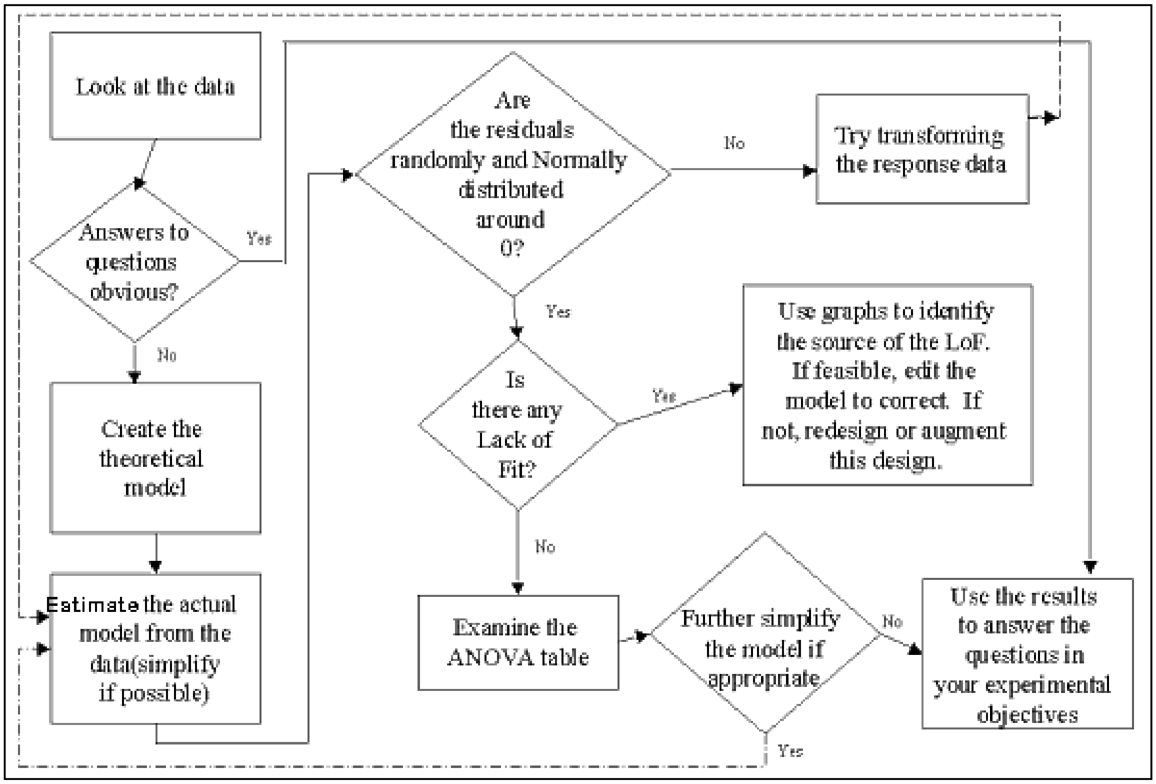


Figure B-2 – DOE Flow