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SYNERGISTIC UNMANNED MANNED INTELLIGENT TEAMING (SUMIT) SIMULATION EVALUATIONS COGNITIVE WORK ANALYSIS (CWA)

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14. ABSTRACT

With the ever-increasing complexity of military operations and adversary abilities, merely possessing advanced autonomous capabilities is not sufficient for battlespace superiority. Human-Autonomy Interfaces (HAIs) must be designed to ensure effective collaboration and coordination between human operators and the autonomous systems available to them. This report details the methods and results of a Cognitive Work Analysis (CWA) that informed the development of an integrated suite of autonomous tools that enables an Air Mission Commander (AMC), teaming with autonomous capabilities, for example, play calling, route planning, and asset allocation, to effectively command and control a team of multiple unmanned and manned aerial systems to complete an air assault mission. This report will highlight the practical applications that the CWA results provided for generating designs for the HAIs. In addition, feedback from Army Aviation Subject Matter Experts (SMEs) during the simulation interview is discussed since these results not only informed system development and design but illuminated critical details to ensure that the most ecologically valid and operationally relevant tasks and events were selected for the program's empirical evaluations.

15. SUBJECT TERMS

Cognitive Work Analysis (CWA), Human-Autonomy Interface (HAI), Human-Autonomy Teaming, Manned-Unmanned Teaming (MUM-T)

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EXECUTIVE SUMMARY

Advanced autonomous systems are being developed to enable a single operator to have the ability to effectively and simultaneously manage, command, and control a team of multiple Manned-Unmanned (MUM) vehicles. Critical to the teaming of human operators with autonomous systems is the Human-Autonomy Interface (HAI), which should be designed to ensure effective collaboration and coordination between the human operator and the autonomous systems available to them.

The first step in our HAI design process was to gain a deeper understanding of the complex work that an Air Mission Commander (AMC) performs during air assault operations. A Cognitive Work Analysis (CWA) was therefore conducted to uncover the behavior-shaping constraints of an AMC, including a set of semi-structured interviews with Army Aviation Subject Matter Experts (SMEs). Results of the CWA will be discussed, as well as examples of how the results informed the design of the HAI, the variables and constraints the suite of autonomous systems reasoned about, and the selection of events, tasks, and details later used for empirical evaluations of the human-autonomy team during simulated air assault mission.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONCLUDED)

LIST OF TABLES

I. INTRODUCTION

New and recently developed autonomous systems, decision-aiding technologies, and Human-Autonomy Interfaces (HAIs) have the potential to assist an Air Mission Commander (AMC) tasked with conducting Manned-Unmanned Teaming (MUM-T) operations from the cockpit of a Vertical Takeoff and Landing (VTOL) aircraft. However, many of these technologies have failed to appreciate the critical role that human-to-autonomy communication and coordination play in successful human-autonomy teaming, instead they focus on optimizing separate human and autonomous components and leaving the design of interfaces and team processes as an afterthought [1]. However, team performance is more than the sum of the abilities of the individuals that compose the team [2, 3], and simply pairing the best human with the best autonomous system will not necessarily result in the best performance.

Effective collaboration is essential to the success of human-autonomy teams, especially in the context of sociotechnical systems where multiple agents, both human and autonomous, must work together to solve complex problems [1]. Reference 4 identified three stages for enabling successful collaboration:

- Understand—develop an accurate representation of the domain and ensure that the autonomous system can reason about relevant domain aspects
- Generate—design interfaces that enable a rich coupling between the human operator and the autonomous systems
- Validate—evaluate the human-autonomy team in a realistic test environment

This report details the methods and results of the initial Cognitive Work Analysis (CWA) designed to inform each stage for the development of Tasking and Execution of Collaborative Unmanned and Manned Systems with Autonomy (TECUMSA), a system designed to achieve the goals of the Synergistic Unmanned Manned Intelligent Teaming (SUMIT) program. Also covered in this report are examples to highlight the practical application of the CWA results, including designs that were generated for TECUMSA's HAI as well as critical aspects of an air assault mission that were integrated into the logic of the autonomous systems, for example, air route optimization parameters. Finally, this research will detail the results of the collaboration with Army Aviation Subject Matter Experts (SMEs) to ensure that the most ecologically valid and operationally relevant tasks and events were selected for the SUMIT program evaluation of the human-autonomy team.

II. UNDERSTANDING ARMY AIR ASSAULTS

In an air assault, mission helicopters transport ground-based military forces and supplies in order to gain a military advantage. Mission objectives include penetration and security of strategic terrain and engagement and neutralization of enemy forces. During an air assault mission, the AMC is the overall mission leader with delegated authority over decision making and providing oversight and directives to up to 16 or more aircraft in a hostile, dynamic, and largely unpredictable environment. While adding Unmanned Aerial Vehicles (UAVs) to the AMC's resources has the potential to benefit mission performance, it could also increase the AMC's already high workload. Thus, autonomous technologies that assist the AMC in managing UAVs, such as Cooperative Control Algorithms (CCAs) that plan optimal routes, Intelligent Agents (IAs) that recommend optimal courses of action, and autonomic frameworks that monitor ongoing events, are critical for MUM-T missions.

IAs are being developed that can recommend a plan to satisfy an operator request, for example, provide overhead surveillance, while taking into account relevant situational variables, such as fuel use and time enroute [5]. Reference 6 illustrated how these IAs reason, as shown in Figure 1, using a scenario in which an operator manages three UAVs (FN-11, FN-12, and FN-13) and two Unmanned Ground Vehicles (UGVs) (TR-21 and TR-22). In this example, all of the unmanned vehicles are equipped with Electro-Optical (EO) sensors, two unmanned vehicles (FN-12 and TR-21) also have an Infrared (IR) sensor, and the UGVs have better sensor resolution than the UAVs. The operator's task in Figure 1 is to image Point Charlie on a cloudy day, thus making IR sensors more capable than EO sensors. In this scenario, the IA reasons about the time it takes each unmanned vehicle to get to Point Charlie as well as their respective capabilities.

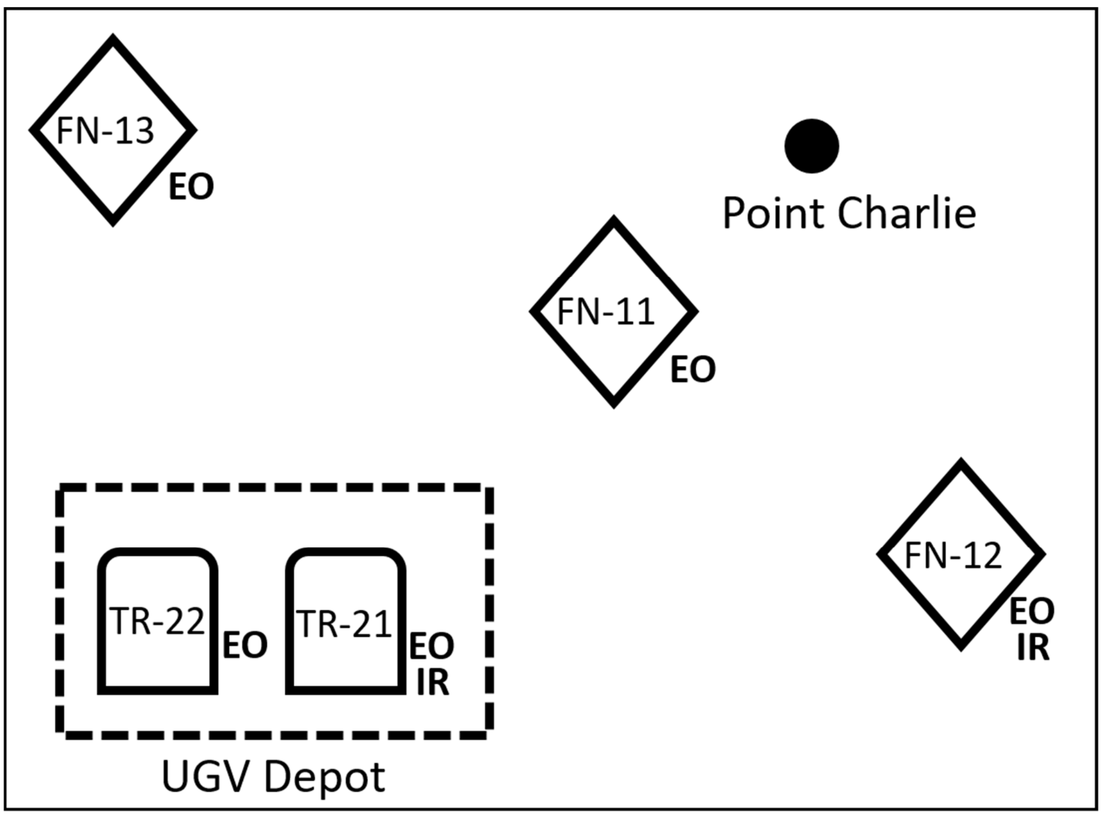


Figure 1. IA Reasoning Example Scenario [6]

The IA's reasoning is based on Pareto efficiency, whereby a plan is eliminated if another plan is better on all relevant dimensions [6]. Figure 2 illustrates the Pareto efficiency of each unmanned vehicle for this task, with Pareto optimal vehicle choices (FN-11, FN-12, and TR-21) on the dashed line. For example, FN-11 can get to Point Charlie the quickest so it is a better choice than FN-13, which has the same sensor capabilities but is farther away. Similarly, TR-21 is more optimal than TR-22 because even though both unmanned vehicles can reach Point

Charlie in the same amount of time, TR-21 has better sensor capabilities, that is, an IR sensor. This leaves three Pareto optimal vehicles for the operator to choose from:

- FN-11—fastest speed and worst capability
- TR-21—slowest speed and best capability
- FN-12—average speed and average capability

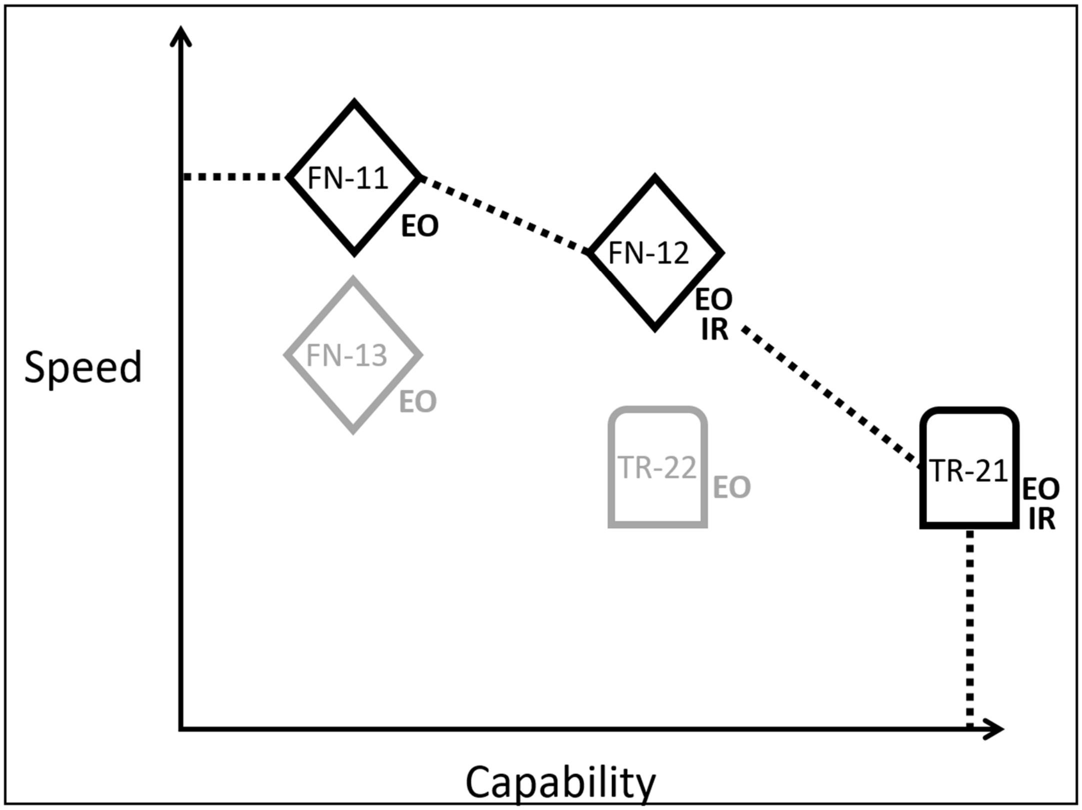


Figure 2. Pareto Optimal Vehicles Located on Dashed Line With Grayed Out, Sub-Pareto Optimal Vehicles [6]

The key to this process lies in the IA's Cognitive Domain Ontology (CDO), which is a representation of domain knowledge used to categorize situations, develop hypothesis, and plan and recommend courses of action [7]. With a CDO that accurately represents the constraints of the mission, which is in this case speed and sensor capability, the IA can rank and compare plans to determine which unmanned vehicle is the best to use. Thus, research to develop an IA that can support an AMC during an air assault mission must begin with an understanding of the work domain.

Researchers and developers can gain this understanding using a CWA, which is a set of methods used to understand how situational dynamics impact performance [8, 9]. For this effort, data were sourced from Army doctrine on procedures, tactics, and regulations, along with extensive interviews using several different methods, as described in Section V.A, with experienced AMCs.

III. GENERATING USER INTERFACES

Although understanding the mission domain is necessary for autonomous systems to improve mission performance, it is not sufficient. Interfaces are needed that not only reflect the constraints and relationships of the complex work environment but also enable a rich coupling between the human operator and the autonomous technologies in order to bridge [10] gulf of evaluation and gulf of execution. The size of the gulf of evaluation depends on how well the human-autonomy team can observe, perceive, and understand the state of the world in terms of their intentions, for example, to see the best move on the chess board, while the size of the gulf of execution depends on the effectiveness of the actions or controllability the human-autonomy team has to achieve its goals [6]. However, if there is a poor coupling between the humans and autonomous technologies, for example, incompatible intentions, insufficient understanding of competency boundaries, then another gulf, known as coordination gulf, is introduced that creates additional uncertainties for each component, as shown in Figure 3.

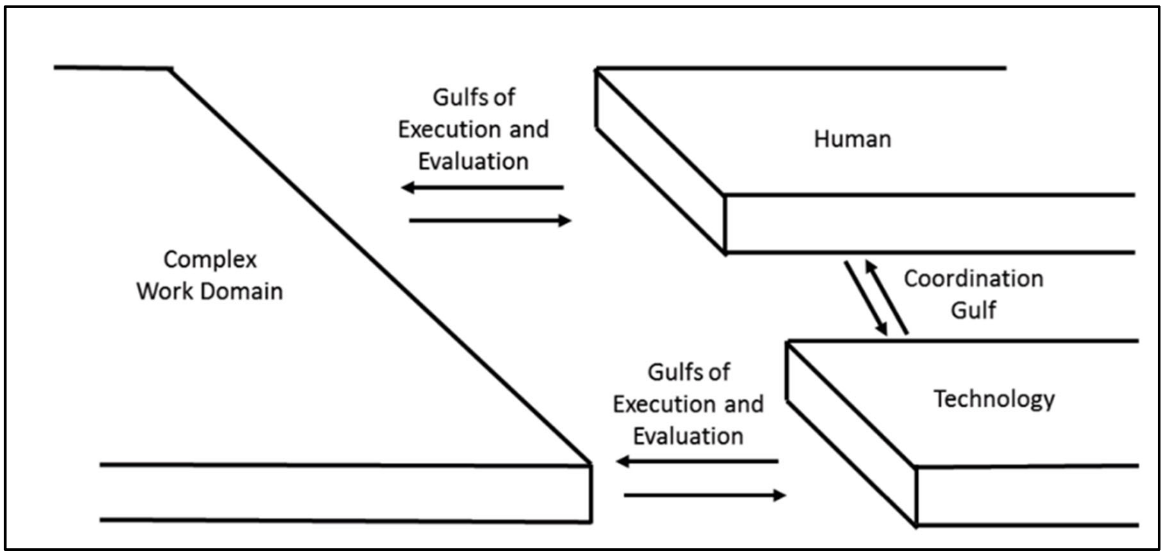


Figure 3. Gulfs of Evaluation, Execution, and Coordination [1]

In essence, a HAI must make the constraints of the work domain salient to the human-autonomy team in a manner that is consistent with the human operator's reasoning capabilities [11]. In Reference 12, Skill-Rule-Knowledge (SRK) framework has been proposed as a method for understanding alternative ways to represent constraints, signals, signs, and symbols, which in turn distinguish three levels of human performance, including skill-, rule-, and knowledge-based [1].

In the context of unmanned vehicle operations, an example of skill-based behavior is an unmanned vehicle operator manually controlling a sensor to keep a moving target in view. The location of the target in time and space provides the operator with the signal, and the goal is to continuously adjust the sensor any time the target deviates from the center of the screen.

In rule-based behavior, an operator has a set of predetermined solutions that are triggered by specific conditions, that is, signs. Figure 4 illustrates rule-based behavior for determining the best search pattern to use in the presence of a specific combination of signs for an unmanned vehicle operator to find a target. For example, if an operator is searching in a nonmountainous region for a target that is likely to still be near the last known location but the target's direction of travel is unknown, a sector search is the best option. These rule-based solutions often help an operator quickly identify a good enough solution [13].

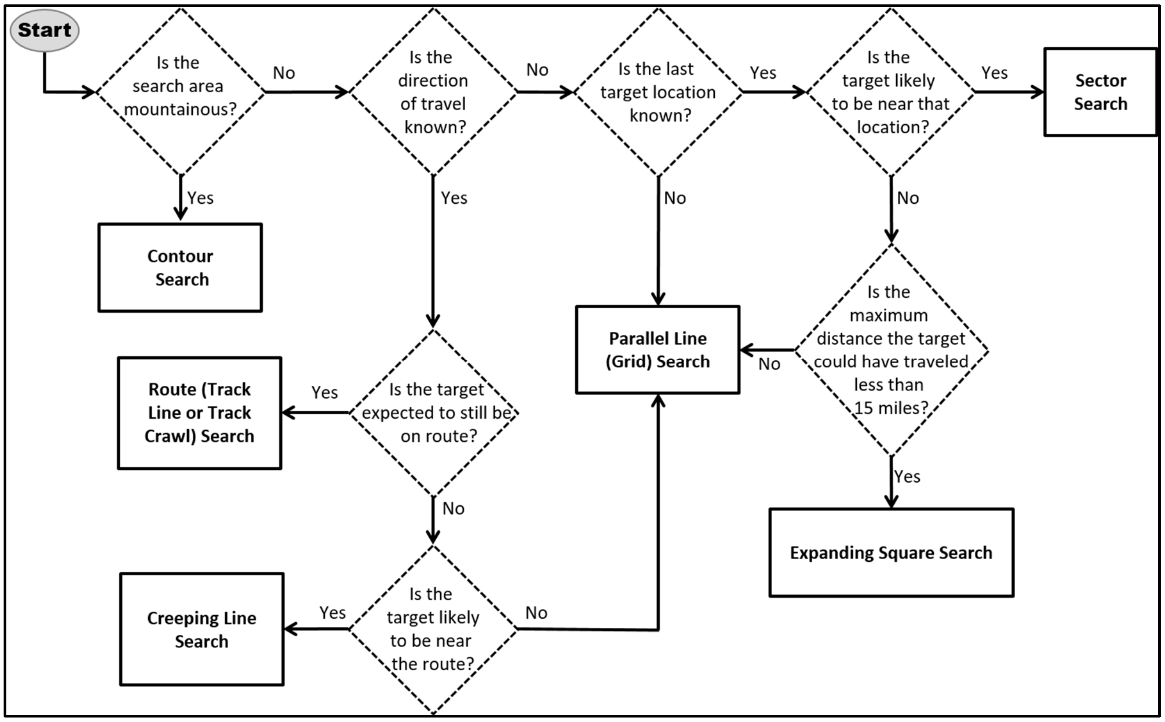


Figure 4. Optimal Search Pattern Decision Tree [13]

Knowledge-based behaviors occur when an operator encounters a novel unexpected situation for which no procedure exists [12]. In these instances, an operator may evaluate and critique skill- and rule-based tactics in order to learn from mistakes, take advantage of opportunities, and avoid threats that arise due to changing situation contingencies. For example, an operator may modify a rule-based strategy to find a target based on their knowledge of insurgent activity in the area or the limitations of the only unmanned vehicle that they have available [13].

Reference 14 developed an HAI that was designed to support rule- and knowledge-based behaviors for operators tasked with managing multiple unmanned vehicles in support of base defense missions. To support rule-based behaviors, interfaces were developed that allowed operators to quickly call high-level plays, which are adaptable plans of action using one or more unmanned vehicle, in response to different mission events. For example, in response to a report of an unidentified watercraft at Point Alpha, an operator can quickly call an Air Inspect play. In response, the IA recommends an unmanned vehicle that can get eyes on the unidentified watercraft in the least amount of time, plans a route for that unmanned vehicle, and monitors the unmanned vehicle's progress as it travels to Point Alpha.

By default, the IA will recommend an unmanned vehicle that can reach the desired location in the least amount of time. However, the Play Workbook window allows the operator to provide the IA with information that will help it develop a better plan and change priority variables quickly to see how it impacts the IA's recommendations. For example, the operator can select the size of the target that they are searching for, which impacts the altitude a UAV would search at and/or the zoom level of the sensor. Additionally, environmental conditions that impact the effectiveness of unmanned vehicles, for example, if it is cloudy, an IR sensor might be better than an EO sensor. Since the Play Workbook provides parameters to optimize the plan, the operator can communicate to the IA what needs to be optimized, such as time to objective, fuel use, detectability, presence, crowd control, and/or tracking. With this interface, the operator can quickly tell the autonomy to find the target while keeping a low profile, optimize on time, and consider that it is cloudy.

The HAI also supports knowledge-based behavior by allowing the operator to explore the search space. For example, the Plan Comparison tool allows an operator to quickly determine the best plan based on a specific parameter as well as quickly view the overall quality of each plan based on weightings assigned to each parameter. For example, Plan 1 will consume the least amount of fuel, Plan 2 contains the best assets for deterring possible insurgent activity, and Plan 3 has the best crowd control and tracking capabilities.

In order to successfully bridge the gulfs of execution and evaluation, the user interface must support all three modes of interaction—skill-, rule-, and knowledge-based. Within the aforementioned HAI, extended play-based control was implemented to support a variety of human-autonomy teaming requirements [15]:

- Capturing the operator's intent
- Enabling plays that define the actions of one or more unmanned vehicles to be called or edited
- Allocating unmanned vehicles to tasks
- Routing unmanned vehicles
- Providing visibility into the autonomy's reasoning
- Monitoring play progress [15]

This HAI illustrates the importance of an interface design that supports skill-, rule-, and knowledge-based behaviors so that the human-autonomy team is able to perform not only in familiar events, but able to cope and adapt to unfamiliar and unanticipated events as well.

IV. VALIDATING HUMAN-AUTONOMY TEAMING

The goal of this research is to design HAIs that enable effective collaboration between human operators and autonomous tools to support AMC performance during air assault missions. To achieve this goal, any evaluation must support multiple performance measures in an experimental setting that, to the extent possible, captures and represents the constraints of the natural work domain. Reference 16 calls this type of experimental setting a synthetic task environment. The key is not the physical fidelity of the simulator but how well the research question maps to the properties of the real-world mission environment.

The Future Open Rotorcraft Cockpit Environment (FORCE) simulator, which is a Government-owned and operated simulation environment, contains all the features necessary for a synthetic task environment. An initial set of vignettes was developed by the United States (U.S.) Army Combat Capabilities Development Command (DEVCOM) Aviation & Missile Center (AvMC) Aviation Development Directorate (ADD) to evaluate the impact of TECUMSA on MUM-T missions. A simulation interview technique was used to identify the critical features of each vignette as well as map TECUMSA capabilities to each vignette's mission events.

V. METHODS, ASSUMPTIONS, AND PROCEDURES

A. Methods

Section V.A describes the various Cognitive Task Analysis (CTA) methods implemented during the semi-structured interviews for eliciting knowledge in regard to the general air assault work domain as well as specific AMC tasks.

1. Daily Walkthrough Method

In this portion of the interview, participants were asked to provide an initial, high-level description of their daily job duties as an AMC. The purpose of this segment was to put the participants into a reflective frame of mind and identify potential lines of questioning as the interview continued. The daily walkthroughs provided information about the general sequence of events that occurs upon receiving the operations order and the various considerations that go into air assault mission planning.

2. Task Diagram Method

The goal of the Task Diagram method is to elicit how a particular job is actually performed, not how doctrine prescribes it to be done [17]. In this case, the Task Diagram method was used to elicit the major components of the AMC's job during air assault missions. The interviewers placed a large piece of paper in front of the participants and asked if they could explain the 3-6 major aspects of their jobs as AMC. They were told to draw 3 to 6 circles, and each one would represent a major component of their job. Each component would be labeled, and bullets would be generated in each circle to describe that aspect of the job. Arrows would indicate if the major components were dependent on each other or occur in chronological order.

3. Wagon Wheel Method

The Wagon Wheel method [18] was used to understand the communication channels that exist between an AMC and their surrounding team during an air assault mission. For this exercise, participants were presented with the diagram in Figure 5 and asked to identify each individual the AMC communicates with during mission execution, including the direction of communication flow, which is indicated by the arrows; the information communicated; and the method by which the communication occurs, for example, radio, chat, and so forth. Communication channels that exist for an AMC can vary depending on mission type and available mission support; therefore, participants were initially told to consider including the communication channels that were generally present across a variety of missions and circumstances.

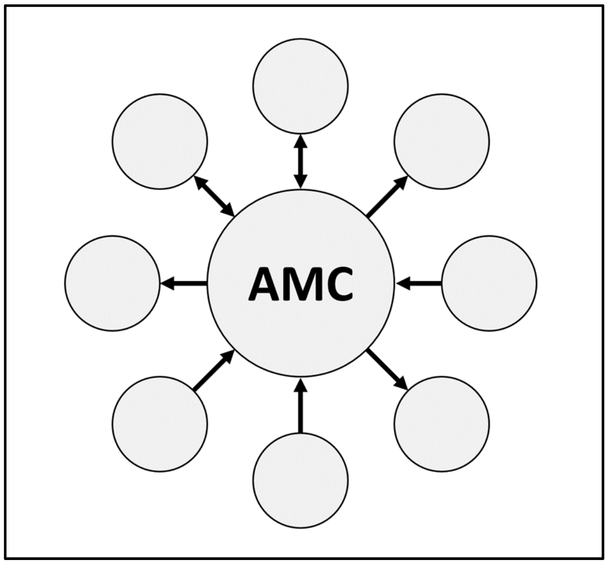


Figure 5. Wagon Wheel Template [18]

For each communication node the participant were asked the following questions [18]:

- What type of information is passed?
- From where did you receive the information you are transmitting?
- From where did they receive the information that was transmitted to you?
- Did you modify the information in any way? Was the information passed in its original form or was it altered, filtered, prioritized, and so forth in any way?
- What decisions does this information affect?
- Could this information be passed in another format, for example, digitally instead of voice?
- How do you know they received the information?
- How do you know when to provide them with this information?
- Would you consider this piece of information to be critical to the team's success?
- What's the impact to the team if this communication line is broken?

4. TECUMSA Demonstration Method

For this portion of the interview, participants were given a brief demonstration of the TECUMSA HAI, including the play calling interfaces, plan comparison tool, and vehicle dashboard as well as TECUMSA's autonomous capabilities, including the route planner and IA. Participants were then asked to provide feedback on what they liked, disliked, and found confusing about the HAI as well as what modifications needed to be made to adapt the HAI for air assault missions.

5. Simulation Interview Method

A simulation interview was used to derive the contextualized judgements and decision making processes that experienced AMCs make across a variety of mission configurations and environmental circumstances [19]. For this effort, the simulation interview focused on how each participant would use their ownship and UAVs to accomplish different vignette tasks, for example, reconnaissance, surveillance, overwatch, and so forth. Using a paper and pencil method, SMEs were provided with a map of a battlespace with various terrain characteristics, including mountain ridges, Restricted Operating Zones (ROZs), known enemy locations, dense population areas, Named Areas of Interest (NAIs), a Landing Zone (LZ), and an objective location. Participants were encouraged to brainstorm events, tasks, constraints, and obstacles to include in future scenarios and asked to provide feedback on the fidelity of the vignettes as well as explanations for the courses of action that they considered and the respective optimality for mission success, crew survival, and so forth. Finally, participants were asked to map existing TECUMSA plays to the vignette mission events as well as determine the number of new plays that needed to be developed.

B. Participants

Three veteran Army helicopter pilots with a combination of over 55 years of experience in Army Aviation and extensive combat service as AMCs, as shown in Table 1, were interviewed. All three participants were male with an average age of 46.5 years. Combat deployments included Iraq, Afghanistan, Pakistan, South Korea, and Kosovo.

Table 1. Total Participant Experience

Aircraft	Noncombat Hours	Combat Hours
CH-47D/F Chinook	3500	3000
UH-60A/L (Sikorsky S-70)	1420	700
Bell 206	300	
OH-58A/C Kiowa	220	
AS350 AStar	200	
UH-1H Iroquois	110	
MH-47E Chinook	100	

C. Assumptions

The methods of eliciting information from participants will ultimately determine the quality of the information that is gathered. To ensure both breadth and depth of the information received from participants, a broad set of knowledge elicitation methods were utilized to provide sufficient insight into the air assault work domain and the tasks of an AMC. In addition, participants answered all interview questions and knowledge elicitation prompts honestly and had a sincere interest in providing beneficial results.

D. Procedure

Participants were given an overview of the goals of the project, including the design of an intelligent human-autonomy team that can optimally manage multiple Manned-Unmanned (MUM) aerial systems in air assault mission environments, as well as a briefing on the capabilities of TECUMSA's autonomous systems. Basic demographic data, including rank and years of service, were then collected. Participants were also asked about their deployment history, specifically focusing on their experience as an AMC. After collecting this demographic data, interviewers conducted semi-structured interviews using the aforementioned methods described in Section V.A.

VI. RESULTS

A. Understanding Role of AMC During Air Assault Mission

During an air assault mission, the AMC is the leader and final authority of all air assets during the mission. Reference 20 states that "The AMC is the aviation unit commander. He/she receives and executes the Air Assault Task Force Commander's AATFCs guidance and directives, and controls all aviation elements. The AMC ensures continuity of command for all supporting aviation units and employs attack helicopters and artillery along the air route, fighting the battle from Pickup Zone (PZ) to LZ while keeping the AATFC informed." Participants identified three major phases of an air assault that the AMC plays an instrumental role in:

- Planning
- Briefing
- Execution

The final phase of an air assault mission would technically be the debriefing; however, participants suggested that there is not always time available to complete this phase. Figure 6 illustrates these three different phases and includes the primary activities of the AMC during each, according to SME feedback. Using the Task Diagram method, the major phases of the air assault and associated tasks of an AMC during each were identified.

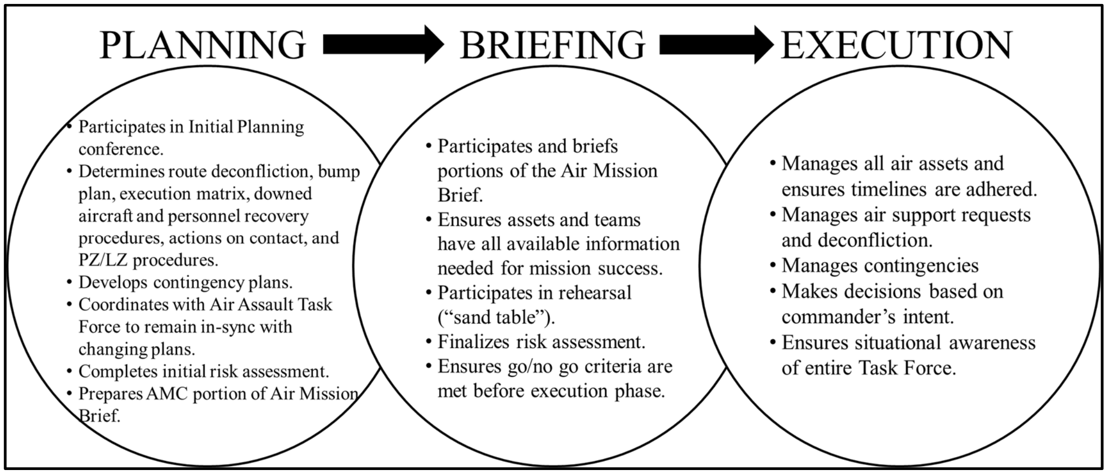


Figure 6. Task Diagram Method

1. Planning

Air assaults are not spontaneously executed. While a mission can be hastily planned for, it will not be unplanned for. The nature of air assaults is not very forgiving. They take place in hostile, unpredictable, and ever-changing environments where the slightest error can carry with it an unforgiving and often irreversible consequence. It is therefore critical that the objective is considered with respect to the desired end state of the battlespace. Therefore, extremely detailed and precise reverse planning that works backwards from the ground tactical plan, or the last stage of mission execution, is completed before the aircraft takeoff to ensure mission success, as shown in Figure 7. Figure 7 shows that air assault planning starts with the desired end state of the Ground Tactical plan and then works backwards, rather than planning in the chronological order that the air assault will actually be executed in. This is known as reverse-order planning. Contingency plans are also developed in the event that if something does not go according to plan, there is a prepared secondary course of action to take.

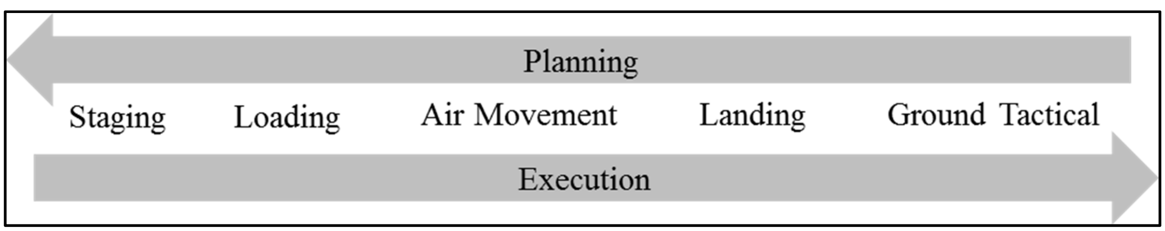


Figure 7. Stages of Air Assault

While the AMC does not lead every step of the planning process, they are considered one of the most knowledgeable personnel and leaned heavily upon for their expertise throughout the planning process. The primary tasks of an AMC during the planning phase include the following:

- Participating in Initial Planning Conference (ICP)—the ICP is an initial meeting between the Air Assault Task Force (AATF) and supporting aviation unit, for example, AMC, liaison officer, and flight leads, where they can address environmental factors, such as climate, weather, terrain, and altitude, which may impact the performance capabilities of the aircraft. The ICP is held as early as possible in the air assault planning process to ensure the crew is adequately prepared to successfully accomplish the upcoming mission.

- Determining route deconfliction, bump plan, execution matrix, downed aircraft and personnel recovery procedures, actions on contact, and PZ and LZ procedures
- Developing contingency plans
- Coordinating with AATF to remain in sync with changing plans
- Completing initial risk assessment
- Preparing AMC portion of Air Mission Brief

2. Briefing

The briefing phase is a critical step to ensure everyone involved in the air assault is on the same page. During this phase, planning should be finalized and only minor changes to the plan should occur. The AMC's role during briefing is to verify that every detail of the mission is accounted for and that the sequence of events will maximize the chance of success while minimizing the risk of losing personnel and/or equipment. The AMC's briefing activities include the following:

- Participating and briefing portions of the Air Mission Brief
- Ensuring assets and team members have the necessary information for mission success
- Participating in mission rehearsal (sand table exercise)
- Finalizing the risk assessment
- Ensuring go/no go criteria are met before the execution phase

3. Execution

During the execution phase, the AMC plays the most prominent role, with duties including:

1. Maintaining situation awareness over the entire battlespace, including aircraft states, mission flow, enemy status, and the Ground Commander's intent
2. Coordination with subordinates and superiors regarding updates and changes to the mission execution status
3. Making executive decisions under extreme time constraints and disseminating these action commands to the fleet of aircraft under their command, for example, whether to engage a newly materialized enemy, whether to recover a downed aircraft

Primary tasks of an AMC during the execution phase include:

- Managing all air assets and ensures timelines are adhered
- Managing air support requests and deconfliction
- Managing contingencies
- Making decisions based on commander's intent
- Ensuring situational awareness of entire Task Force

At each of these three stages, the crux of almost every decision centers around Mission, Enemy, Terrain and Weather, Troops and Support Available, Time Available, and Civil (METT-TC) factors. Table 2 provides a high-level deconstruction of typical AMC considerations within each METT-TC factor. Note that this is not an exhaustive list.

Table 2. METT-TC Factors

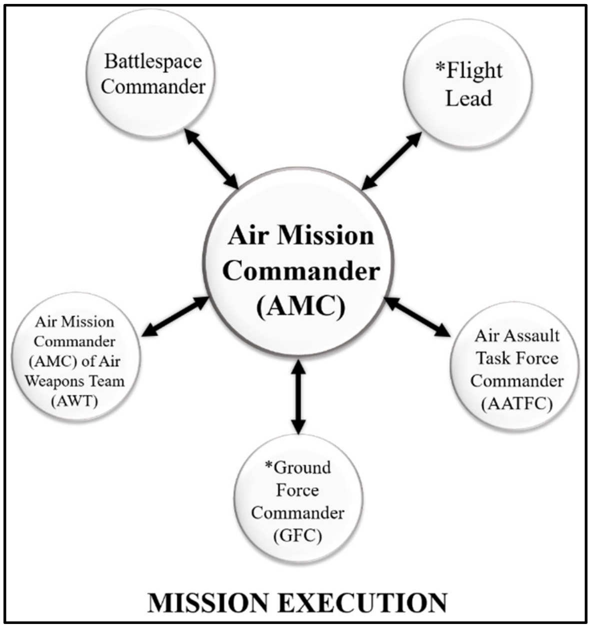
Factor	Typical Considerations
Mission	• Answers to Who, What, When, Where, and Why • Commanders Intent • Desired End State • Concept of Operations • Scheme of Maneuver • Tasks to Subordinate Units
Enemy	• Composition, for example, number of personnel, vehicles, and weapons • Disposition, for example, organization, strengths, vulnerabilities, and tactical mobility • Equipment, for example, armored vehicles, and anti-aircraft artillery • Location • Capacity, strengths and weaknesses • Mission and Purpose • Possible and Probable Courses of Action • Recent Activities and Patterns of Life
Terrain	• Artificial and Natural Obstacles • Avenues of Approach • Advantageous Terrain Features, for example, cover, concealment, and reduced intervisibility • Disadvantages of Terrain Features, for example, affords enemy cover and concealment
Weather	• Wind • Temperature • Visibility • Cloud Cover • Precipitation • Humidity

Table 2. METT-TC Factors (Concluded)

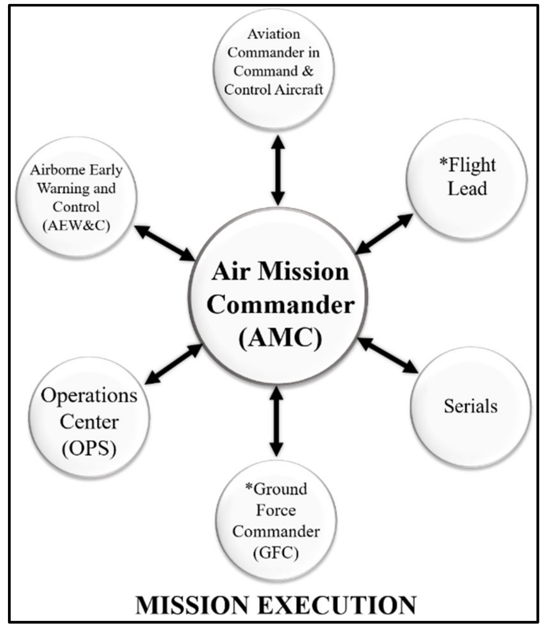
Factor	Typical Considerations
Troops and Support	• Number, type, capabilities, and condition of available friendly troops and support. These include supplies, services, and support available. • Crew Availability, for example, crew members require superior's approval to work in excess of 12 consecutive hours and crew strengths guide personnel selection • Aircraft Status, for example, in maintenance • Support Systems, for example, MEDEVAC aircraft available for standby • Combat Resources, for example, finite weapons and fuel onboard
Time	• Planning and Preparation of combat orders, that is, deliberate, constrained, and hasty • Inspection and Rehearsals • Timeline for Movement, for example, PZs, Start Phases, Air Control Points, Release Points, and LZs • Movement: Strict Time Constraints During Air Movement, for example, aircraft are only allowed to be +/- 30 seconds off of the flight plan during air movement
Civil Considerations	• Cultures and Activities • Civil Institutions • Infrastructures and Organizations • Populated Areas

4. AMC Communication

Coordination and communication, particularly before and during mission execution, ensures that command and control is maintained and mission objectives are successfully accomplished. The wagon wheel interview methodology was employed as a tool for taking a brief audit of the main communication channels that exist for the AMC during the air assault execution. Although it is common for the acting AMC of the mission to also be the pilot-in-command of their aircraft, this particular aspect of communication within the aircraft between the pilot-in-command and their aircrew, for example, a copilot or flight medic, was not discussed in detail during the wagon wheel exercise and is therefore not included in the results. Figure 8 contains two completed wagon wheel diagrams that were filled out independently by interviewees. Figure 8 also includes asterisks that indicate a position included in both SME 1 and 2 diagrams.



a. SME 1



b. SME 2

Figure 8. Wagon Wheel Diagram Filled Out Independently

Noting the similarities and differences between the two diagrams provided a concrete artifact from which to resolve discrepancies during a joint session with participants. Having participants explain and justify the inclusion of each personnel in their diagram helped fully capture how air assault teams communicate. This discussion resulted in the agreed-upon revised wagon wheel shown in Figure 9. The updated wagon wheel diagram includes Contingency Assets (CAs) that are not universally available across every air assault mission but are considered essential elements to include in the diagram. If available, any of the CA support can be requested by the AMC, at which point the AATFC can then temporarily assign the requested CA to support the AMC, thus creating an additional branch of communication with the AMC. Note that the AMC will probably not be the only one communicating with the newly assigned CA. Flight leads, AATFC, Unmanned Aerial Systems (UASs) and Air Weapons Team (AWT), and Ground Force Commanders (GFC) can and likely will all be coordinating directly with the newly assigned CA as well. To facilitate the process of rebuilding a united wagon wheel diagram, participants focused on specific details of SUMIT's Simulation Evaluation Plan training vignettes. For example, the node in Figure 9 labeled UAS and AWT was largely included based on the parameters of the vignette. Although this communication channel, that is, node, is not necessarily uncommon, it is less universal across missions.

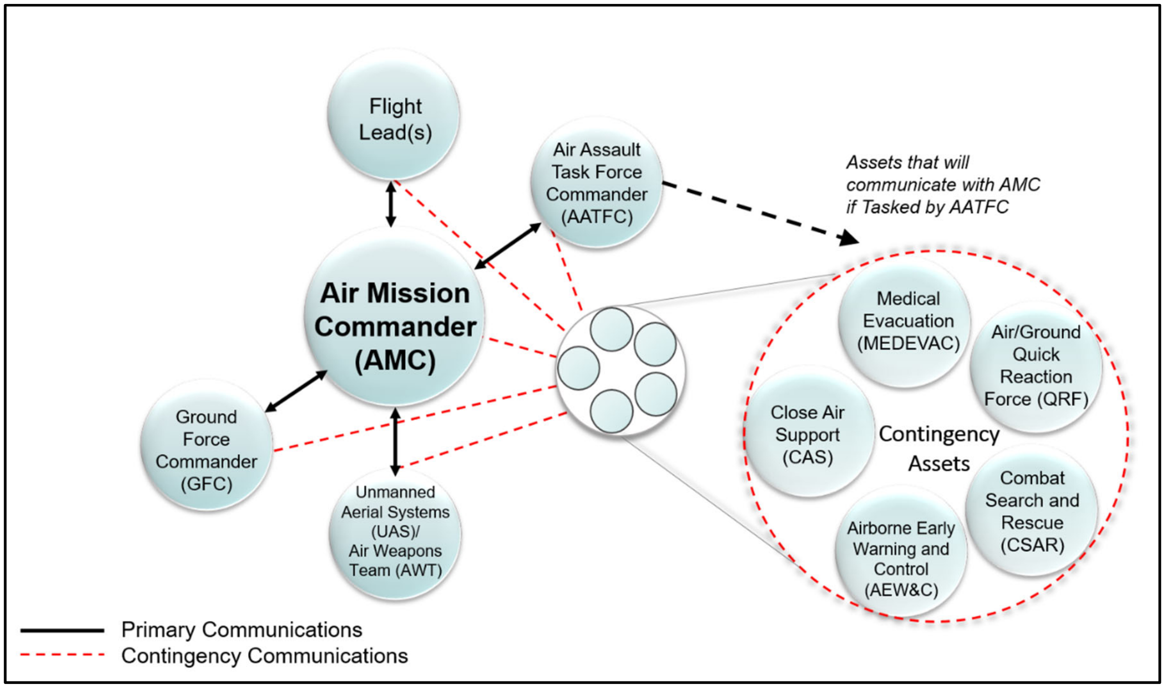


Figure 9. Updated Wagon Wheel Diagram

Table 3 provides more details regarding each communication node listed in Figure 9, including a description of that individual's roles and duties, what information that individual sends to and receives from the AMC, and the method of communication, for example, radio and chat via the tactical internet.

Table 3. AMC Communication Channels

Position	Roles and Duties	Communications From AMC	Communications to AMC	Communication Method
AATFC	• Overall commander of the AATF • Ensures continuity of command throughout the operation • Overall responsibility for the air assault operation	• Mission event milestones, for example, Ex-check • Additional support unit requests • Updates and mission changes	• Additional tasking or mission changes • Updates regarding the AMC's requested contingency assets, for example, approval of request and estimated time of arrival for asset	• Radio • Chat
GFC	• Commands largest ground maneuver force inserted during air assault • Usually one of the AATFC's subordinate maneuver commanders • Maintains communication with AATFC throughout operation	• AMC monitors GFCs execution checklist transmission to the AATFC • Mission event milestones - only source of situation awareness for the GFCs	• Requests additional support, for example, surveillance and fire support	• Radio • Chat
Flight Lead(s)	• Navigation • Enroute communication, for example, keeps AATFC updated on flight status • Obstacle and threat avoidance • Monitors energy state of all aircraft	• Mission changes or deviations, for example, route changes • Request for updates and aircraft status	• Flight status, for example, obstacles and threats	• Radio • Chat
UAS and AWT	• Reconnaissance of the route, LZ, and NAIs • Fires and overwatch for ground forces	• Tasking requests, for example, video feed of LZ	• Video feeds • Laser designation data • Target identification data	• Radio to UAS operators • Chat

Table 3. AMC Communication Channels (Continued)

Position	Roles and Duties	Communications From AMC	Communications to AMC	Communication Method
MEDEVAC	• Called in to evacuate any wounded service member • Would also communicate directly with the owning unit of the injured service member	• Situation awareness information, for example, threats in or around the point of injury, safest ingress, and egress routes • Status updates, for example, location of friendly and enemy forces	• Estimated time of arrival • Request for safest ingress and egress routes • Status of friendly forces • Patient status	• Radio • Chat
Air and Ground QRF	• On standby to assist in any emergency situation that may arise, for example, down aircraft, troops in contact, vehicle accident or any other troop isolating event	• Change to activation status • Guidance and situation reports pertinent to both air and ground forces • Airspace deconfliction information, for air QRF	• Estimated time of arrival to the incident site • Onboard assets, for example, equipment, personnel • Request for incident site updates, for example, threats and friendly forces in the area	• Radio • Chat
CSAR	• Typically used specifically for rescues and extractions deep in enemy territory • Equipped with special equipment and weapons that MEDEVAC aircrews do not have	• Situation awareness information, for example, threats in or around the incident site, safest ingress and egress routes • Status updates, for example, location of friendly and enemy forces • Airspace Deconfliction	• LZ and PZ updates, for example, obstacles, threats, friendly forces status • Best ingress and egress routes • Status of the source of the call out, for example downed aircraft, isolated personnel	• Radio • Chat

Table 3. AMC Communication Channels (Concluded)

Position	Roles and Duties	Communications From AMC	Communications to AMC	Communication Method
AEW&C	• Provides airborne radar services and threat detection to give early warning of incoming aircraft or missiles • Assist AMC with airspace deconfliction	• Request for assistance with airspace deconfliction	• Incoming threats, for example, aircraft and surface-to-air missiles	• Radio • Chat
CAS	• Provide ground troops with additional fire support and enemy suppression	• Request for BDA • Request amount of ordinance on board • Request time available on station	• Time to target and response time • BDA reports • Any new threat updates • Weapons status for follow on missions	• Radio

B. Participant Feedback on TECUMSA Demonstration

Participants were asked to provide feedback on the original user interface during a brief demonstration of TECUMSA. Participants received introductions to features including the play calling interface and vehicle dashboards as well as TECUMSA's autonomous capabilities including the route planner and IA. In-depth discussions were largely focused on the details in the Simulation Evaluation Plan, prompting context relevant insights into how to better tailor the HAI to assist an AMC during an air assault mission.

1. Map

Participants provided inputs regarding TECUMSA's map display. For example, when asked whether a satellite or topographic map was preferable, participants explained that different information can be gleaned from each. Roads, heavily traveled paths, and possible obstruction and characteristics of the LZ cannot be seen in topographic maps; however, terrain elevation is vague in satellite imagery. Allowing TECUMSA users to switch between or even overlay the two map types would cover the largest range of user needs. Participants also mentioned that it would be beneficial to incorporate Military Grid Reference System (MGRS) into TECUMSA's map display.

2. Icons

Due to the range of aircraft and capabilities in the simulation vignettes, it became apparent that certain distinguishing characteristics should be emphasized in the aircraft icons so entities in the map, vehicle dashboard, and so forth can be easily recognizable. Distinctions and information that participants agreed were valuable to include in the icon design included the following:

- manned versus unmanned
- missile quantity on-board
- current Level of Interoperability (LOI)
- fixed or rotorcraft airframe
- whether the aircraft is ownship, friendly aircraft with LOI, or friendly aircraft but without LOI

While all of these characteristics have the potential to be represented in the icon design, there is a point of diminishing returns where the mass of information will merely serve to clutter the icon and display and confuse the user. Figure 10 shows the original TECUMSA icon representing unmanned fixed-wing aircraft.

Figure 10. Original TECUMSA Icon Representing Unmanned Fixed-Wing Aircraft

3. Vehicle Status Panel

One participant mentioned the benefit of a weapons summary page to keep track of the quantity and type of armament onboard each of the UAVs available to the operator. Since missiles were not part of the payload previously utilized in the TECUMSA system, the need to represent the quantity and type of missiles onboard each UAV became an HAI requirement. However, with the limited armament considered in the initial evaluation of TECUMSA since only Hellfire missiles are available, the solution concept involved revamping the Vehicle Status Panel into a Vehicle Summary Panel that provides a high-level snapshot of each aircraft's payload information. The Vehicle Status Panel design is discussed further in Section VI.D.3.

4. Vehicle Dashboard

The TECUMSA system includes vehicle dashboards that provide vehicle state information for each vehicle, such as speed, altitude and elevation, payloads, fuel level, sensor status as well as the current sensor feed. One notable suggestion from participants was to have an indicator of the time remaining until bingo fuel, that is, when the UAV needs to return to base to refuel. The participants explained that having this information would be helpful for task management decisions since a blue force overwatch task would be best served by an aircraft that could remain overhead for the entire duration of the overwatch. Participants also suggested that weapon information, such as type and quantity, be added to the vehicle dashboard, again due to the influence this information would have on aircraft assignments and mission planning.

5. Airspace Deconfliction

One of the techniques used to elicit participant HAI ideas and feedback was to provide concrete constraints and mission details to reason about during a demonstration of the TECUMSA interface. Based on SUMIT's Simulation Evaluation Plan vignettes, participants were provided a scenario where four UAV's were concurrently in the air and under the AMC's command and control. These were specifically two Gray Eagle (GE) MQ-1Cs, one Shadow (SH) RQ-7, and one Fire Scout (FS) MQ-8. This specific scenario details prompted participants to draw a stack diagram similar to the one seen in Figure 11. This diagram is used as a clear and concise way for air assault crews to visually represent the altitudes of each aircraft flying in the mission and ensure adequate separation. Note at the highest altitude in Figure 11, there is a dashed line representing a lateral separation, which is required since both of the GEs begin the vignette at the same altitude above Mean Sea Level (MSL). This dashed line could represent a predetermined division of the battlespace where GE 1 covers one half of the battlespace and GE 2 covers the other half.

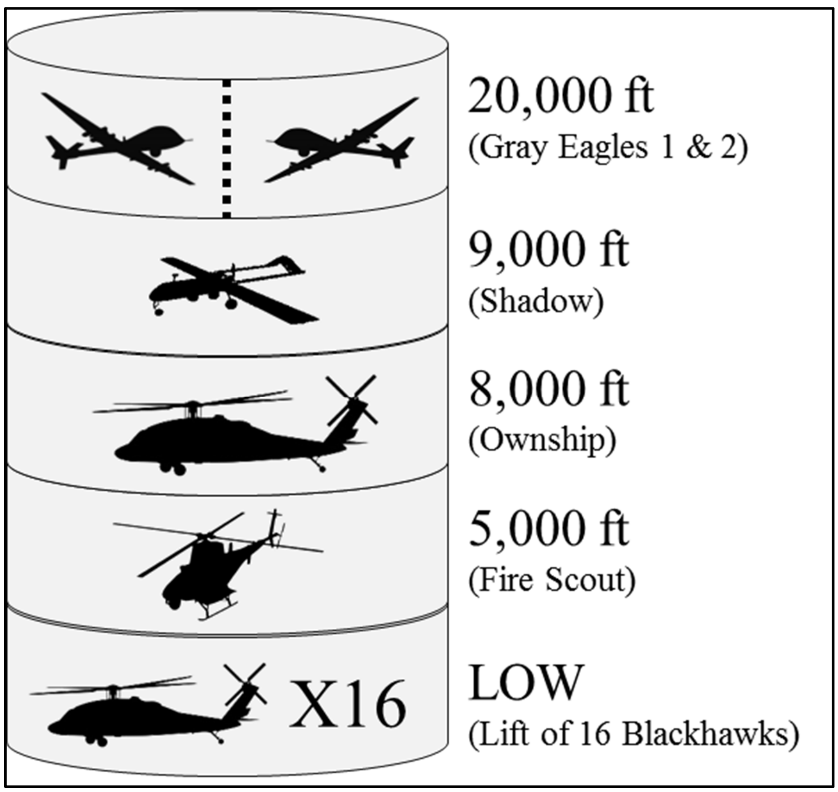


Figure 11. Altitude Deconfliction Stack Diagram in MSL

C. Participant Feedback During Simulation Interview

Developing an IA that can support an AMC during an air assault mission requires understanding the realm of possibility considered by the AMC during a wide range of tasks. The simulation interview technique was used to elicit the step-by-step decision making that a veteran AMC would make across a variety of different scenarios. Example questions included the following:

- What would you do if an enemy was found behind this ridge?
- What route would you take if a ROZ was called along this section of your current lift route?
- How would this dense population area effect your decisions?

Think-out-loud procedures provided explicit data regarding veteran AMC's thought processes, reasons for action selection, combat strategies, situation assessments, and critical cues to look for. Participants identified how they would complete each of the Intelligence, Surveillance, and Reconnaissance (ISR) tasks listed in Table 4 while utilizing a fleet of up to two manned and four unmanned aircraft. The results of the simulation scenarios were used to guide future TECUMSA play development and optimization parameters for the IA to reason about, for example, an additional play for engagements that optimizes aircraft selection for combat power. For example, participants indicated that the ability to hover could be valuable for certain tasks or in certain environments since in mountainous terrains, a fixed-wing UAV that needs to loiter may have its sensor obstructed by the terrain at various times during the loiter. In contrast, a rotorcraft could avoid these obstructions by hovering in place.

Table 4. TECUMSA's IA Feedback

Vignette Event	Optimization Parameters(s)	Optimal Vehicle	Play	Priority (Order of Operation)
Conduct Renaissance at LZ Direwolf	1. Undetected 2. Sensor Capability	Ownship	Rout Inspect	2
Conduct Renaissance at Axis Mormont	1. Undetected 2. Sensor Capability	SH	Point Inspect	1
Renaissance NAIs	1. Sensor Capability	GE	Parallel Search	3
Overwatch Friendly Forces	1. Combat Power	FS	Air Overwatch	4
Locate Militia Vehicles and Engage if Positive ID	1. Combat Power 2. Laser Capabilities	Depends Where Found	Engage (1 Aircraft Designates and Engages)	*
Surveil Possible Militia Compounds	1. Undetected 2. Sensor Capability	Depends Where Found	Point Inspect	*

Table 4 summarizes participant feedback regarding TECUMSA's IA. Note that an asterisk in the priority column indicates a subtask that would be accomplished during the prioritized tasks.

During the simulation interview session, participants were asked to provide feedback on the evaluation scenarios and asked if anything in the scenarios needed clarification. Sections VI.C.1 through 7 are a sample of the questions participants asked during the simulation interview, along with implications for the IA's logic and future scenario design.

1. What are the weather conditions along the route and at the LZ? Are there clouds?

After further probing, these questions revealed the importance of weather considerations for planning and executing an air assault. For example, the aircraft may need to land into the wind depending on how strong the winds are and how experienced the pilots are. If landing into the wind is too difficult or unfeasible, it may require deferment to the alternate LZ. Aircraft sensor capabilities are also affected by weather conditions. For example, in foggy or hazy conditions, an IR sensor might be required for reconnaissance of the ingress route, which may not be a capability of any available aircraft and could require a contingency asset to be requested or a task to be reassigned.

The implication is that the sensor type, for example, EO and IR, should remain an optimization parameter that the operator can select to narrow the search space for the IA to optimize vehicle assignment during play calling.

2. Is it day or night?

There are advantages and disadvantages to both. While day operations are easier to operate aircraft in, there is also an increased risk of enemy fire since the air assault is more visible in daylight. Night operations have the advantage of reducing enemy fire risks but also increases the risk of blue force operator errors and friendly air collisions. Other factors also contribute to whether day or night is preferable, such as the skill levels of the pilots, forecasted weather conditions, and the error tolerance of aircraft movability by the specific characteristics of the LZ.

The implications presented supports the preservation of the sensor type optimization parameter, for example, EO and IR. Furthermore, in the future, default settings for the IA could be set so that in night operations, UAV's are set to fly with higher lateral and vertical separation to avoid collisions that could be particularly beneficial in instances where the AMC chooses to manually fly a UAV.

3. What is the purpose of the dead cow in the LZ? Is it an obstacle?

Participants suggested that power lines or an antenna are more common obstacles. There are even cases when enemy forces have erected power lines in anticipation of an incoming air assault.

The implication is that there is an endless array of obstacles and threats that can be used to evoke a variety of responses from participants during system evaluations; therefore, it is prudent to build simulation scenarios that span both the common and atypical events to promote the development of an adaptable system.

4. Is there an alternate LZ or just the one?

Participants pointed out that there would typically be an alternate LZ for the lift aircraft to land in so that if the risk of landing in the primary LZ was too high, they could defer to the alternate LZ. For example, if enemy forces appeared in or around the primary LZ, or a suspicious foreign object materialized soon before the lift was scheduled to land. While the alternate LZ will not always be used, part of contingency planning is to ensure that foreseeable risks are prepared for. As such, if the terrain affords it, a secondary LZ will be included in the landing contingency plan.

The implication is that in the future, TECUMSA's IA could be capable of alerting the AMC of newly detected entities found within the primary or alternate LZs within x minutes of the lift's arrival. In addition, customizable scheduling of play execution, for example, execute a Point Inspect of the primary LZ in 15 minutes, and task reminders, for example, a reminder to call a Point Inspect of the alternate LZ in 20 minutes, are in development. This would allow the AMC to offload some of the task and time management workload onto the TECUMSA system, which can be particularly valuable when nearing the arrival of an incoming lift.

5. When during the vignette should the AMC engage positively identified enemies?

Engaging enemy targets is done very strategically in air assaults. Participants interpreted the vignette details to mean that any positively identified enemies are to be engaged at any point during the 30-minute vignette. However, based on their experience, participants would avoid engagement in the LZ until the last possible minute before the lift arrives in order to preserve the element of surprise and avoid giving nearby threats time to prepare for the lift's arrival. One participant recalled a time where the LZ was cleared and enemies were kinetically engaged just 30 seconds prior to their aircraft arriving in the LZ area. A similar strategy to delay enemy engagement can be applied to enemies along the ingress route; however, target engagement can be unnecessary altogether since changing a route is typically easier than changing a LZ.

The implication is that similar to the actions the IA takes with ROZs, the IA could suggest a re-routed ingress path for the lift to take once hostiles are identified, thus minimizing risk of enemy fire.

6. What is considered PID?

Participants requested clarification of what constitutes Positive Identification (PID) of enemy forces. For example, is it an individual in a uniform, the presence of a weapon, or suspicious activity, such as multiple military-age figures moving in a tactical formation or digging by the roadside?

The implication is that if Automatic Target Recognition (ATR) is integrated into TECUMSA, these types of cues and engagement rules will be important to train the system on.

7. What are the highest altitudes that can be flown by each aircraft to still provide the ATR with usable sensor data to spot a militia compound and an anti-aircraft artillery system? How large of a field of regard is available for each aircraft's sensor, that is, how much area can each aircraft reconnaissance?

This question revealed a strategy for surveying large areas with a limited number of aircraft. The participants suggested that they would plan the mission so that they could assign a high altitude UAV to be positioned central to multiple NAIs. If the sensor on the UAV could provide usable video feed at a high altitude, this strategy would allow the AMC to survey multiple NAIs at once, exemplifying an experienced mission planner's strategy to always optimize the number of tasks achieved and the amount of resources required.

The implication is that there are certainly more and less optimal aircraft allocation and tasking strategies; therefore, in the future the IA could consider variables, such as area of coverage in the logic for recommending vehicles to fulfill operator play calling.

D. Generating Human-Autonomy Interface to Support Air Mission Commander

Sections VI.D.1 through 7 describe solution concepts based on participant feedback on TECUMSA's HAI components, including updates to the vehicle dashboard, vehicle icons, Play Calling Tile, and Play Workbook, as well as an initial design for a possible airspace deconfliction tool. However, interface concepts described within Section VI.D may be adapted and revised as TECUMSA development progresses.

1. Map

Figures 12 and 13 are screenshots of a portion of the current TECUMSA map display that provides the operator with a pan-, tilt-, and zoom-able map that can be tilted to a 2 ½ dimensional view, which is rendered using Digital Terrain Elevation Data (DTED). Figure 12 includes a bird's eye view of the terrain in TECUMSA's map as well as three UAVs and their corresponding sensor footprints. The user is able to cursor over any spot on the map and get the latitude and longitude decimal coordinates as well as elevation at that location. All known aircraft are represented on the map at all times. Note that the UAV icons used in the map were designed as Two-Dimensional (2-D) images and that modifications may be needed to improve the discriminability from a tilted 2 ½ dimensional vantage point, as shown in Figure 13. Sensor footprints can be seen projecting out from GE2 and FS1 in Figure 13. Note that Figure 13 was taken at a different time than the image in Figure 12.

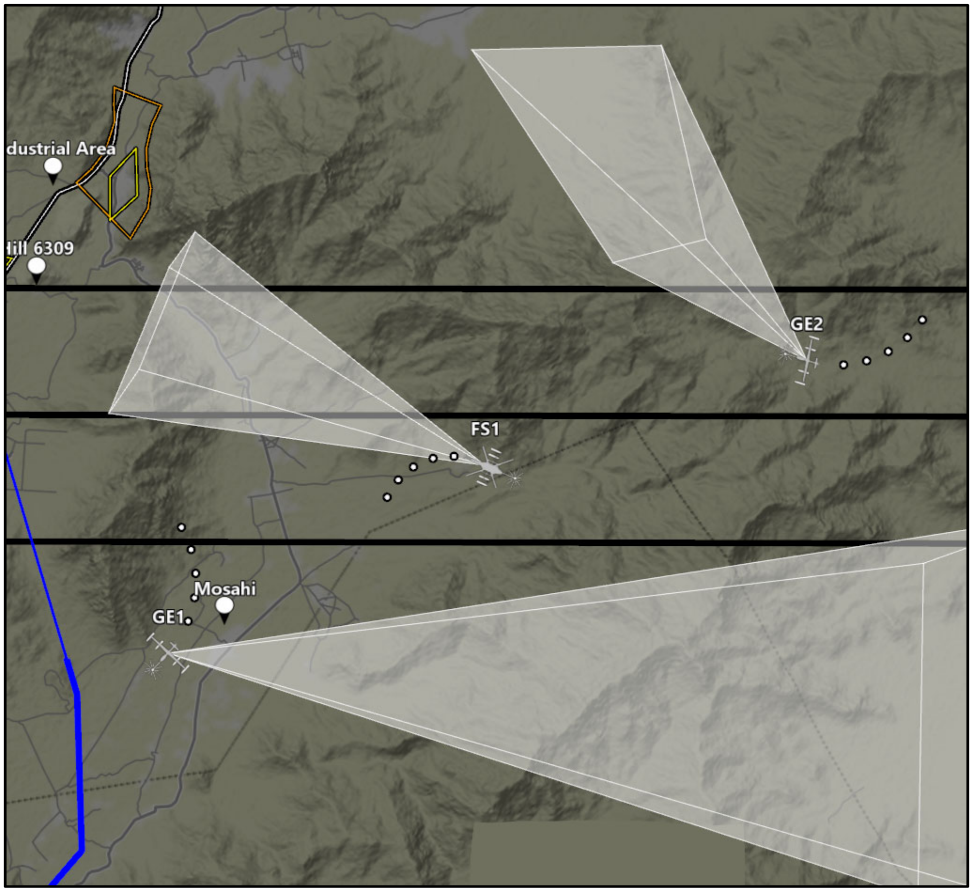


Figure 12. 2-D Vantage Point Terrain in TECUMSA's Map

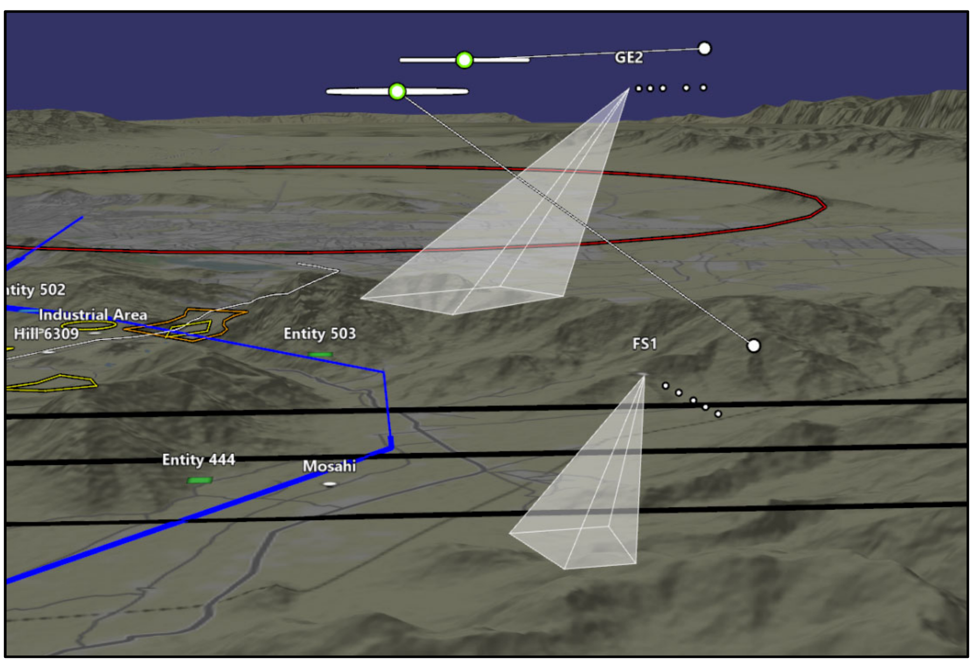


Figure 13. 2½ Dimensional Vantage Point of Terrain in TECUMSA's Map

2. Icons

Figure 14 shows a sample set of icons for a Blackhawk Utility Helicopter (UH) 60 (ownship), GE MQ-1C, FS MQ-8, and SH RQ-7. As these icons are based on the actual aircraft, characteristics such as fixed-wing versus rotorcraft are inherently represented in the design. The narrow black cylindrical shapes attached to the sides of the aircraft icons represent Hellfire missiles. The SH RQ-7 is the only aircraft that does not carry missiles. Furthermore, the number of missiles attached to each vehicle icon updates as they are fired, creating direct perception of the aircraft's current payload, as seen in Figure 15.

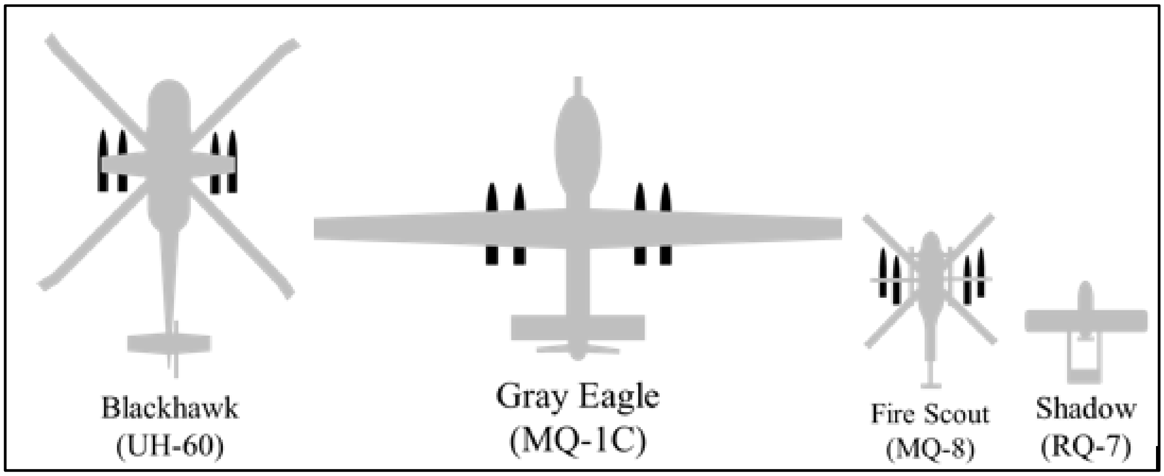


Figure 14. Aircraft Icon Design With Number of Missiles Seen in Black

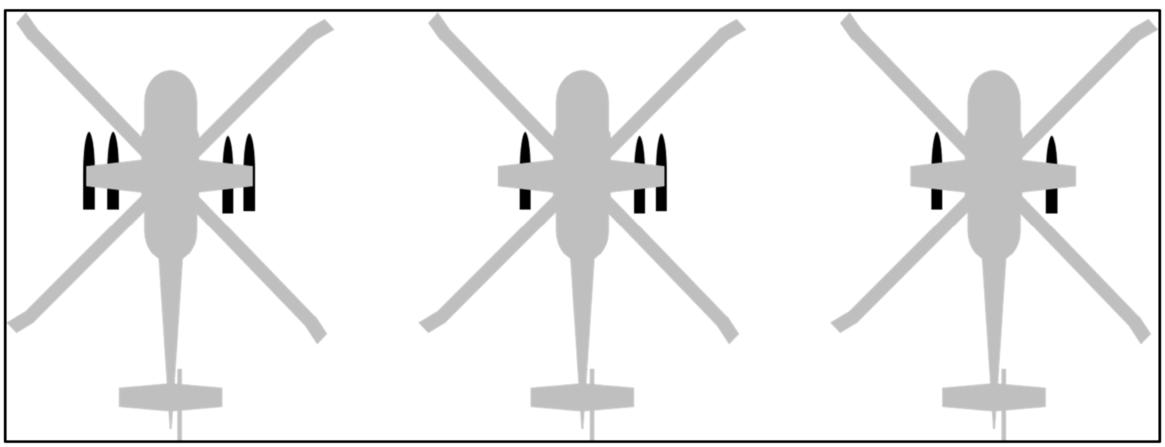


Figure 15. Icon Updating as Missiles are Fired

Figure 16 is an anticipated design that includes features indicating laser designation status, current LOI, aircraft error notification, and play assignment status. For example, after calling a point inspect at Point Charlie, the vehicle changes its course of action and the icon for the assigned aircraft changes from gray to orange. After revisiting this proposed design, it became clear that the LOI value that is depicted in the anticipated design would be illegible when the aircraft icon is scaled down to fit the TECUMSA map, as shown in Figure 12. In addition to being illegible, there is potentially more informational value when the LOI is communicated in terms of functionalities associated with that LOI as opposed to a mere numerical value. Sections VI.D.3 and 4 will cover the graphical representations, that is, icons, for the associated functionalities at a particular LOI.

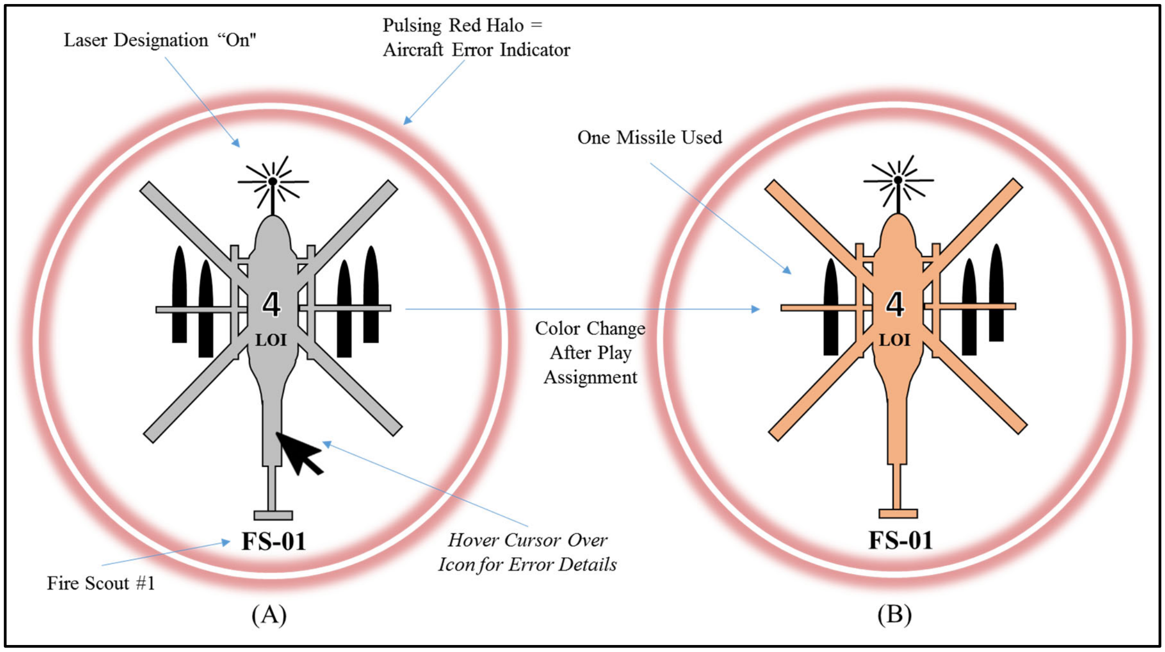


Figure 16. Conceptual Design for Aircraft Icon and Status Features

3. Vehicle Summary Panel

Based on participants' desire for more detailed weapon information, TECUMSA's Vehicle Summary Panel, as shown in Figure 17, was updated to provide a high-level snapshot of each available aircraft as well as the number of missiles onboard, laser designation status, and functionality associated with each aircraft's LOI. The row of icons in each aircraft in Figure 17 are designed to quickly communicate to the AMC what functionalities are available based on the current LOI. For example, the row of icons under the leftmost vehicle (GE-01) indicates that sensors, weapons, and aircraft are all controllable by the AMC. The white fill or background of an icon indicates that the operator has control over that feature, whereas a dark gray or transparent background indicates receipt and transmission of that features data. For example, the operator can view sensor feed but cannot steer it. From left to right in Figure 17, the first UAV (GE-01) has LOI 4, SH-01 has LOI 2, FS-01 has LOI 4, and GE-02 has LOI 3. A potential feature may be added to allow the AMC to have the vehicles sorted and ordered from left to right based on LOI, number of missiles onboard, recency of use, or some other variable. Note that there are pros and cons to having fixed versus dynamic positioning, which can be more thoroughly explored during TECUMSA's HAI testing. In addition, future development efforts may be dedicated to making the LOI icons actionable buttons. For example, clicking the mortar icon opens play calling options where weapons are required.

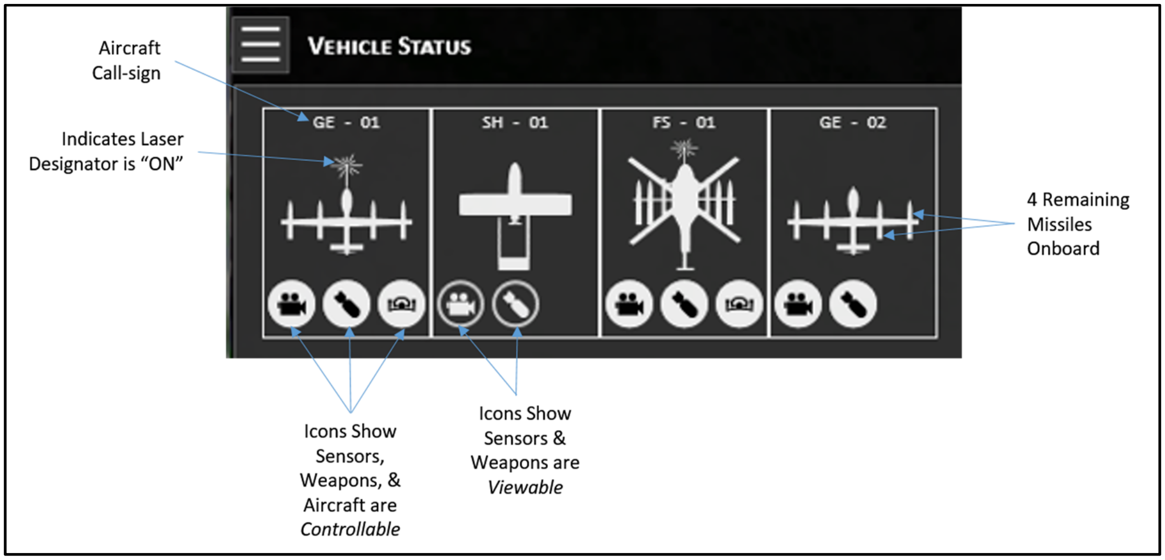


Figure 17. Vehicle Summary Panel Offers Details of Each Aircraft

4. Vehicle Dashboard

Revisions to the vehicle dashboard were made based on the SME's feedback. Figure 18 shows the modified vehicle dashboard display, which includes the following:

- Call sign of aircraft
- Laser Designator Status
- Numerical LOI value as well as icons representing features associated with that LOI
- Fuel Gauge - percentage of remaining fuel
- Low Fuel Icon
- Knots True Airspeed
- Altitude
- Available Sensors on the aircraft
- Remaining Hellfire Missiles onboard
- Station Time - a countdown clock indicating the remaining time before the aircraft reaches Bingo fuel and must return to base, which is a dynamic value since it depends how far away the aircraft is from base.

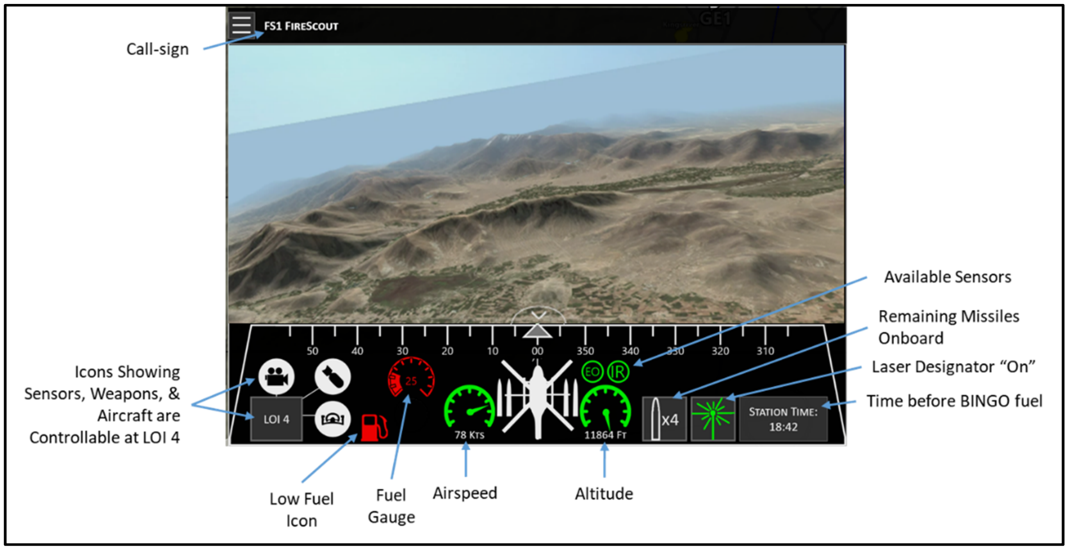


Figure 18. Vehicle Dashboard

Additionally, during a hostile entity engagement, the vehicle dashboard of the engaging aircraft provides a missile release confirmation to the operator, as shown in Figure 19. Providing this information in the sensor feed of the engaging aircraft allows the operator to maintain situation awareness over the unfolding battlespace, both minimizing the probability of casualties and preserving positive identification of the target. The availability of the Fire Now button is context sensitive and is only available once the engaging aircraft is within range of missile release, for example, less than or equal to 9 kilometers (km) slant range.

Figure 19. Vehicle Dashboard Confirming Missile Release During Target Engagement

Once the Fire Now button is selected, a secondary safety popup appears so that the operator can either confirm or cancel the missile release. Although a subtle design detail, the decision to have an additional input from the operator to confirm weapons release was deemed essential. Popups that require operator input should be implemented cautiously as they can be jarring to a user and can pull attention away from potentially more important tasks occurring at the time. However, in this case, the cost of an additional operator input is greatly eclipsed by the consequence of an unintended and irreversible user input that has a high probability of resulting in a casualty event.

Additional changes may be made to the vehicle dashboard later in the development process to allow quick access to information regarding the diverse set of onboard weapons, for example, cursor hover-over text and/or expandable Weapons Information page. Future updates may also allow an operator to directly manipulate certain features in a vehicle's dashboard, such as the desired units, for example, switching altitude from meters to feet or fuel from liters to pounds. Other features may be added, such as a fuel bug marker on the fuel gauge that informs the operator of the Bingo fuel level, as shown in Figure 20, or another countdown timer that indicates how long an operator has control over a particular UAV. The countdown timer would be beneficial in situations where control of the asset is time limited. It may be helpful to think of there being operator station time with an aircraft as well as global station time and the latter being independent on who has control over the aircraft. Figure 20 shows the fuel bug updates throughout the flight from A to D that reflect the amount of fuel needed for the aircraft to return to home base.

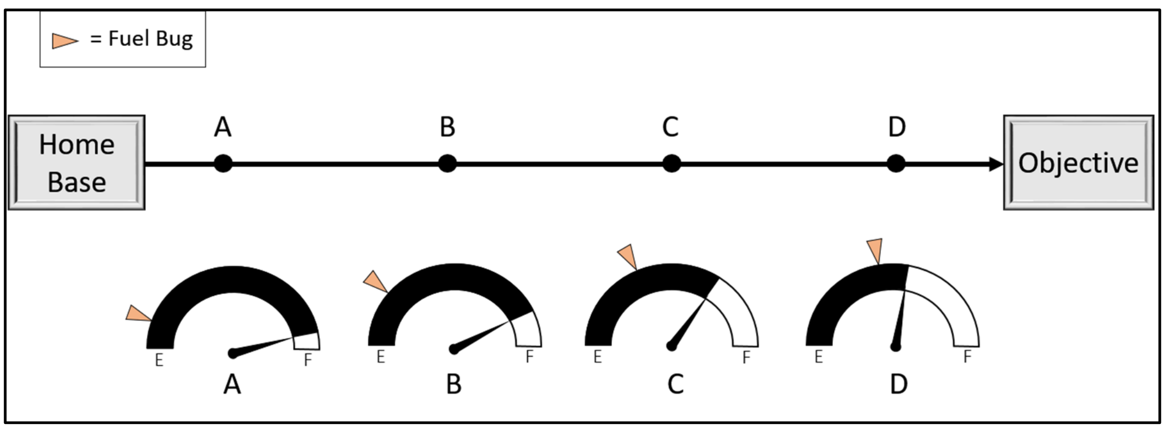


Figure 20. Dynamic Fuel Bug or Bingo Fuel Marker

5. Airspace Deconfliction

Figures 21 through 23 show three airspace deconfliction tools that are designed to provide an AMC direct perception of the occupied airspace and direct manipulation capabilities as a means to quickly manage and correct impending problems via drag-and-drop capabilities. Used in coordination, the tools are expected to prove instrumental for unmanned-manned teaming operations where a single operator is in charge of maintaining situation awareness over multiple aircraft in the same airspace.

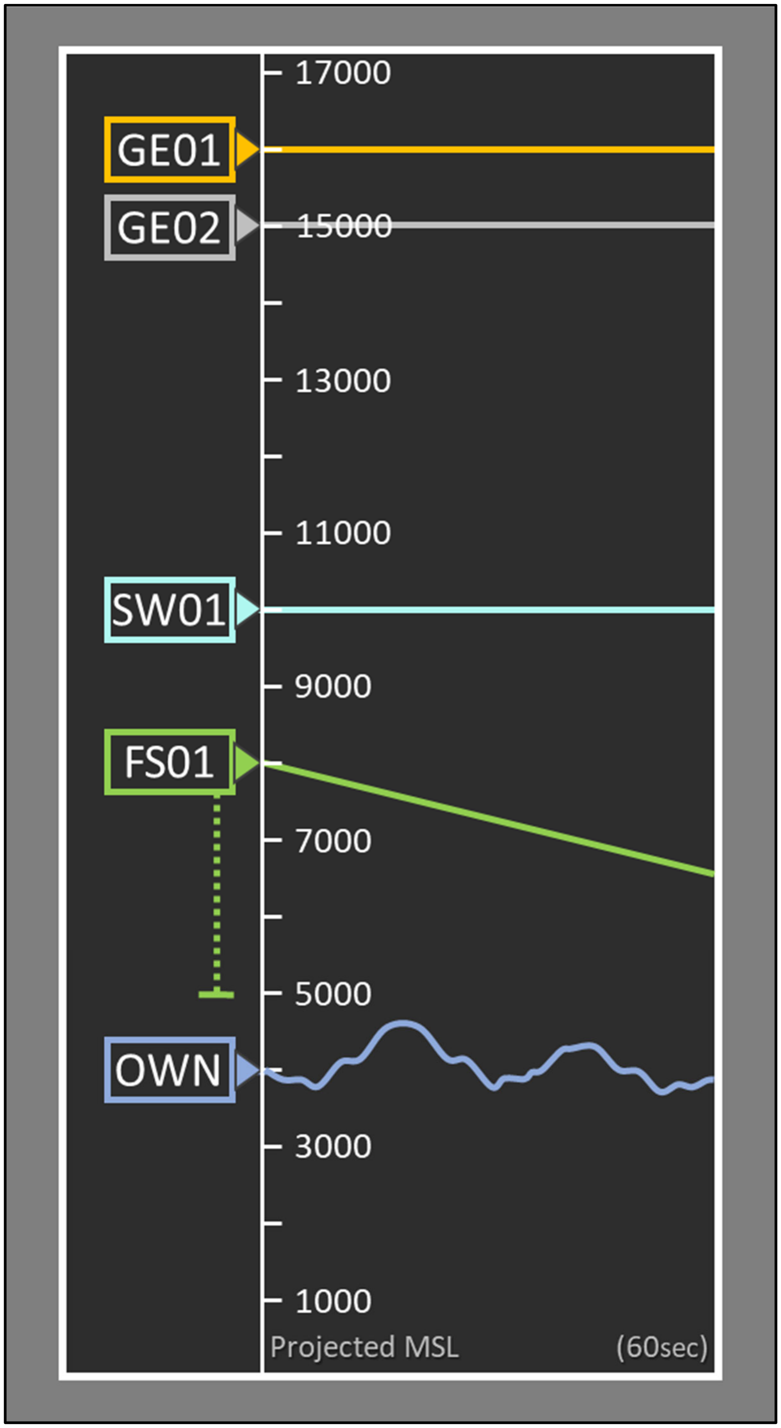


Figure 21. Fleet Altitude Management Tool

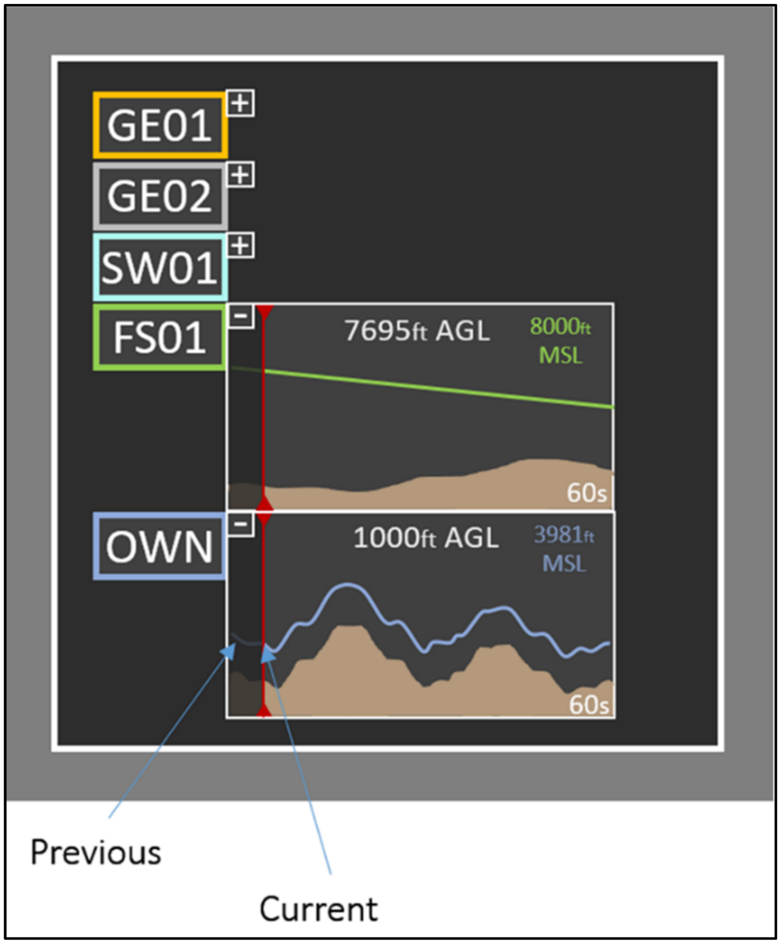


Figure 22. Individual Altitude Management Tool

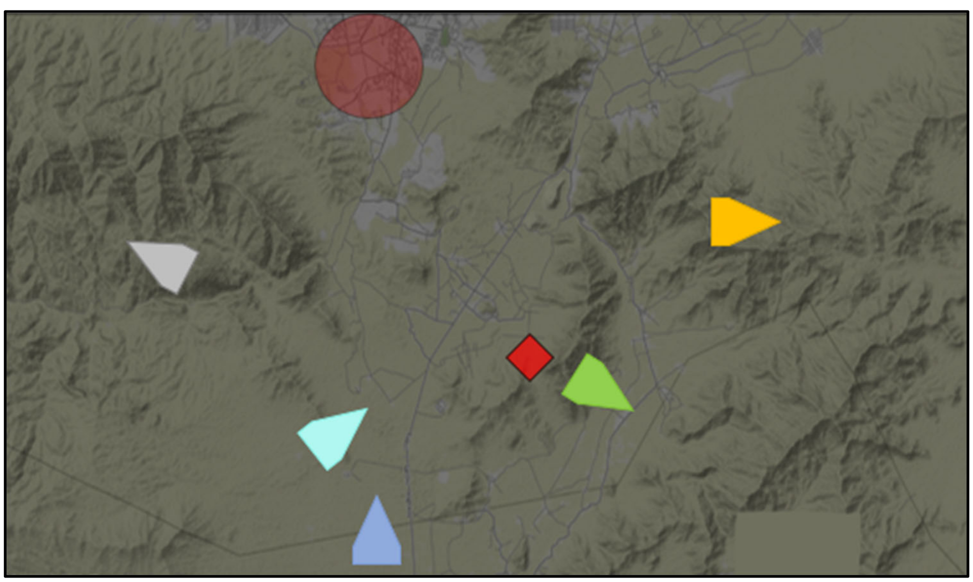


Figure 23. Abbreviated Map

Figure 21 illustrates the Fleet Altitude Management tool, which includes the current altitudes in MSL of all known aircraft in the airspace, projected altitudes of these aircraft in the next 60 seconds, and commanded altitude if an aircraft is directed to ascend and descend. The scale range of the display dynamically adjusts to include the highest and lowest altitudes of the represented aircraft, and the projected altitude is designed to be operator-adjustable, for example, 60 and 120 seconds. The color of each aircraft is consistent with the color coding observed in all other displays, for example, Vehicle Summary Panel, aircraft icon in the map, and vehicle dashboard, as a way to manage situation awareness of aircraft that are actively executing plays.

A drag-and-drop feature is intended to allow the operator to quickly move an aircraft's call sign box to the desired altitude. Once set, the aircraft begins to descend and ascend to the newly commanded altitude. Figure 21 shows that the newly commanded altitude for FS-01 is set to 5,000 feet (ft), and after 60 seconds of descending, FS-01 is projected to be flying at just below 7,000 ft. This tool could also allow the operator to hover their cursor over a particular aircraft's call sign box to see additional flight information, such as the altitude Above Ground Level (AGL) and ascent and descent rate.

Using the Fleet Altitude Management tool, the operator can quickly determine if there are any current or near-term airspace conflicts between aircraft. In addition, context sensitive warnings can be tied in to warn the operator of possible problems. A sample of the warning conditions that the autonomous system could be programmed to look for include aircraft violating a minimum vertical separation of 500 meters, an impending collision between aircraft based on altitude and heading, an aircraft that is violating or going to violate a ROZ, and/or an aircraft that is in range of a known hostile.

Representing aircraft altitudes in MSL ensures a stable reference point, that is, the average MSL, allowing an operator to easily know where the aircraft are relative to one another. If the FS is at 8,000 ft MSL and the ownship is at 4,000 ft MSL, the operator immediately knows that there is 4,000 ft of vertical separation between them. However, only having altitudes in MSL can become problematic, particularly when aircraft are flying at lower altitudes in mountainous areas. The Individual Altitude Management tool was therefore designed to provide the operator with information regarding an aircraft's position relative to the terrain, emphasizing the AGL altitude, as shown in Figure 22.

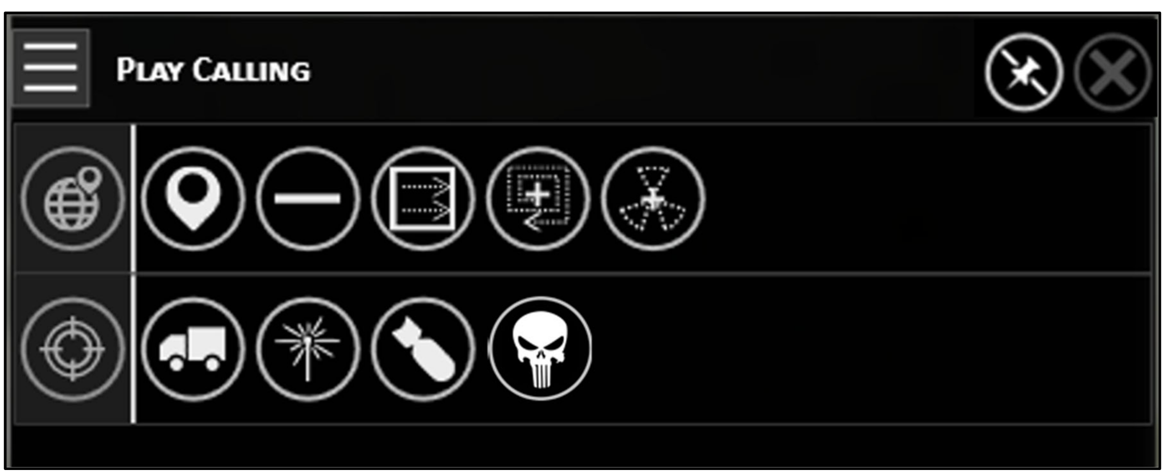
Only the FS and ownship's displays are opened in Figure 22. SME's indicated that having the individual displays with terrain information might only be useful for certain aircraft at certain times, so a collapsible display for each aircraft provides the capability to reduce unnecessary clutter when it is not needed by the operator. There is also the MSL altitude indicated in the individual aircraft displays to make pertinent information available across both of the altitude management tools.

Although the Fleet and Individual Altitude Management tools provide a comprehensive view of the vertical airspace, there remained a concern of being able to quickly communicate the lateral separation between aircraft. A task saturated operator may want a quick representation of the battlespace without the need to pan and/or zoom the TECUMSA map. Figure 23 illustrates the idea for an abbreviated map display that offers the operator a small decluttered version of the full TECUMSA map. This would provide the operator with an updating top-down snapshot of the critical elements for airspace management. The abbreviated map in Figure 23 shows the current location and heading of each known aircraft (irregular pentagons) as well as the location of a ROZ (red semi-transparent circle) and a known hostile entity (red diamond).

6. Plays

Participants provided feedback on the existing play calling interface, identifying existing plays that would be relevant to air assault missions and suggesting new plays that need to be developed. Based on this feedback, Figure 24 shows a revision of the play calling interface was developed that contains two rows of plays. The top row contains location-based plays, including the following from left to right:

- Point Inspect—UAV travels to a point and hovers and loiters with its sensor focused on the point.
- Route Inspect—UAV travels along a route with its sensor focused on the route.
- Parallel Search—UAV searches a specified area using a bidirectional raster scan search pattern.
- Expanding Square Search—UAV searches around a specified point using an expanding square search pattern.
- Sector Search—UAV searches around a specified point using a sector search pattern.



- *Figure 24. TECUMSA Play Calling Tile*

The bottom row contains target-based plays and from left to right:

- Overwatch—UAV continuously updates its position to ensure its sensor is on a target. The route planner will adjust appropriately according to the type of target, for example, friendly, neutral, unknown, or hostile.
- Designate—UAV continuously updates its position to ensure that it is successfully lasing a target.
- Engage—UAV uses a weapon to engage a target.
- Remote Engage—A dual-UAV play where one UAV laser designates the target and a second UAV engages it.

In addition to these plays, a possible multi-vehicle play was identified which would task multiple UAVs to search multiple NAIs or Points of Interest (POIs)

7. Optimization Parameters

Based on SME feedback, the optimization parameters in the Play Workbook were modified to the parameters shown in Figure 25 in order to capture the parameters most vital for air assault missions. The optimization parameters include from left to right:

- Speed—time to reach the play location and target
- On Station Time—duration on task before needing to be refueled
- Low Observable—remain undetected
- Combat Power—maximal firepower
- Sensor Capability—range of sensor
- Laser Designation Capability—range of laser

Figure 25. TECUMSA Optimization Parameters

Figure 26 shows additional Play Workbook modifications to allow the AMC to specify the desired fixed-wing or rotorcraft airframe, required EO or IR sensors, and need for weaponry, whether or not missiles are required. Due to the nature of certain plays, some parameters could be automatically disabled. For example, the engage play would disable the no weapons required option since an engage play could not be executed without at least one missile.

Figure 26. Airframe, Sensor, and Weapons Parameter

E. Validating Human-Autonomy Team

In order to validate TECUMSA's ability to support an AMC during air assault missions, TECUMSA will be tested in a realistic test environment using a variety of scenarios and tasks. AMC SMEs provided valuable inputs on SUMIT's Simulation Evaluation Plan, which was largely focused around increasing the ecological fidelity of the vignettes, as shown in Section VI.B. However, no matter how well the properties of the real world are mapped to the synthetic task environment, capturing all of the variables, constraints, events, and unpredictability that an AMC can experience during an air assault is a monetary and temporal investment that few can afford.

For that reason, TECUMSA has been designed to allow the user to finish the design or adapt to scenarios that TECUMSA may or may not have been planned for. TECUMSA is capable of allowing the operator the full spectrum of control, as shown in Figure 27, where the operator can:

- Manually pilot the UAVs
- Work collaboratively with the autonomy, where the user issues high-level commands and the autonomy carries out lower level tasks such as route planning
- Let the autonomous tools in TECUMSA automatically respond to events and re-routing requirements, for example, re-routing an aircraft to avoid a pop-up ROZ

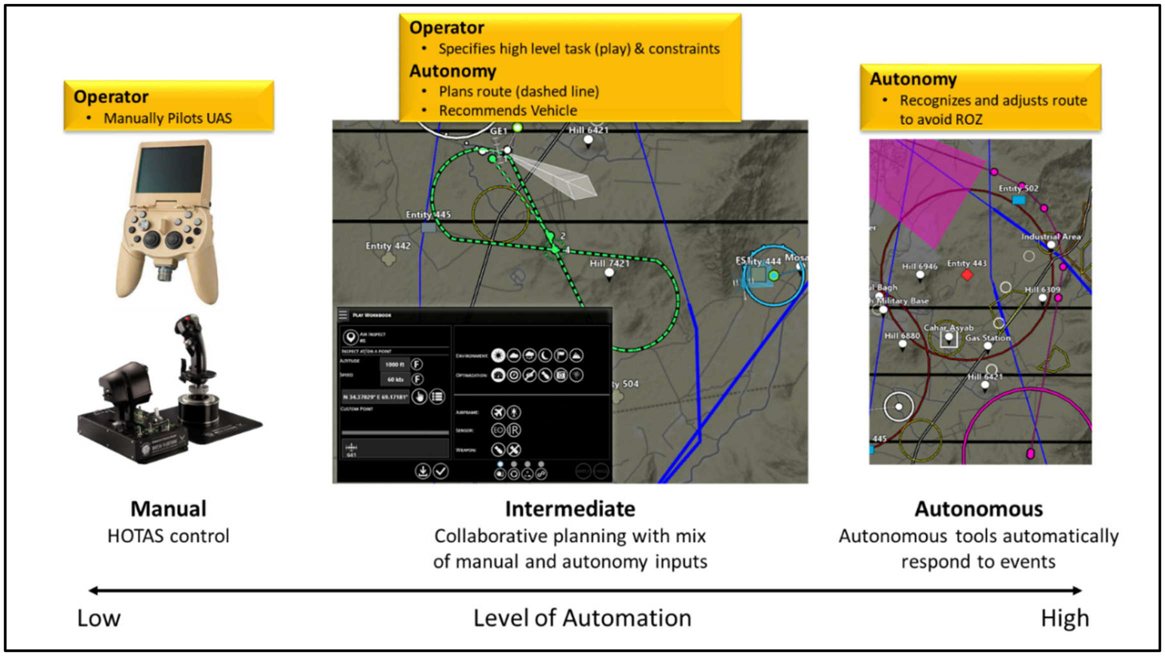


Figure 27. TECUMSA's Spectrum of Control Ranging From Fully Manual to Fully Autonomous Control

This spectrum of control is designed to enable the effective collaboration that is critical to the success of human-autonomy teams, especially in the context of complex sociotechnical systems.

VII. RESULTS AND DISCUSSION

The importance of collaboration between a human-autonomy team was central to the goal of this research. Therefore, this research followed the process of understand, generate, and validate framework employed by Reference 4 in order to develop an HAI that supports an AMC controlling multiple unmanned aircraft in the context of an air assault mission. The CWA revealed the complexity of the domain possibilities along with the boundaries on action. CWA methods using information from Army doctrine and SME interviews provided an understanding of the processes and procedures in an air assault, uncovered the general composition of an air assault team, and identified the specific tasks and duties of an AMC. The CWA began with defining the sequence of events in air assaults, that is, planning, briefing, execution, and the associated tasks of an AMC during each, for example, develop contingency plans, finalize risk assessments, and ensuring timeline adherence. Subsequently, the wagon wheel exercise was used to uncover the communication and coordination that occurs between an AMC and their surrounding team members during mission execution.

In order to generate an HAI that supports AMC performance across a range of air assault missions, TECUMSA's current autonomous capabilities were demonstrated to expert AMCs. They provided feedback on TECUMSA's HAI components, including the play calling interface, Play Workbook, and vehicle dashboard. This feedback was used to tailor existing HAI components to support air assault missions, for example, adding laser designation capability and combat power to the Play Calling Workbook optimization parameters, as well as adding new HAI components, for example, airspace deconfliction tools.

An additional goal of this research effort was to provide feedback to SUMIT's evaluation team on their proposed simulation evaluation plan. Participants generated an extensive list of questions, clarifications, and comments in response to a simulation interview in which they were guided through each simulation plan vignette. This feedback not only helped strengthen the fidelity of the simulation evaluation plan, but it deepened the team's understanding of the complex work domain and provided valuable inputs for the autonomous system development, for example, preserve sensor's last commanded stare-point even once an engage play is ended to allow for Battle Damage Assessment (BDA).

Reference 1 compares a human-autonomy team to a pair of scissors, with one blade representing the human and the other blade representing the autonomy. Regardless of the sharpness of the blades, that is, the respective abilities of the human and autonomy, the scissors' effectiveness is dependent upon the hinge or interface between them. With respect to the current research, the CWA not only helped to sharpen the blade but also polished the hinge, which is indicative of refinements to TECUMSA's autonomy capabilities and HAI.

VIII. CONCLUSION

While this initial CWA was greatly informative, it will not suffice to end analysis at this point. Air assaults are very complex work domains with many prioritization hierarchies, decision makers, scenarios, resources, and so forth. There are still a range of topics that have yet to be thoroughly investigated, including documents used in flight, for example, air movement table, route cards, Excheck, and kneeboard packets, and the range of technology and software being utilized inside of an air assault aircraft, for example, Blue Force Tracker. These additional topics will be addressed with AMC SMEs in follow-up discussions. Additionally, a spiral development method will be used in which AMC SMEs are brought in throughout the development process to test and evaluate TECUMSA as new features are added. Including SMEs throughout the design process will ensure that TECUMSA will be able to effectively support AMCs during current and future air assault MUM-T missions.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

&	and
#	number
2-D	Two-Dimensional
AATF	Air Assault Task Force
AATFC	Air Assault Task Force Commander
ACTA	Applied Cognitive Task Analysis
ADD	Aviation Development Directorate
AEW&C	Airborne Early Warning and Control
AGL	Above Ground Level
AMC	Air Mission Commander
ATR	Automatic Target Recognition
AvMC	Aviation & Missile Center
AWT	Air Weapons Team
BDA	Battle Damage Assessment
CA	Contingency Asset
CAS	Close Air Support
CCA	Cooperative Control Algorithm
CDO	Cognitive Domain Ontology
CSAR	Combat Search and Rescue
CTA	Cognitive Task Analysis
CWA	Cognitive Work Analysis
DEVCOM	Combat Capabilities Development Command
DTED	Digital Terrain Elevation Data
EO	Electro-Optical

FORCE	Future Open Rotorcraft Cockpit Environment
FS	Fire Scout
ft	foot
GE	Gray Eagle
GFC	Ground Force Commander
HAI	Human-Autonomy Interface
HOTAS	Hands-On Throttle and Stick
IA	Intelligent Agent
ICP	Initial Planning Conference
ID	Identification
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
km	kilometer
LOI	Level of Interoperability
LZ	Landing Zone
MEDEVAC	Medical Evacuation
METT-TC	Mission, Enemy, Terrain and Weather, Troops and Support Available, Time Available, and Civil
MGRS	Military Grid Reference System
MSL	Mean Sea Level
MUM	Manned-Unmanned
MUM-T	Manned-Unmanned Teaming
NAI	Named Areas of Interest
PID	Positive Identification
POI	Point of Interest

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONCLUDED)

PZ	Pickup Zone
OPS	Operations Center
QRF	Quick Reaction Force
ROZ	Restricted Operations Zone
s, sec	second
SH	Shadow
SME	Subject Matter Expert
SRK	Skill, Rule, Knowledge
SUMIT	Synergistic Unmanned-Manned Intelligent Teaming
TECUMSA	Tasking and Execution of Collaborative Unmanned and Manned Systems with Autonomy
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UH	Utility Helicopter
U.S.	United States
UV	Unmanned Vehicle
VTOL	Vertical Takeoff and Landing