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Determining Intelligence, Surveillance and Reconnaissance (ISR) system effectiveness, and integration as part of force protection and system survivability

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THESIS

DETERMINING INTELLIGENCE, SURVEILLANCE AND RECONNAISSANCE (ISR) SYSTEM EFFECTIVENESS, AND INTEGRATION AS PART OF FORCE PROTECTION AND SYSTEM SURVIVABILITY

by

Sze Shiang Soh

September 2013

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13. ABSTRACT (maximum 200 words)

Situation awareness plays a critical role in all battlefields. It monitors activities, and provides essential information about the battle. It is an operational requirement, high in demand, for the forces to fight the battle smartly and accomplishing the objectives set with minimal casualties. Situation awareness enhances survivability of the fighting forces by avoiding adversary detection and acquisition, achieved via the deployment of a variety of sensors that are part of an effective and integrated ISR system network.

This thesis analyzes the impact of ISR system effectiveness and integration on unit survivability, in the context of a combined arms unit. The study was approached using the Nearly Orthogonal Latin Hypercube to generate design points for simulation study. Map Aware Non-uniform Automata (MANA) was used to simulate the behavior of the units in the combined arms unit. During simulation, the parameters are varied to create a changing situation picture, as perceived by the troops. This determines the impact on survivability, by measuring the force exchange ratio between the RED and BLUE force, once the simulation is completed. The sensor capabilities and level of integration between the ISR sensors in the combined arms unit are analyzed based on the simulation results.

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DETERMINING INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE (ISR) SYSTEM EFFECTIVENESS, AND INTEGRATION AS PART OF FORCE PROTECTION AND SYSTEM SURVIVABILITY

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Submitted in partial fulfillment of the
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ABSTRACT

Situation awareness plays a critical role in all battlefields. It monitors activities, and provides essential information about the battle. It is an operational requirement, high in demand, for the forces to fight the battle smartly and accomplishing the objectives set with minimal casualties. Situation awareness enhances survivability of the fighting forces by avoiding adversary detection and acquisition, achieved via the deployment of a variety of sensors that are part of an effective and integrated ISR system network.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAIV	Cost As Independent Variable
CAB	Combined Arms Battalion
CAU	Combined Arms Unit
DCGS	Distributed Common Ground/Surface Systems
DoD	Department of Defense
DoE	Design of Experiment
EFP	Explosively-Formed Penetrator
FER	Force Exchange Ratio
FoS	Family of Systems
HBCT	Heavy Brigade Combat Team
IED	Improvised Explosive Device
IFV	Infantry Fighting Vehicle
ISR	Intelligence, Surveillance and Reconnaissance
ISR-ICSP	Intelligence, Surveillance and Reconnaissance-Integrated Capstone Strategic Plan
LH	Latin Hypercube
MAJIC	Multi-sensor Aerospace-ground Joint ISR Interoperability Coalition
MANA-V	Map Aware Non-uniform Automata-Vector
MBT	Main Battle Tank
MOE	Measure of Effectiveness
NIIA	NATO Intelligence, surveillance and reconnaissance Intelligence Architecture
NOLH	Nearly Orthogonal Latin Hypercube
OMOE	Overall Measures Of Effectiveness
OODA	Observe, Orient, Direct, Act
RPG	Rocket-Propelled Grenade
QFD	Quality Function Deployment

SA	Situation Awareness
SBCT	Stryker Brigade Combat Team
SoS	System of Systems
STANAG	Standardization Agreement
TAUV	Tactical Aerial Unmanned Vehicle
UGS	Unmanned Ground Station

EXECUTIVE SUMMARY

Advanced technology and capabilities enable and create opportunities to realize holistic battlespace awareness, which is a critical role in all battlefields. However, the biggest challenge remains the ability to synchronize both effectiveness and capabilities of the Intelligence, Surveillance and Reconnaissance (ISR) systems for the intended mission. Situation awareness of the battlefield needs to be achieved through effective and and proper integrated ISR network, where its effectiveness is determined by its utility to decision superiority.

While military organizations may seem obsessed with the notion of achieving ISR system integration, in reality, it is not easily achievable. Integration of a wide array of sensors is in fact challenging, if there are no appropriate measures and policies in place, such as DOTMLPF (Doctrine, Organization, Training, Materiel, Leadership, Personnel and Facilities), STANAGs (STANdard Agreements) and NIIA (NATO Intelligence, surveillance and reconnaissance Interoperability Architecture). The task of information sharing and hence integration of ISR systems based on its architecture framework, interoperability policies as well as some form of evaluation tools help to determine, if not ensure the overall effectiveness of such integration efforts.

This thesis builds upon a capstone project in Systems Engineering by studying the impact of situation awareness on ground combat unit survivability. Expanding on the capstone team's work, one of the identified functions, "Provide Situation Awareness" forms the main focus of this thesis. Additionally, through the re-use of the model and operational scenario developed by Major Tobias Treml in his thesis, the overall results of this study determine how situation awareness may impact force protection and vehicle survivability.

The study was approached using a few tools to generate the parameters for simulation analysis. One is: Model-Based Systems Engineering (MBSE) utilizing Vitech CORE® to provide the overall framework necessary for uncovering the system-level relationships of the system. With it, the ISR system architecture can be studied by

decomposing it down to its system-functions level, and by mapping out its various interactions and relationships.

Another is Quality Function Deployment (QFD) table to facilitate the translation of a set of subjective requirements into a set of system-level requirements. In this thesis, the ISR system parameters are identified and mapped, against the sub-systems in the Combined Arms Unit (CAU). The mapping reveals the parameters to be modeled under those specific sub-components. QFD table also shows traceability of the modeled parameters and their impact on mission effectiveness of the combined arms unit.

Additionally, advanced Design of Experiments (DOE), such as the Nearly Orthogonal Latin Hypercube (NOLH), was used to generate design points of these identified ISR system parameters for subsequent simulation. A total of 10,950 simulation runs were generated based on 365 design points with 30 replications each. A correlation study was carried out on the generated design points to ensure they are of low correlation.

Finally, a modeling and simulation tool such as Map Aware Non-uniform Automata (MANA) was used to simulate the behavior of the units in the combined arms unit, and by varying parameters, the impact on the unit survivability can be analyzed. During simulation, the parameters are varied to create a changing of situation awareness level received by the troops. This determines the impact on situation awareness based on the force exchange ratio between the RED and BLUE once the simulation is completed. The sensor capabilities and level of integration between the ISR sensors in the combined arms unit are analyzed based on the simulation results.

The results from the Force Exchange Ratio (FER) calculation revealed outgoing communication accuracy of Infantry and Armored Vehicles, sensor classification accuracy of Unmanned Aerial Vehicles (UAVs), the number of UAVs, as well as UAV latency to have the most influence on situation awareness. The high FER reflects lesser BLUE force being annihilated during the battle and hence implying a better flow of information among the agents during the process. The result also shows that information of interest on monitored area(s) once properly integrated and shared among the units in the combined arms unit will result in enhanced situation awareness.

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The author would like to express great appreciation to her thesis co-advisors, Professor Eugene Paulo, for his valuable, dedicated guidance and encouragement on the thesis, without which, the development of this paper would not be possible; and Research Associate Paul Berry for his advice on modeling related issues. Despite his busy schedule, his willingness to give his time so generously has been very much appreciated, and second reader Professor Douglas Nelson, for his invaluable input on this thesis and sharing on armor tactics. Their continual support and encouragement have been a very great motivational factor, without which the thesis would not have been able to be completed successfully.

The author would also like to extend special thanks to Major Tobias Treml for his insightful critiques of this thesis, his willingness to share his knowledge on modeling and generosity in providing information about his thesis model, which the author is also using as part of the study. Special appreciation to the MANA modeling team Mary Mcdonald and Stephen Upton, who have willingly advised and helped with the model inputs and advices, and Lieutenant Commander Sim McArthur for sharing extensive background knowledge on U.S. Army Tactics and weapon systems, which plays an important part in shaping the model of this thesis.

Lastly, the author would like to thank her parents for their unwavering support and encouragement throughout the course of this study. Although they are not here physically, their love and encouragement have always been the author's motivation that enables her to successfully complete the thesis.

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I. INTRODUCTION

> *"It is only the enlightened ruler and the wise general who will use the highest intelligence of the army for the purposes of spying, and thereby they achieve great results*."
>
> – Sun Tzu

Intelligence, Surveillance and Reconnaissance (ISR) is often referred to as tactical enabling operations, comprising a broad category of activities designed to support intelligence development, planning and decision-making. Its functions remain principal elements of the United States' defense capabilities (Best 2005), which include a wide variety of systems capable of acquiring and processing information needed by national security decisionmakers, and battlefield commanders. These elements make ISR systems the integral components both at the national policy, and military level (Erwin 2013). The evolution of military intelligence seemed to have emerged since the Great War, with advancement moving so remarkably that the methods and technologies adopted during that period remained throughout the twentieth century. This advancement in technologies has seen the development of aerial reconnaissance, electronic deception and cryptography (Finnegan 2009), which is believed to have triggered the evolution of modern ISR.

This collective term Intelligence, Surveillance and Reconnaissance (ISR) was aptly coined by Admiral William Owens, the Vice-Chairman of the Joint Chiefs of Staff, in the mid 1990s. During that period, integrated ISR was presented as an important component of military affairs revolution, defined by the information age and was implemented through the concept of net-centric warfare. Since the common usage in the 1990s, there were many versions of the definition of the term. Joint Publication (JP) 1-02, Department of Defense Dictionary of Military and Associated Terms defines ISR as "an activity that synchronizes and integrates the planning and operation of sensors, assets, processing, exploitation, and dissemination systems in direct support of current and future operations." The military dictionary also defines the individual terms as: "Intelligence–the product resulting from the collection, processing, integration evaluation, analysis and interpretation of available information;", "Surveillance–the systematic observation of aerospace [air, space and cyberspace], surface, or subsurface areas, places or things, by visual, aural, electronic photographic or other means;” and “Reconnaissance–the mission undertaken to obtain, by visual observation or other detection methods, information about the activities and resources of an enemy.”.

While the JP 1-02’s definition of the integrated ISR highlights the synergy interdependence of its individual components, Deptula and Brown (2008) suggest that ISR is more of an essential operational function. In today’s information age warfare, precision of engagement, and timeliness of critical information have evolved to a single, integrated process, interdependent with other operations of all the services and commands, and across all domains. ISR today makes up the vast majority of the operations required to achieve security objectives (Deptula and Brown 2008), providing the war fighter the required battlespace information.

Consider the following scenario (extracted from Henderson 1993):

> The Cavalry platoon leader views the tactical situation on his reconnaissance/strike vehicle’s visual display. Along with his semi-autonomous, robotic outrigger vehicles, he has Coalition Company. The green blip, two kilometers to his right, is a vehicle from his cavalry regiment. The blue symbol on his left is another vehicle from one of the allied armies in this combined operation. On this totally blacked out night, the mission is to reconnoiter and disable any forces found in the sector ahead and report back any reconnaissance over the real time video link to higher headquarters. A constant stream of intelligence information is pouring into each vehicle from headquarters, airborne intelligence platforms and satellite broadcasts. Only seconds to minutes old, the reconnaissance vehicle’s vetronics now displays red symbols behind the hills 4000 meters ahead. Automatic cross-correlation of data identifies the enemy as a squadron of tanks and supporting forces on the move, which must be destroyed. The highly automated targeting and weapon system on this two person vehicle has already computed firing parameters and will soon give a cue on the screen when the target is within the firing envelope. The tactical situation display in the airborne command post shows the same ground targets, as well as displaying the combined forces aircraft streaking to pounce on them in near real time. As the reconnaissance/strike vehicles fire their long range, millimeter wave, terminal homing rounds at the lead vehicles, the fighter pilots launch their long range stand-off attack weapons which will also guide themselves to their individual targets while the aircraft stay out of the range of defensive fire. Meanwhile, an airborne jamming aircraft hooked into the tactical situation net jams the enemy’s

> counter battery radar systems to mask the position of the reconnaissance/strike vehicles. Near real time weapons damage assessment collected and transmitted back from unmanned air vehicles and other sources simultaneously confirms to all parties that the enemy formation has been destroyed or disabled.

This scenario, though futuristic, depicts the inherent link between intelligence, surveillance, and reconnaissance that clearly points towards situation awareness as the common thread. It has also saliently highlighted the importance of integrated systems in order to achieve highly-effective combat success. Highly-integrated systems enable timely collection, accurate correlation and processing of information, and at the same time generating coherent and holistic battlespace awareness to the war fighters and to the Force Commander. This allows the decision maker to successfully plan, operate and preserve forces, conserve resources and accomplish campaign objectives (Deptula and Brown 2008), thus achieving force protection and vehicles survivability.

A. BACKGROUND

Armored vehicles have long concerned themselves with balancing the iron triangle of protection, lethality, and mobility as part of force protection and vehicle survivability requirements. Unfortunately, threats increasing in severity and complexity, as well as the extensive use of Improvised Explosive Devices (IEDs), Explosively-Formed Penetrators and Rocket-Propelled Grenades (RPG), have eluded the inadequacy of considering single vehicle enhancement to achieve overall system survivability.

The Capstone project team *Ground Combat Vehicle Survivability Robustness Analysis through Model-Based Systems Engineering (MBSE)*, uses MBSE to discover the system-level interconnections and relationships, to achieve integrated survivability of the armored vehicle(s), as part of a combined arms unit (Capstone Cohort 311-114G 2013). The four functions identified under the Capstone project are: (1) Avoid Penetration; (2) Provide Mobility; (3) Provide Lethality; and (4) Provide Situation Awareness. Although each of these categories possesses possibilities in impacting the overall survivability of the unit, the focus of this thesis will only be centered on the last type: Provide situation awareness. The objective of studying this category of survivability is how situation awareness can be achieved through the (effective) use of ISR systems, within the context of a traditional combat scenario. Achieving situational awareness, “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley 1995, 36), “has been recognized as a critical, yet often elusive, foundation for successful decision-making across a broad range of complex and dynamic” (Rajant 2013, 1) environment such as the battlefield. Ensuring a high degree of situation awareness, while denying it to the enemy, has long been recognized as paramount, and involves more than just having more data than the enemy. It will require such data to be translated into the required intelligence in a timely and accurate manner, in order for effective decision to take place.

Successful integration and employment of ISR enables comprehensive situation and battlespace awareness. This is the effect sought by national-security decision makers. The success of ISR lies with whether it is able to provide timely and accurate information for such decision making. In essence, intelligence provides improved battlespace awareness for decision makers, supported by surveillance, a sustained process not associated with specific target, and reconnaissance, designed to collect information against specific targets (Bosworth 2006).

This thesis is approached using a Systems Engineering methodology to initially identify the area of interest, followed by defining the scope for the research. This thesis attempts to understand the underlying factors that influence the performance of any given ISR system and in addition, to explore the system architecture pertaining to integration of the ISR systems.

B. PROBLEM STATEMENT

While advanced technology and capabilities enable and create opportunities to realize holistic battlespace awareness, the biggest challenge remains to synchronize both effectiveness and capabilities of the ISR systems for the mission (Bosworth 2006). Situation awareness of the battlefield needs to be achieved through ISR, where its effectiveness is determined by its utility to decision superiority. The challenge is the main impetus of this thesis: *Determining Intelligence, Surveillance and Reconnaissance (ISR)* *system effectiveness and integration as part of force protection and system survivability* by: (1) deriving the requirements and hence functions of ISR systems for a ground combat mission; (2) determining the parameters that will impact ISR system effectiveness; and (3) the integration of these systems by exploring the parameters identified.

C. RESEARCH QUESTIONS

This approach to this thesis is guided by the following questions:

- What are the parameters that will impact ISR systems operational effectiveness in a ground combat mission, and how integration of these search systems can be achieved as part of force protection and system survivability?
- What are the readily available technologies that can be used to support ISR requirements?
- What are the requirements of such ISR systems in supporting such missions?
- Are there existing integration policies or implementations in place in any of the Services?
- What are the possible materiel or non-materiel approaches to improve ISR effectiveness and system integration (in particular cross-domain systems) for force protection and system survivability?

D. SCOPE

The scope of this thesis is premised on achieving situation awareness by varying the parameters that impact the effectiveness of ISR systems. The focus is centered on Army ISR systems with the operational context referenced against that of a Combined Arms Unit (CAU). The overall results of this study will determine how situation awareness will in turn affect force protection and vehicle survivability of the unit. Figure 1 shows the relationship between ISR, SA, and integrated survivability (force protection and vehicle survivability). This thesis provides a research extension to the Capstone project, which completes the holistic study approach on how the four functions identified earlier in this chapter impact the overall integrated survivability of the combine arms unit in the given scenario.

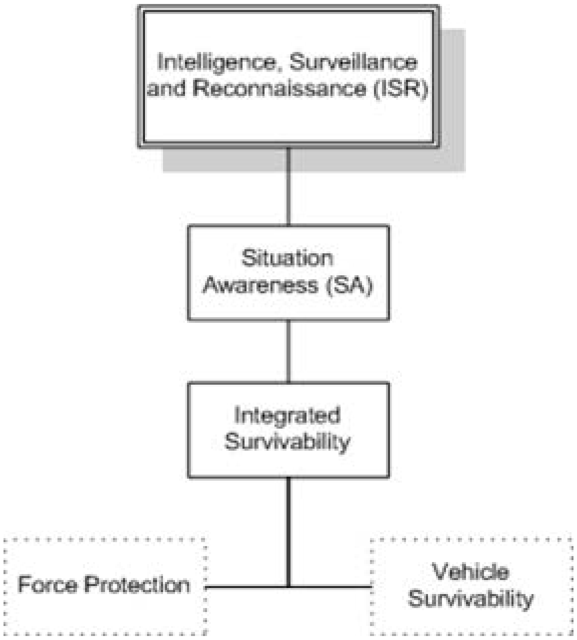

Figure 1. Flow Model Relationship between ISR and Integrated Survivability

E. APPROACH

Model-Based System Engineering (MBSE) is used in this thesis to provide the overall framework necessary for uncovering the system-level relationships of a given system. In this case, it is used to study the functional requirements of an ISR system, with the use of Vitech CORE®[1]. With it, the system architecture can be studied by decomposing it down to its system-functions level, and by mapping out its various interactions and relationships. Once that is identified, they are translated into parameters to be used in Map Aware Non-uniform Automata-Vector (MANA-V), an agent-based modeling software. MANA models the parameters according to the scenario(s) (missions) of the system, and helps to validate the assumptions made in the model and the impact on situation awareness and hence mission success of the given scenario.

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[1] CORE is a comprehensive systems engineering and project management toolset designed for efficient management of complex systems engineering problems (Vitech CORE).

F. METHODOLOGY

The thesis is divided into nine phases as follows:

- Discuss ISR Interoperability Architecture
- Define the ISR system architecture
- Identify ISR system capability needs
- Identify the functions of the ISR system and translate them into system requirements
- Translate the requirements into model-able parameters
- Define the MOEs
- Construct DOE using NOLH
- Simulate the identified parameters using MANA-V
- Analyze the results to identify the impact of the parameters on survivability according to the MOEs and scenario

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II. LITERATURE REVIEW

A. PREVIOUS WORK

As mentioned in Chapter I, this thesis builds upon a recent Capstone project in Systems Engineering by studying the impact of situation awareness on ground combat unit survivability. The operational context of both this thesis and the Capstone project is shared by another thesis titled *A Revolutionary Approach for the Development of Future Ground Combat System Specifications*, by Major Tobias Treml. The prior thesis by Major Treml and the Capstone project, are briefly discussed to give the background context to the current thesis.

1. Thesis–A Revolutionary Approach for the Development of Future Ground Combat System Specifications

Normal project acquisition process is kick-started due to systems obsolescence issues, evolving threats, and/or identified capability gaps. Since the need for new systems is centered on such factors, systems acquisition teams and program managers often find themselves dealing with changing requirements that lead to changing system specifications. The task of determining correct specifications of a system becomes more challenging, especially in an ever-changing security climate amid technological advances. In addition, determining specifications of systems might be biased, especially after simulation runs were conducted to evaluate the system performance. The design trade-space might be skewed in order to achieve certain desired property, while sacrificing others. This inaccurate system specification or skewing of design trade-space leads to the failure of some delivered land combat systems that harness good potential in survivability (for example), but are unable to perform in the real world mission. As a result, a system is designed according to the identified threat(s) or capability gap at that certain point in time. In other words, the whole acquisition process is not holistic.

Major Treml proposed looking from the perspective of Measure of Effectiveness (MOEs) as the main outcome in any acquisition project. By defining the MOEs of the given mission scenario and the desired performance (capabilities) of the new system, an un-biased conclusion can be drawn with respect to the system design. With such information, decision makers are able to visualize the trade-offs made between different factors and the defined MOEs, which will scope the specification process accordingly, hence improving the overall performance of (future) ground combat systems.

By using MANA to model a realistic scenario, using a combined arms unit as the system for this simulation, variances in parameter changes, as well as the different configurations of parameters, are recorded and analyzed. This model forms the baseline model for both the Capstone project in determining effect of survivability and this current thesis in determining the effect of ISR on situation awareness, as part of survivability.

2. Capstone Project–Ground Combat Vehicle Survivability Robustness Analysis through Model-Based Systems Engineering (MBSE)

Plagued with the need to balance the iron triangle of lethality, survivability, and mobility regarding vehicle designs of land combat systems, the Army often finds itself having to struggle with an optimal solution to the requirements. Whether it means more armor, hence compromising mobility, or having more mobility, which could also translate to enhanced survivability, such judgments are often made by subject-matter experts with limited, or non-existent, analytic metrics, that could be applied to support such design trade-offs with quantitative analysis. The Capstone project team *Ground Combat Vehicle Survivability Robustness Analysis through Model-Based Systems Engineering (MBSE),* discusses the conceptual methodology utilizing MBSE techniques to define such design trade space of a combat vehicle in the context of a combined arms unit, to uncover and understand the intricacy of the interactions within the system, with respect to integrated survivability (Capstone Cohort 311-114G 2013).

The system identified by the team for the study is compared to the operational hierarchy of an actual Combined Arms Unit (CAU) that comprises a Mechanized Infantry Company Team, which is made up of a Mechanized Infantry Platoon and a Mechanized Platoon. The breakdown of the CAU organizational tasks displayed in Figure 2 is modeled after the actual combat CAU, which form the basis for combat simulation model for subsequent study of this thesis (Capstone Cohort 311-114G 2013). This Combined

Arms Maneuver Company model comprises the Infantry Fighting Vehicle crews, Main Battle Tank crews and (Squads of a)[2] Rifle Company of a (Mechanized) Infantry Battalion, supported by a Helicopter Platoon (Section), a Howitzer Battery (Battalion) and the Tactical UAV Platoon (Section). The sub-units highlighted in green were subsequently modeled as agents in MANA to study the impact they have on integrated survivability of the combat vehicle.

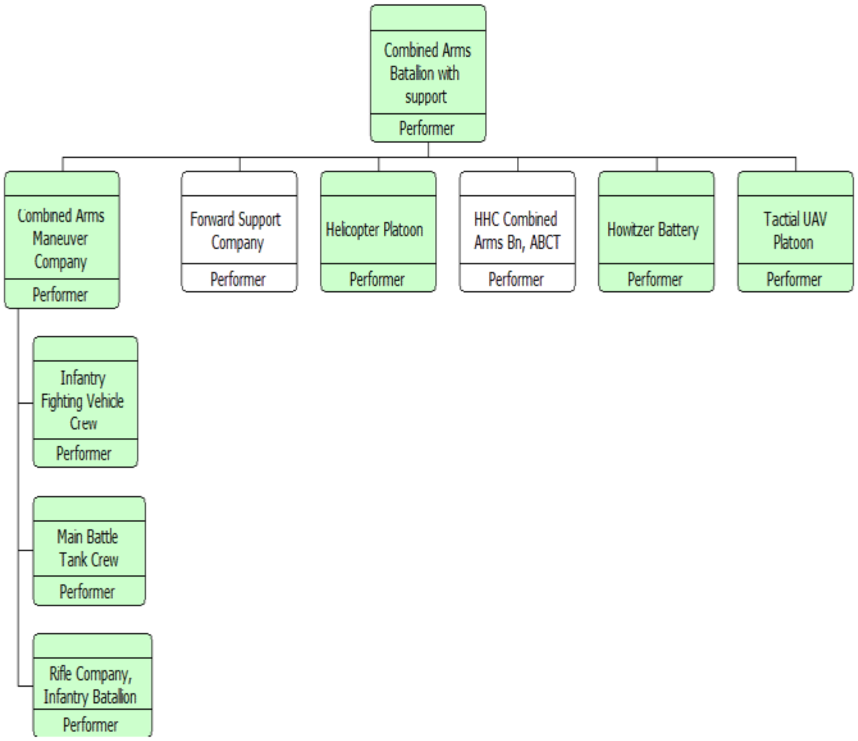

Figure 2. Organization Structure for Combined Arms Scenario (From Capstone Cohort 311-114G 2013)

The functional capabilities of a generic combat ground vehicle were investigated to provide the basis for the combined arms maneuver company's functions required to accomplish the desired objectives. Identified as one of the main functional capabilities, the "Provide Survivability" function was further defined to highlight four areas of study

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[2] The size and type of unit depicted in parenthesis is the actual representation of the real Combined Arms Unit. This differentiates the make-up between the actual and modeled Combined Arms Unit.

(highlighted in green) that were subsequently evaluated using MANA with regard to vehicle survivability enhancement (see Figure 3).

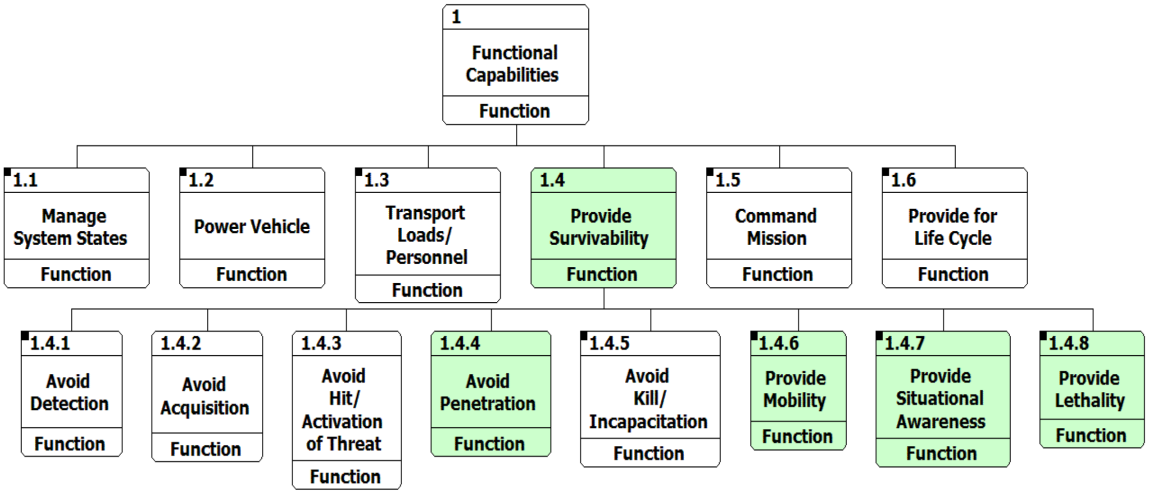

Figure 3. Functional Hierarchy for the Combined Arms Company (From Capstone Cohort 311-114G 2013)

These four sub-functions (1.4.4, 1.4.6, 1.4.7 and 1.4.8) were explored in the context of trade-space against three critical capabilities, namely: lethality, mobility, and situation awareness pertaining to survivability. The units identified earlier were used in the simulation analysis with respect to these critical capabilities in the trade-space defined. The results from the MANA simulation, together with Cost As Independent Variable (CAIV), and Overall Measures Of Effectiveness (OMOE) assessments, concluded that a materiel approach with improved detection systems (equipped with STARlite or GEN III FLIR) would yield the lowest cost with greatest enhancement to performance on survivability.

B. OPPORTUNITIES FOR FURTHER EXPLORATION

Both the thesis and report have included situation awareness as one of the modeling parameters that impacts both ground combat system specifications and vehicle survivability, albeit not in detail. The Capstone project *Ground Vehicle Survivability Robustness Analysis through Model-Based Systems Engineering (MBSE)* has indicated the possibility of survivability enhancement by increasing situation awareness capabilities in the CAU. In that study, the UAV was accorded a low probability of detection throughout the simulation, which has prevented the team from analyzing the impact of situation awareness on Force Exchange Ratios (FERs) and/or survivability. Despite that, the Capstone project has provided a good foundation for in-depth study into situation awareness, with a direct impact on the system survivability. Situation awareness enhances survivability by avoiding adversary detection and acquisition, achieved through effective and integrated ISR systems.

Using the model created by Major Treml, and re-using the operation scenario and combat units, effects of ISR on situation awareness of the battle can be determined. This will in turn give an indication of how situation awareness impacts force protection and vehicle survivability through the effectiveness of ISR systems.

In this thesis, effort is concentrated on the parameters that may impact ISR system effectiveness and integration, as part of force protection and system survivability (see Figure 4). Expanding on the Capstone team’s work, the function “Provide Situation Awareness” as part of survivability enhancement (circled in red in Figure 5) will be researched in greater detail. The combat units used in MANA simulation remained largely unchanged, with details elaborated further in Chapter V.

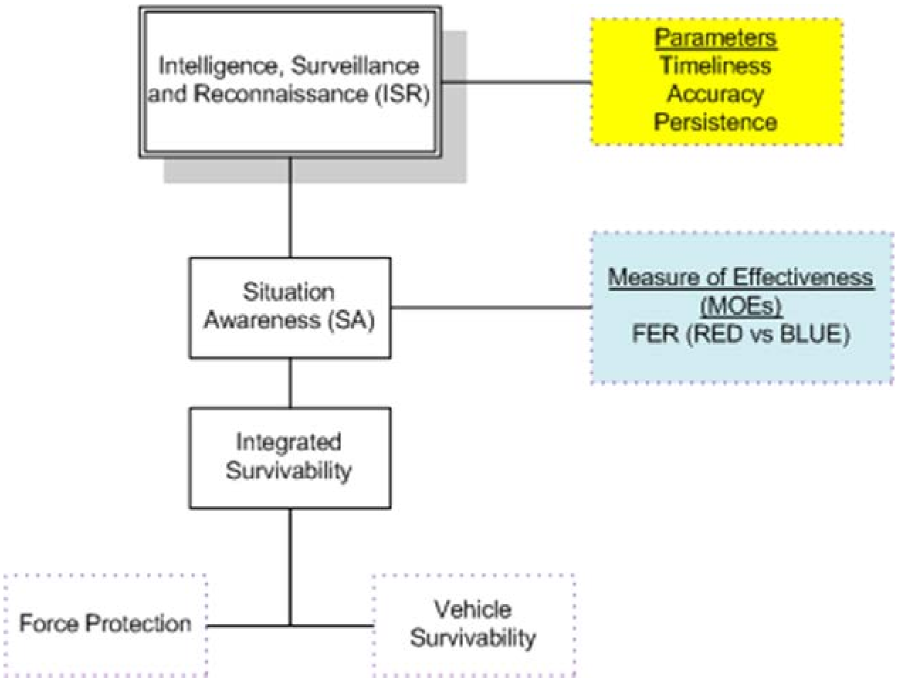

Figure 4. Flow Model Relationship, Effects and MOEs of ISR on Situation Awareness

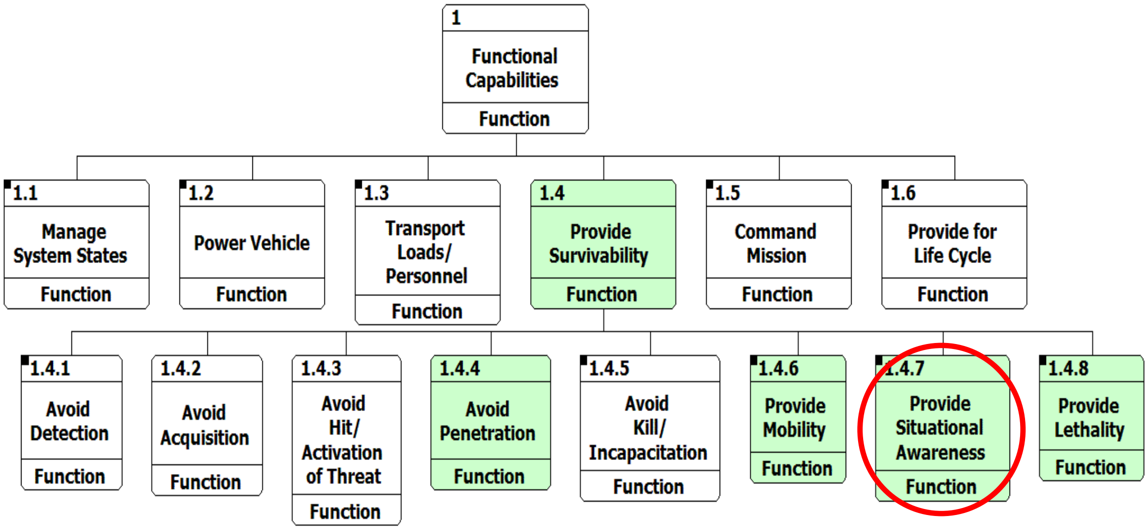

Figure 5. Functional Hierarchy for the Combined Arms Company (From Capstone Cohort 311-114G 2013)

III. ISR INTEROPERABILITY FRAMEWORK

A successful ISR Enterprise, comprising different aspects of information gathering with human and technical sources, enables the military echelons to achieve enhanced battlespace awareness that effectively meets the ground commander’s operational needs (Odierno 2008). The measure of success of such ISR campaign lies in the providence of accurate information at the right time for commanders to make sound tactical and operational decisions (Department of Defense 2007). Figure 6 depicts the ISR assets allocated to the respective echelon, from the Brigade Combat Teams up to the National level.

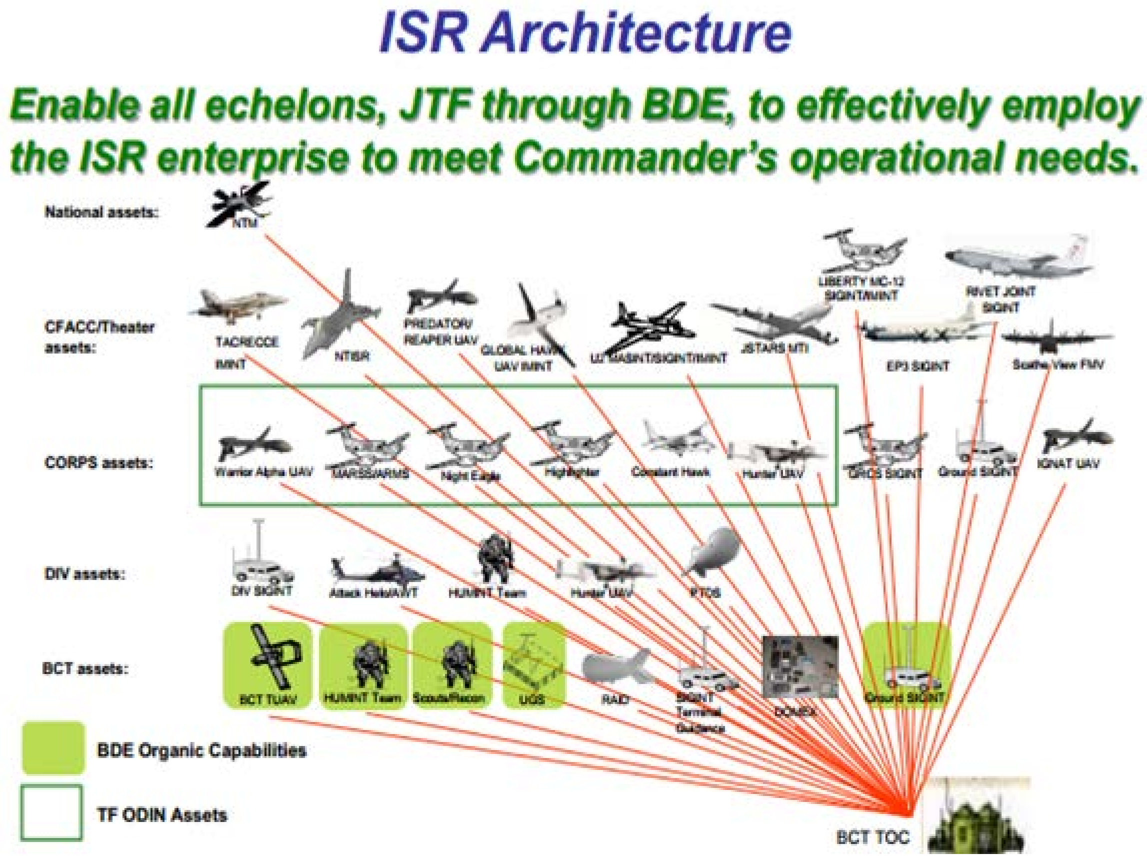

Figure 6. ISR Architecture (From Odierno 2008)

Information sharing within the ISR happens on different organizational levels, and connecting systems responsible for gathering information and exploitation systems in a large environment, can be challenging (Essendorfer 2009). While it might seem a challenge to achieve common system interfaces across the ISR assets in such a complex environment, it is not impossible. Systems capable of handling distribution of data and fusion of collected intelligence are being introduced as solutions aim at creating common awareness critical in operations and missions. The integrated system consists of protocols that include operational concepts, architecture and interoperability framework, key interfaces and formats needed to integrate multiple (including legacy and future) ISR systems (NATO C3 Agency 2007). The following sections discuss: (1) ISR system integration architecture; and (2) deployment of the ISR architecture protocols by the various ISR communities and organizations.

C. ISR SYSTEM INTEGRATION ARCHITECTURE

The goal of integration is to improve the efficiency and effectiveness of the enterprise by having all the enterprise subsystems work together harmoniously. The integration goal includes the following (Giachetti 2010):

- Improving information quality and timeliness, providing information upon demand and wherever required, regardless of the source system
- Coordinating decisions from the different stakeholders, in working towards fulfilling the overall integration efforts, thus avoiding local optimization
- Management of activities among people in the enterprise, synchronizing business processes in producing quality products and services

This integration effort can be categorized into Organizational level and System Level (see Figure 7). The system-level integration looks at the infrastructure, information, and application tiers in which the system is able to achieve interoperability with the other systems to achieve a certain degree of integration. The organizational level will look at the processes and policies mandated by the agencies and parties involved, in order for system-level integration to work effectively.

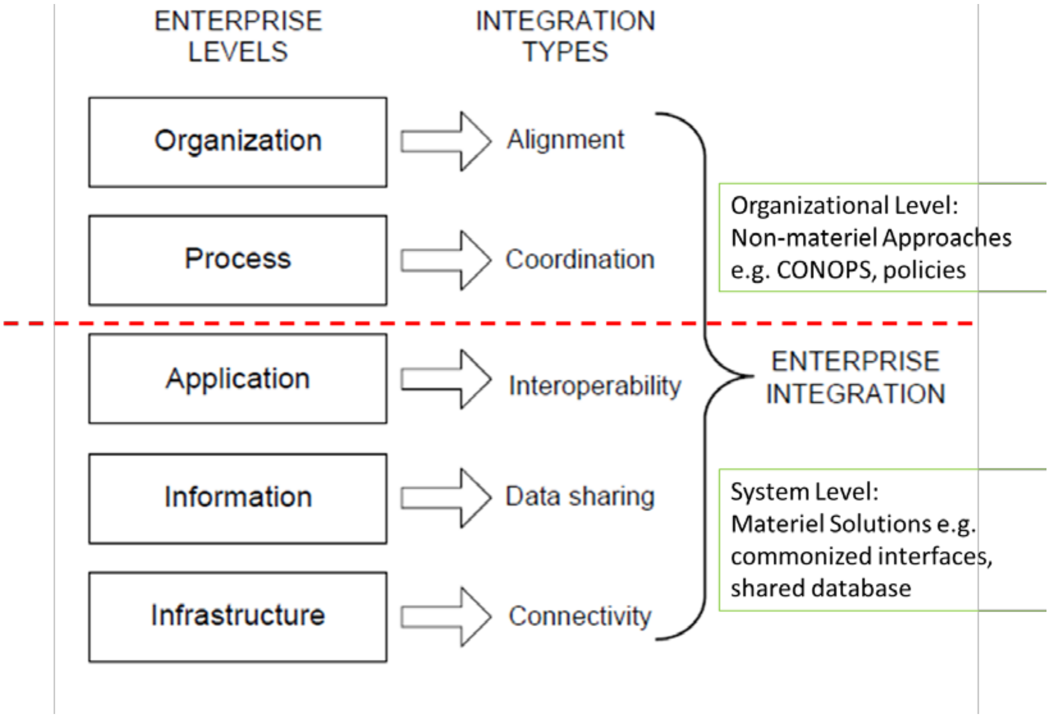

Figure 7. Enterprise Integration Architecture (After Giachetti 2010)

The system level architecture can be further broken down into three basic tiers (as seen in Figure 8):

- ISR system components – Sensors (technical systems and humans), Exploitation Systems and External Information Systems. Sensors are used to collect/gather required information on targets, and can be categorized into long-range, airborne, ground-based, and seaborne sensors. Exploitation systems are used to process and analyze the raw data collected from the sensors, sometimes together with human analysts. Information systems generate and display relevant processed data/information for situation awareness and general information sharing.
- Data formats – Military standards STANAGs and Commercial Standards such as OpenGIS® Catalogue Service. The OpenGIS® Catalogue Service is defined by the OGC (Open GIS Consortium) as a standard for data dissemination that focuses on geospatial data, related services and resources. The selection of the standards is dependent on user need and domain requirements.
- Database middleware such as COBRA for the client-server communication. It allows products to be defined and queryable, enable synchronization of information for sharing and ease of data retrieval.

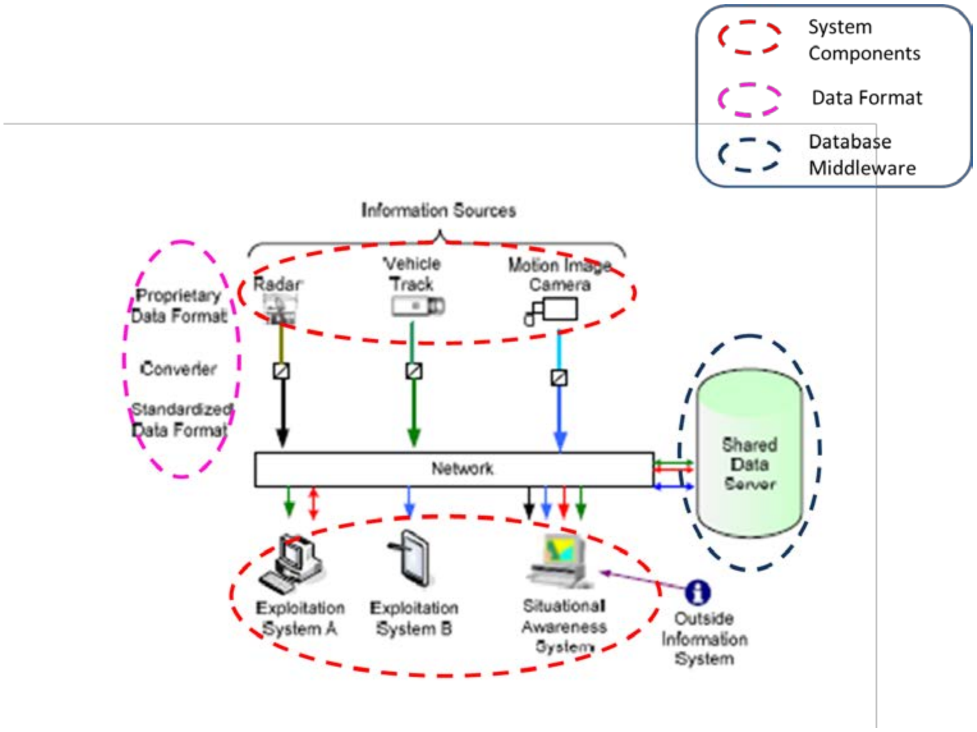

Figure 8. ISR System Integration Architecture (After Essendorfer 2009)

The information or intelligence collected by the (proprietary) ISR sensor systems will be converted (by the converters) into the selected common data format. The standardized (raw) data once transferred over the network will be stored into a local data server. The same network is also connected to a suite of exploitation systems, where they are used to process and analyze the raw data, before the processed and filtered information is again transferred and stored in the same database server. Situation awareness systems will retrieve and generate the selected intelligence picture to support decision makers.

The architecture set-up is scalable and can be modularized in the case of coalition operation. The sensor systems and server can be ‘sub-netted’ to be belonging to certain region or nation participating in the operation. In addition, the local database server can also be utilized to perform other tasks other than data storage, such as data fusion, data clarification/extraction and target recognition. Such architecture flexibility was exercised and implemented in several organizational levels, as discussed in the next section.

D. ISR ARCHITECTURE PROTOCOLS

1. NATO Intelligence, Surveillance and Reconnaissance Integration Architecture (NIIA)

The NATO ISR Interoperability Architecture (NIIA) defines the overall structure of the elements of the ISR community across all levels of NATO and coalition operations, including war operations, peacekeeping, and peacemaking campaigns. It covers the standards developed by NATO Air Group IV[3], as well as commercial and international standards applicable to ISR mission (North Atlantic Treaty Organization 2005). Covering both IMINT and now SIGINT (ELINT reporting format only), the architecture seeks to achieve data interoperability between the NATO assets at Degree 2–Structured Data Exchange, involving human-interpretable structured data intended for manual and/or automated handling, but requires manual compilation, receipt, and/or message dispatch. The architecture focuses on the ISR interfaces between airborne and surface-based elements, and between the outputs of the surface-based elements. This electronic interoperability is achieved via the development of NATO Standardization Agreements or STANAGs. These STANAGs define the processes, procedures and conditions for interoperable interface to the equipment from the members of the alliance, without altering the internal architecture of the individual system architecture. Some of the STANAGs developed were as follows (see Table 1).

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[3] The NATO Air Force Armaments Group (NAFAG) is one of the three Main Armament Groups subordinate to the Conference of National Armaments Director (CNAD). Through its subordinate Level 2 Groups and Working Groups NAFAG is responsible for promoting multinational co-operation and standardization in the area of aerospace armaments via joint activities and information exchange.

STANAG	Description
STANAG 3377	Air Reconnaissance Intelligence Report Forms
STANAG 4545	NATO Secondary Image Format (NSIF)
STANAG 4559	NATO Standard Imagery Library Interface (NSILI)
STANAG 4575	NATO Advanced Data Storage Interface (NADSI)
STANAG 4586	Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability
STANAG 4607	NATO Ground Moving Target Indicator Format (GMTIF)
STANAG 4609	NATO Digital Motion Imagery Standard
STANAG 4633	NATO Common ELINT Reporting Format
STANAG 5500	NATO Message Text Formatting System (FORMETS)
STANAG 7023	NATO Primary Image Format (NPIF)
STANAG 7024	Air Reconnaissance Tape Recorder Standard
STANAG 7085	Interoperable Data Links for Imaging Systems

Table 1. List of NATO STANAGs

The NIIA facilitates some degree of interoperability among the subordinate architectures that may be required to interoperate with the ISR architecture in theatre wide operations. As more intelligence sources are included into the architecture, together with advances in technology and concept of operations, the architecture becomes more complex and complete at the same time. While currently the NIIA only comprises formats for SIGINT and IMINT, it will grow over time to include also other forms of intelligence, as shown in Figure 9.

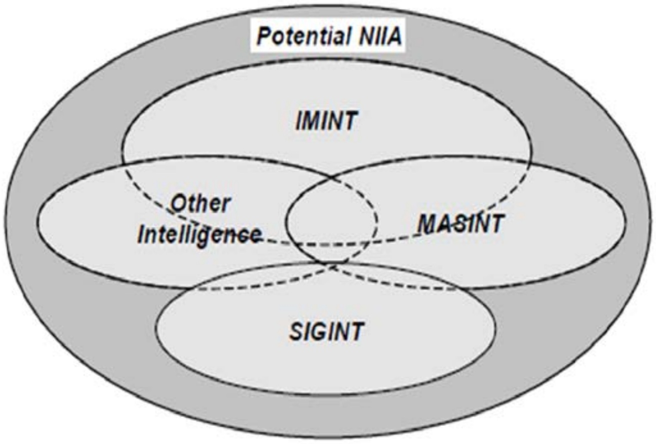


Figure 9. Envisaged NIIA as the Overarching ISR Architecture (From North Atlantic Treaty Organization 2005)

These NATO standards are mapped into the International Standards Organization (ISO) 7-Layer Interface Model, to reflect how they can work in-conjunction with commercial and international standards, while at the same time identifying the gaps for future implementation (see Figures 10 and 11), that show how the NATO STANAGs works in ISR system interfaces, and their relationship with ISO 7-Layer Interface Model.

Despite the fact that such architectures were developed to allow access to shared intelligence among the NATO members in coalition operations, it is significant to note that they are also applicable to non-NATO coalition operations. In fact, the NIIA framework can even be extended to other ISR missions, since the assets and the operations conducted are essentially the same.

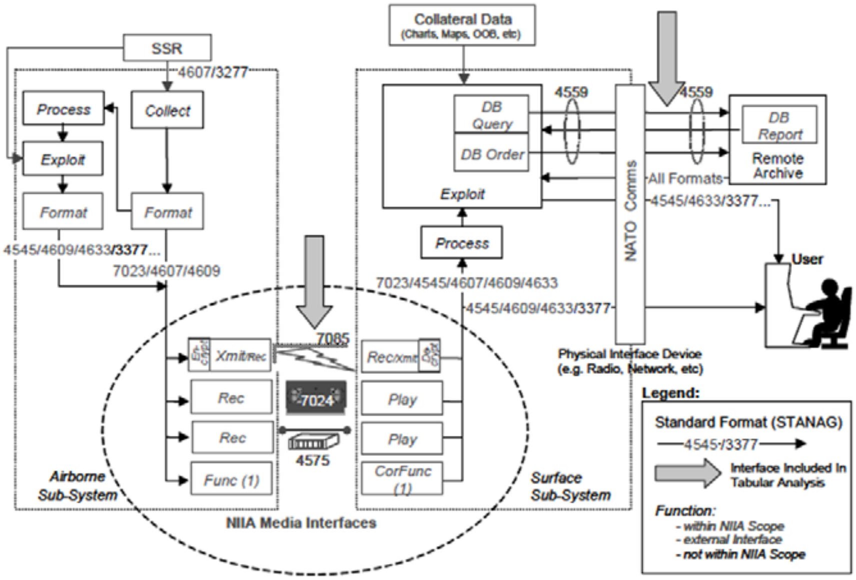
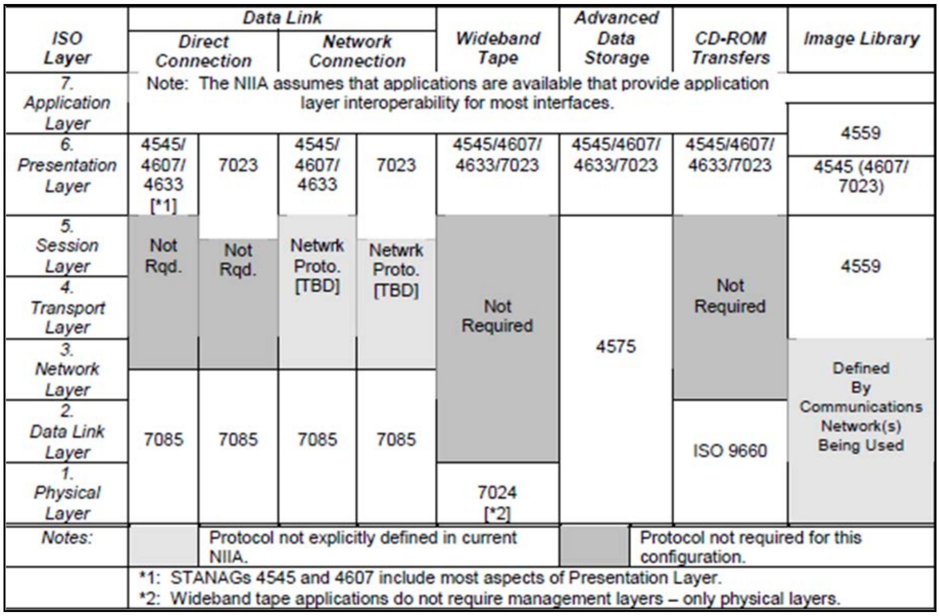


Figure 10. NATO ISR System Interfaces (From North Atlantic Treaty Organization 2005)



ISO Layer	Data Link				Wideband Tape	Advanced Data Storage	CD-ROM Transfers	Image Library
	Direct Connection		Network Connection					
7. Application Layer	Note: The NIIA assumes that applications are available that provide application layer interoperability for most interfaces.							4559
6. Presentation Layer	4545/ 4607/ 4633 [*1]	7023	4545/ 4607/ 4633	7023	4545/4607/ 4633/7023	4545/4607/ 4633/7023	4545/4607/ 4633/7023	4545 (4607/ 7023)
5. Session Layer	Not Rqd.	Not Rqd.	Netwrk Proto. [TBD]	Netwrk Proto. [TBD]	Not Required	4575	Not Required	4559
4. Transport Layer								
3. Network Layer								Defined By Communications Network(s) Being Used
2. Data Link Layer	7085	7085	7085	7085			ISO 9660	
1. Physical Layer					7024 [*2]			
Notes:	░	Protocol not explicitly defined in current NIIA.				▓	Protocol not required for this configuration.	
	*1: STANAGs 4545 and 4607 include most aspects of Presentation Layer. *2: Wideband tape applications do not require management layers – only physical layers.							

Figure 11. ISO 7-Layer Model Mapping of ISR Interfaces (From North Atlantic Treaty Organization 2005)

2. Multi-sensor Aerospace-ground Joint ISR Interoperability Coalition (MAJIC)

The MAJIC is a multi-national effort to enable interoperability between NATO and national ISR and C2 systems through the use of common interfaces for data formats and exchange mechanisms. Working with nine nations[4] under a Memorandum of Understanding (MOU), its aim is to improve commander's situation awareness by developing and evaluating operational and technical means for ISR assets interoperability in the coalition environment. MAJIC has since created an interface based on STANAG 4559 (NATO Standard ISR Library Interface) for metadata-based access to archive data from any Coalition Shared Database (CSD) in the MAJIC environments. With the development of the CSD and CONOPs for coalition ISR operations, the MAJIC also provides a means for the DoD, intelligence and coalition communities to assess new ISR net-centric data sharing concepts and solutions (NATO C3 Agency 2010).

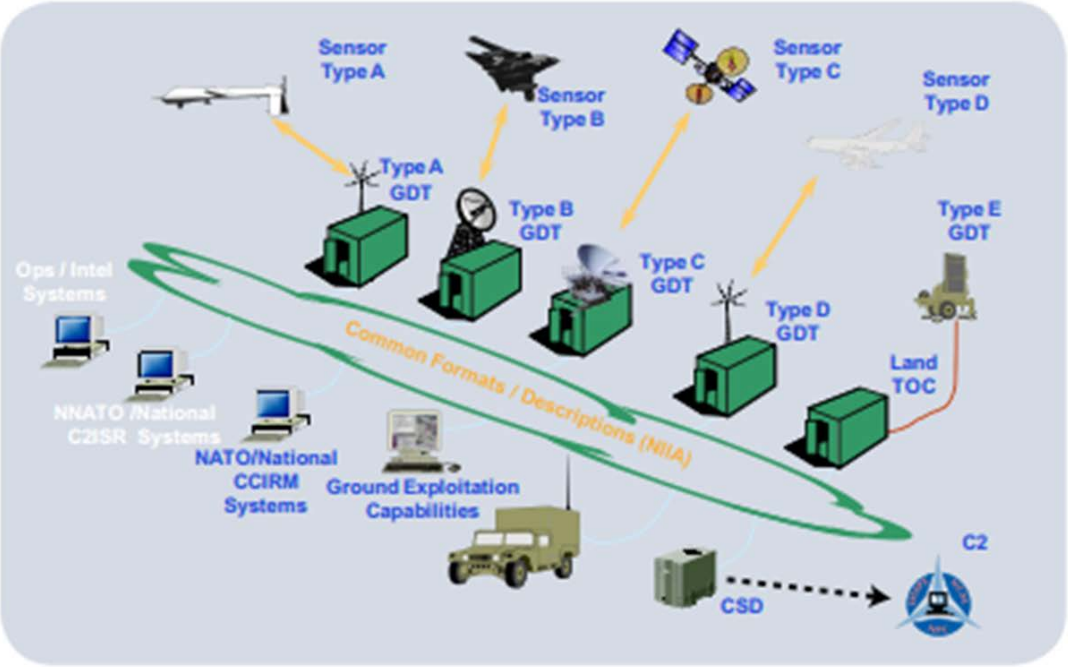


Figure 12. Coalition Network Environment (From (NATO C3 Agency 2010)

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[4] The nine nations are namely Canada, France, Germany, Italy, Netherlands, Norway, Spain, United Kingdom and the United States of America.

3. DoD Distributed Common Ground/Surface System (DCGS)

Within the DoD, a Distributed Common Ground/Surface System (DCGS) program was established in 1996 as a strategy to achieve interoperable systems and an initiative to guide interrelated service and DoD agency programs in achieving interoperable multi-ISR processing and exploitation capability. In essence, it is an ISR system that processes and exploits U.S. and selected coalition sensor data (Army, Navy, Airforce, Marine Corps, USSOCOM) (Martin 2009). It generates consumable intelligence within the ISR Enterprise and is part of the evolution to being net-centric capable. Under this framework, each Service's fielded ISR capabilities will be interoperable with the Joint ISR architecture, despite the Services' differences in requirements of getting data distributed at the tactical level (Ground and Surface Systems) (Martin 2009). Similar to the NATO and MAJIC, the DCGS has common elements such as hardware components, standards, applications, joint documentation and governance structure to facilitate interoperability (Martin 2009). These points of interoperability allow each Service's FoS to share information outside of the DoD DCGS network, without having to be connected to the services outside of it. This is achievable by mandating that the Service's FoS be interoperable with the pre-defined core set of platforms and sensors (Corsano 2003).

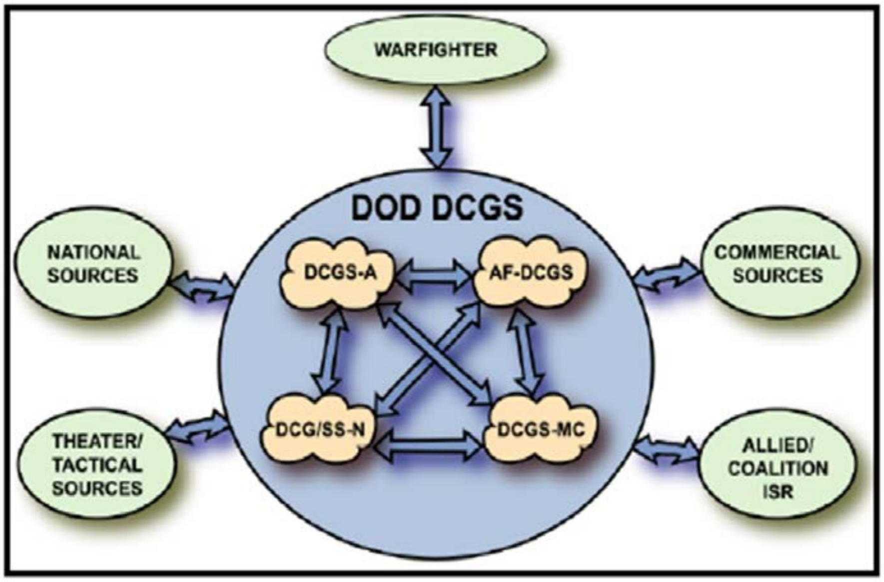

Figure 13. DoD DCGS Concept (From Joint Requirements Oversight Council 2003)

The DoD DCGS program currently comprises a DCGS Integration Backbone, the Block 10.2 Multi-INT Core developed by the Airforce and the DCGS-A, the Army’s single integrated ISR ground processing systems (Airforce Programs 2004). The Block 10.2 is part of the Airforce’s initiation to improve its DCGS capability and to achieve a multi-INT, distributed exploitation capability.

The DCGS Integration Backbone is both a software architectural framework and a developer’s toolkit. It provides the tools, standards, architecture and documentation for the DCGS community to achieve a multi-INT, network centric environment with the interoperability and flexibility of access to information for mission execution (Corsano 2003). As seen in Figure 14, it comprises a Repository Layer, a Service Layer and a Viewer Layer that facilitate scalability and backward compatibility to legacy systems, as well as an integrated information management process that employs metadata tags for data association (Corsano 2003).

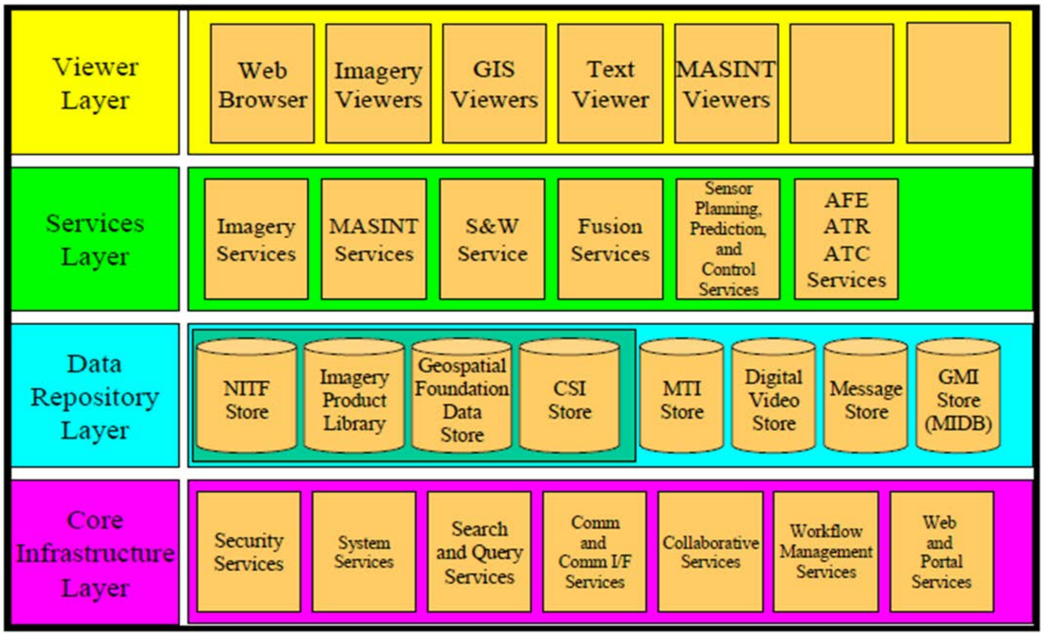

Figure 14. DCGS Integrated Backbone Layers (DIB, DTIC.mil)

The deployment of the ISR interoperability architecture and framework discussed thus far (NIIA, MAJIC and DoD DCGS) has provided good insights to some of the technical implementation measures, on top of operational concepts to achieve systems interoperability. The NIIA implements common interface standards or STANAGs across the NATO nation systems; MAJIC implements a common shared database (CSD) for members of the coalition force, while the DoD mandates a common integration backbone that binds the Service's FoS. Depending on the level of integration or interoperability framework desired, the ISR architecture is selected and implemented accordingly to mission and organizational needs.

III. SYSTEM DESCRIPTION

A. ARMY FORCE STRUCTURE AND RELIANCE ON ISR

Following the DoD's guidance to increase networking and interoperability within and between the Services, the respective Service's DCGS were developed, and in particular for the Army, the establishment of three DCGS-A Blocks under the DCGS program: fixed, mobile and embedded. The change in the future force structure of the Army reduces it from a large heavily armored force to a much smaller and more maneuverable lighter force[5]. This implies an increased demand on battlespace situation awareness, achieveable with ISR systems that encompass multi-INT sensor capability, having powerful correlation/fusion algorithm of multiple sensor data to produce an integrated situation picture that facilitates real-time sensor-to-shooter decision processes, and supports timely battle engagements. Extracted from the Objective Force in 2015 White Paper, the change in force structure leading to greater dependence on ISR assets can be seen in the Army's Operational Concept, based on the following seven principles:

- Net-centric, knowledge based
- Manned and unmanned ground-air systems
- Integrated, fused multi-INT and non-multi-INT sensors
- Multi-skilled, adaptive soldiers and civilians
- Assured access to and interdependent with Joint and National Intelligence systems
- Robust reach and project
- Visualization at the point of decision

The Army's reliance on the ISR systems and the dependence on information operations are evident. In fact, as technology advances and evolve, a successful battle of the future is one that allows fluid allocation and reallocation of ISR systems based on

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[5] *The Objective Force in 2015 White Paper* has revealed the future Army to be a hybrid capability fighting force, comprising five Units of Employment (UE), 15 units of Action (UA), six Stryker Brigade Combat Teams (SBCTs), two 1/3 Digital Division Corps, and a combination of heavy, light and specialty forces brigades (airborne, air assault, Special Forces), USAR units and four Multi-Functional ARNG Divisions (Riggs 2002). While this approach has evolved, it is useful to explore its emphasis on ISR for survivability and force protection.

capabilities and intelligence needs during the different phases of the battle, and no longer depends on the Services that "own" them nor the platform they are mounted on. Using the net-centric environment framework (Figure 15), the relation between ISR systems and unit survivability can be mapped accordingly (Figure 16):

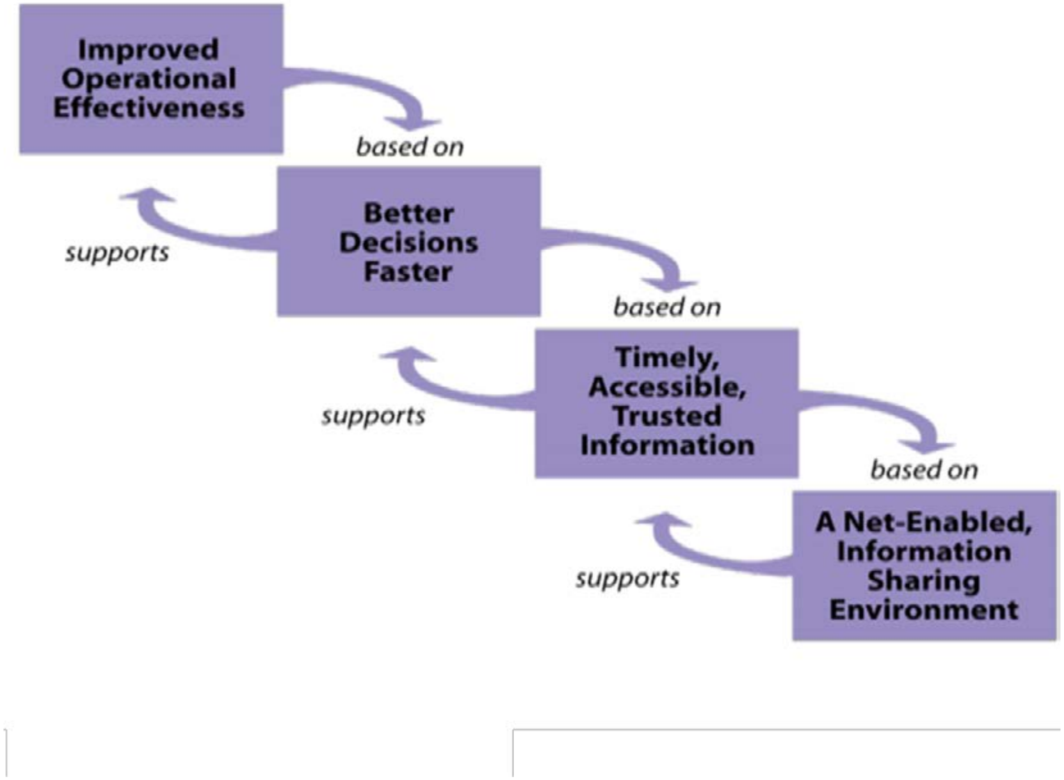

Figure 15. Net-Centric Environment (NEC) (From Zavin n.d.)

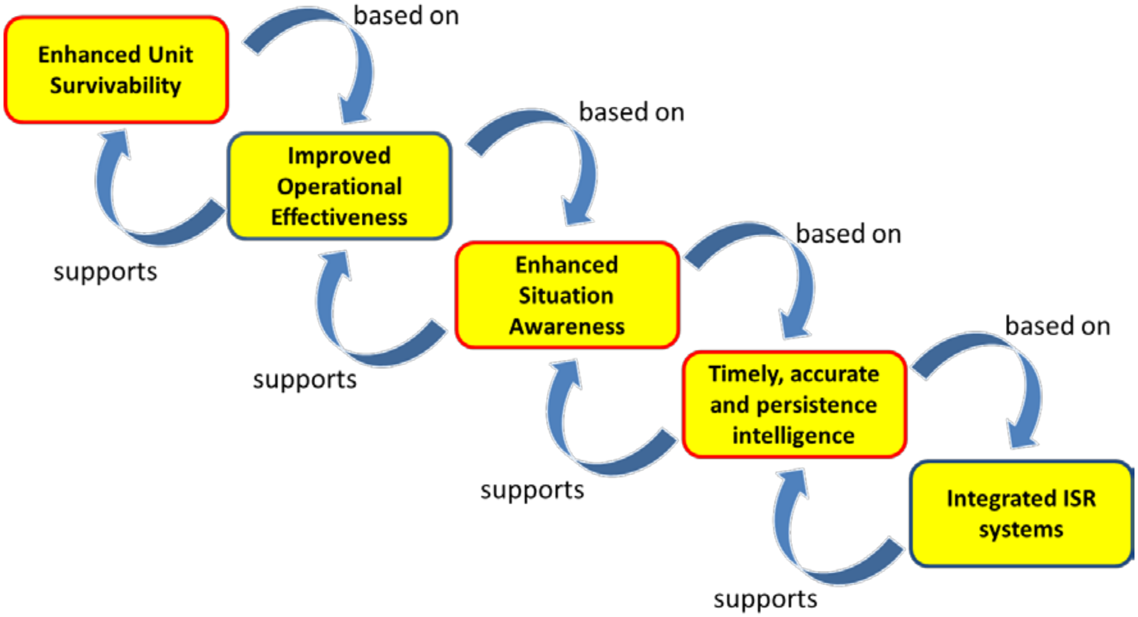

Figure 16. Impact of ISR parameters on Unit Survivability

Discussion in the subsequent sections and chapters will be centered on one slice of the combat unit within the Army. By analyzing the unit's ISR systems, the study will determine the impact of these organic ISR systems on the outcome of the battle, and the overall survivability of the unit. This result based on one slice within the Army can subsequently be promulgated to a level higher or even extend to a larger slice within the Army or other Service, to study the impact of a larger integrated ISR systems within another similar set-up.

B. GROUND COMBINED ARMS UNIT

The system of interest here is modeled after the actual Combined Arms Unit (CAU). The combat model of the Combined Arms Maneuver Company comprises the Infantry Fighting Vehicle crews, Main Battle Tank crews and Rifle Company of an Infantry Battalion, supported by a Helicopter Platoon, a Howitzer Battery and the Tactical UAV Platoon. (see Figure 17, units highlighted in green). The respective sub-units are further broken down to the component levels, highlighting the specific weaponry and combat vehicles forming the sensors under the ISR domain.

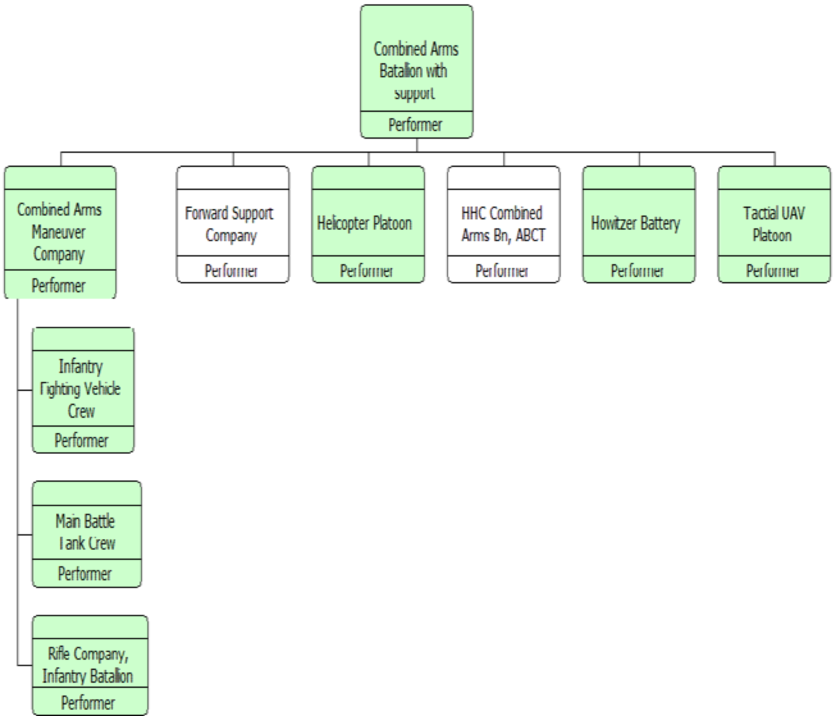

Figure 17. Organization Structure for Combined Arms Scenario (from Capstone Cohort 311-114G 2013)

Since the focus of this thesis is studying the impact of ISR systems on the situation awareness of the battle and hence unit survivability, sensors that provide critical real-time intelligence are of special interest. As such, the study will not consider the helicopter platoon and howitzer battalion by nature of their CONOPS, where they are more likely to act upon the intelligence received rather than actively hunting for it. The following units are hence singled out for further analysis into their ISR system functions:

- The land combat vehicle system
    - Main Battle Tank (Abrams M1A2) – The M1 Abrams main battle tank has the ability to close with and destroy enemy forces on the integrated battlefield using mobility, firepower and shock effect. The M1A2 is a modernization program that includes a commander’s independent thermal viewer, an improved commander’s weapon station, position navigation system, a distributed data and power architecture and an embedded diagnostic system and improved fire control systems (Army Military Features n.d.). New features also include “second generation thermal imaging gunner’s sight with increased range; driver’s integrated display and thermal management system, and a digital data bus and radio interface unit providing a common picture among the M1A2s on the battlefield” (The Armor Site 2012, 1).

Figure 18. M1A2 Abrams Main Battle Tank (From The Armor Site 2012)

- Infantry Fighting Vehicle (Bradley M2A3) – The Bradley fighting vehicle is designed for the mobility; it also protects infantry troops when transporting them to critical battlefield areas (Military Analysis Network 2000). Equipped with a digitized on-board subsystem, and an Army Technical Architecture (ATA) compliant C2 software suite allow the mechanized infantry units to share battlefield information with the rest of the M1A2 SEP-equipped[6] armor units (Military Analysis Network 2000). This digitization upgrade enhances situational awareness and survivability by automating the fault reporting, diagnostics and crew functions. The improved Bradley is also equipped with an array of sensors such as an Improved Bradley acquisition system (IBAS), commander's independent viewer (CIV), and a GPS enabled position navigation system for enhanced target acquisition and engagement, and situation awareness.

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[6] The M1A2 System Enhancement Package (SEP) was an improvement of the M1A1 with commander's independent thermal viewer, weapon station, position navigation equipment and a full set of controls and displays linked by a digital data bus. The M1A2 SEP added digital maps, Force XXI Battle Command Brigade and Below (FBCB2) capabilities.

Figure 19. Bradley Infantry Vehicle (From Military Analysis Network 2000)

- Tactical Aerial Unmanned Vehicle (TAUV) – The RQ-11 Raven is a lightweight unmanned aircraft system designed for rapid deployment and high mobility. Capable of producing live-coverage videos for soldiers to get real-time, up-to-date and over-the-horizon views in area of interest, it has a flight endurance of 60 to 90mins (using rechargeable battery) and an effective operational radius of about 10km (6.2miles). This UAV has a flying speed of 32km/h to 81km/h at an operating altitude between 30m and 152m (Army-Technology.com 2012).

Figure 20. RQ-11 Raven UAV (From Aero Vironment 2013)

- The Bradley Infantry Soldiers – Assumed to be similarly equipped as the Cavalry scouts such as the armored HMMWVs, the Long Range Advanced Scout Surveillance System (LRAS3) enables the soldiers to be able to quickly locate enemy attack forces and relay the information back to tanks.

C. CAPABILITY NEEDS

Combined Arms uses the capabilities of each warfighting function and information in complementary and reinforcing capabilities. It multiplies Army forces' effectiveness, and is a success formula involving both highly trained soldiers and integrated information systems (Department of the Army 2012). The criticality of the integrated systems in fulfilling the generation of near real-time information on areas of interest, objects and people as part of battlespace awareness depends on the capability needs described as follows:

- Timeliness – The ability to present information and data at the required, appropriate time. Timely intelligence has a huge impact on the commander's decision-making ability. It enables the commander to react responsively to situations, creating confusion and disorder in the adversary, thereby gaining an upper hand over the enemy. Timeliness is key to creating strike initiative and leverage in a battle.
- Accuracy – The fidelity of obtained information with respect to actual enemy activity. This is a powerful force enhancer where military planning and execution can proceed with confidence, and is a necessary condition for victory (Payton 1993).
- Persistent Surveillance – The persistence from ISR systems allows commanders and decision makers to monitor activities on a constant basis and determine a pattern of life. This enables better planning and the ability to respond in an effective manner (Bosworth n.d.).

D. SYSTEM REQUIREMENTS

The key design considerations and implementation of the ISR systems, critical in meeting the capability needs, are captured in Table 2. They formed the variables that will be modeled in determining the impact on situation awareness of the combined arms unit in the given operational scenario.

Capability Needs	Implemented by
Timeliness	• Latency of information dissemination systems
Accuracy	• Outgoing communication links • Sensors detection capability
Persistence	• Endurance of UAV • Number of UAVs

Table 2. Capability Needs and System Requirements

E. MISSION

A well integrated ISR system platform enhances battlespace awareness and facilitates decision making. Especially so in a land campaign where range is usually limited, ISR systems provide substantial intelligence of the battlefield over what could be achieved from a single sensor system. As such, the deployment of ISR systems in a combined arms set-up aims to achieve comprehensive and holistic situation awareness, hence providing force protection and system survivability.

F. OPERATIONAL VIEW (OV) – 1

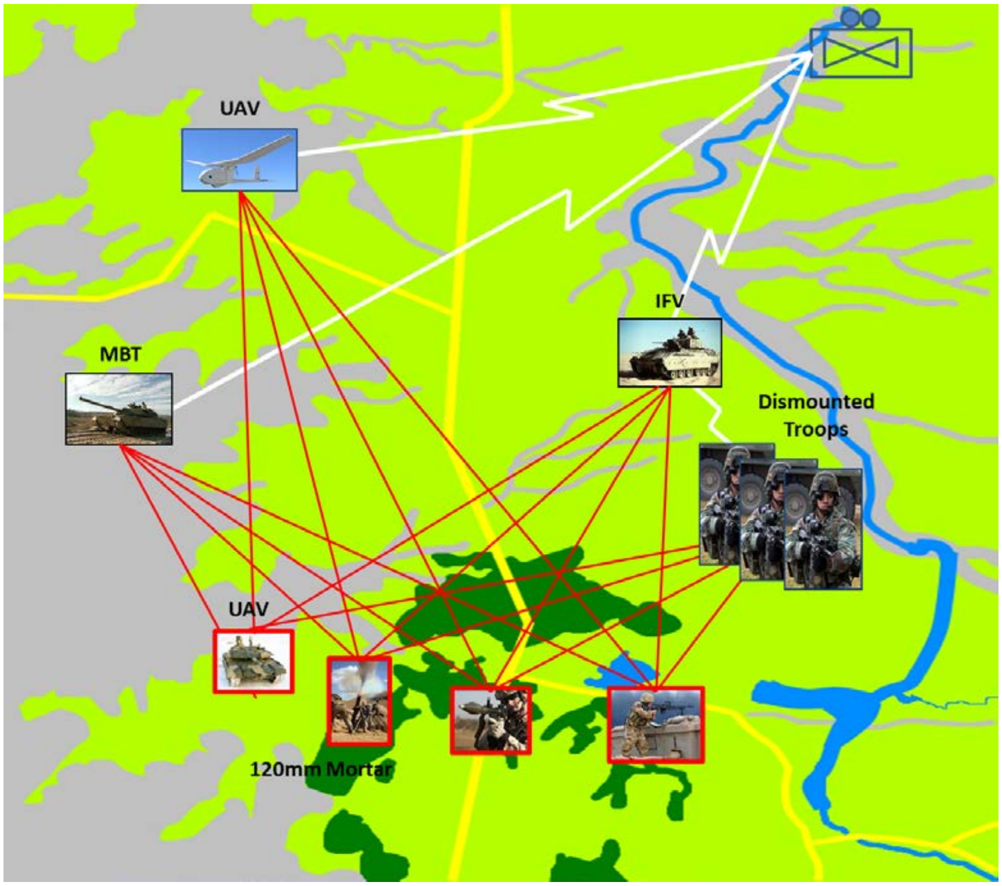


Figure 21. OV-1 of the Combined Arms Unit

The operational view depicts the interaction that take place between the BLUE force (ISR systems in place) and the RED force during the battle. The bolts in white represent the communication links between the ISR systems and the CAU HQ. This form of communication is two-way, where the intelligence from the troops and vehicles will be updated to the HQ command center. Similarly, intelligence of interest to any particular units will be sent from the HQ to the unit. The process will take place throughout the conduct of the battle. The red lines indicate the interaction between the forces (detection of enemies). Of note here is that the Bradley dismounted troops are only able to send intelligence information back to their vehicles and not to the CAU HQ direct.

G. CONTEXT DIAGRAM

The context diagram for this system is reflected in Figure 22. The interactions between the RED force, ISR systems (BLUE force) and the CAU HQ shown in OV-1 are shown to identify the specific parameters affecting information transfer, which could impact the overall unit situation awareness. These parameters are studied via simulation as part of this thesis.

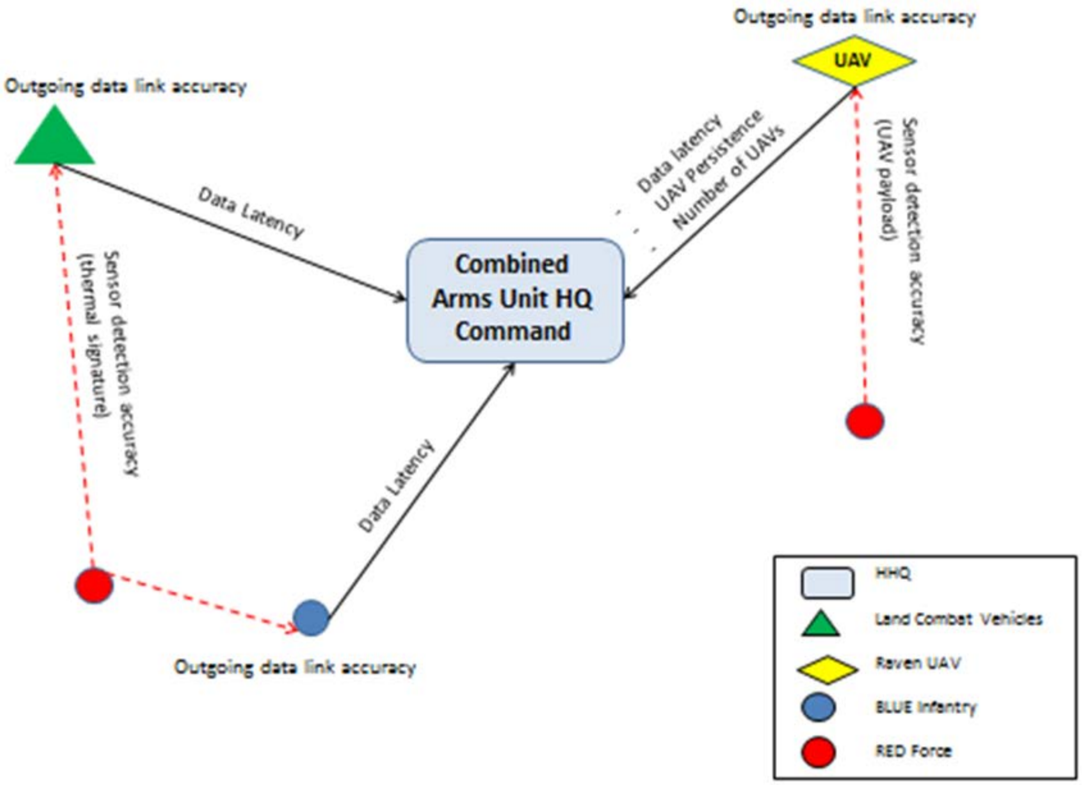
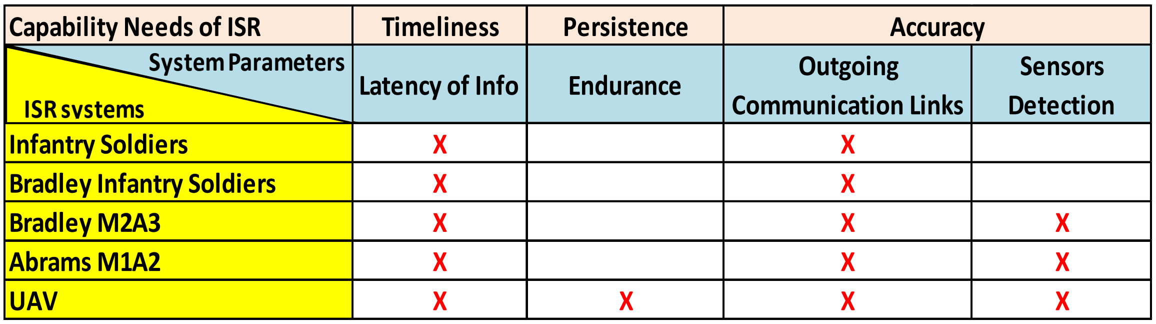


Figure 22. Context Diagram of the CAU ISR Systems

H. QUALITY FUNCTION DEPLOYMENT (QFD)

With capability needs and system parameters identified, what is required now is the mapping of the needs to the parameters, against the sub-systems in the CAU. The mapping reveals the parameters to be modeled under those specific sub-components. The Quality Function Deployment (QFD) is one method used to facilitate the translation of a set of subjective requirements into a set of system-level requirements (Blanchard 2011).

The translation is shown in the matrix form in Table 3. This QFD table shows traceability of the modeled parameters and their potential impact on mission effectiveness of the combined arms unit.



Capability Needs of ISR	**Timeliness**	**Persistence**	**Accuracy**	
System Parameters **ISR systems**	**Latency of Info**	**Endurance**	**Outgoing Communication Links**	**Sensors Detection**
Infantry Soldiers	X		X	
Bradley Infantry Soldiers	X		X	
Bradley M2A3	X		X	X
Abrams M1A2	X		X	X
UAV	X	X	X	X

Table 3. QFD for ISR Capability Needs

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IV. MODELING AND SIMULATION

The study uses Nearly Orthogonal Latin Hypercube (NOLH) experimental design to examine all possible combinations of the parameters identified in the QFD in Table 3. These parameters are subsequently refined into “variants” during results analysis for better understanding of their impact on situation awareness, which contributes to the overall unit operational effectiveness and survivability of the troops and vehicles.

A. VARIANTS

The parameters identified to have impact on ISR system effectiveness and integration are grouped accordingly into two variants: Sensor effectiveness variant, and the Common Operating Picture (COP) variant (Horn 2002). The sensor effectiveness variant looks at performance of sensors in generating information advantage for the BLUE force. As such, system parameters affecting ISR sensor accuracy in identifying and engaging the adversary are studied under this variant. The COP variant is used to simulate the effects of sensors integration and the overall changes in situation awareness of the combined arms unit. Here, system parameters affecting the timing and building up of information or situation picture are studied under this variant.

1. Sensor Effectiveness

Two sensor functionalities are identified under this variant – sensor detection and classification accuracy and outgoing communication links accuracy. These functionalities are used as surrogates for full sensor capability of the ISR systems, since they are modifiable in MANA. Enhancing sensor capability should have a positive impact on the ISR systems, hence improving the COP, situation awareness and overall Force Exchange Ratio (FER) of the unit (Horn 2002).

This variant is examined across a range of values defined for the simulation. The response behavior of the simulation is investigated to determine the level where COP is enhanced, as well as where further enhancement on sensors effectiveness no longer has an improved effect on overall unit survivability.

2. Common Operational Picture (COP)

The COP variant is used to study the outcome of sensor integration and the overall changes in situation awareness by manipulating the timeliness and persistence involved in building up the operational picture. The three functionalities identified are persistence of UAV, the number of UAVs and latency of information. The persistence of the UAV determines the flow of the information being updated to the COP; the number of UAVs implies the extent of coverage and hence the comprehensiveness of the COP. Lastly, the latency of information from the various sensors determines the timeliness and criticality of intelligence flow that impacts the mission effectiveness.

The value of ISR system integration is explored using this variant because the output of the disparate sensors can only be collated or fused to form a common situation picture when there is (effective) integration in place. The parameters to be examined under this variant are evaluated at the predefined ranges. The detailed discussion of the variables at the different levels takes place at a later section.

B. DESIGN OF EXPERIMENT

Design of Experiment (DOE) is a tool used for selecting the set of parameters by which an experiment is being performed, by controlling the trade space for the levels of factors. By considering all the variables simultaneously and making deliberate changes or modifications to them, the effects on the response over a wide range of values can be measured. This multivariable testing overcomes traditional experimental method by eliminating the inefficiency and inability in determining the effects that are caused by several factors in combination, therefore allowing a causal predictive model to be determined (Telford 2007).

A design matrix is constructed with every column corresponding to a factor to be investigated and each row representing a design point. Five fundamental principles are applied in DOE when constructing such a matrix, thus improving the efficiency of experiments (Telford 2007). These principles by Telford 2007 are briefly described below:

- Randomization – Protects against results distortion due to an unknown bias. An example of bias could be an instrumental drift used to compare a baseline procedure to a modified one. This can be eliminated by randomizing the testing order to average out the bias.
- Replications – Increases sample size and is one of the methods to increase precision of the experiment. It increases the signal-to-noise ratio by eliminating the noise from the uncontrolled nuisance variable.
- Blocking – Another method for increasing precision by removing the effect of known nuisance factors. However, blocking is a restriction of complete randomization since both the baseline and modification procedures are applied to the same block of design or experiment. In this way, batch-to-batch variability is removed from the "experimental error", hence improving precision.
- Orthogonality – Results in factor effects being uncorrelated and hence more easily interpreted, since they are varied independently of one another. The main results can be computed by taking the differences of averages.
- Factorial experimentation – The effects due to each factor and to the combinations of the factors are estimated. Factorial designs are constructed geometrically and factors are varied simultaneously and orthogonally. They can be full or fractional depending on whether the data are collected from all of the vertices of a cube or from specific subsets of all possible vertices. These designs increase precision because of the built-in internal replication. The difference in factorial experimentation is shown in Figure 23 below:

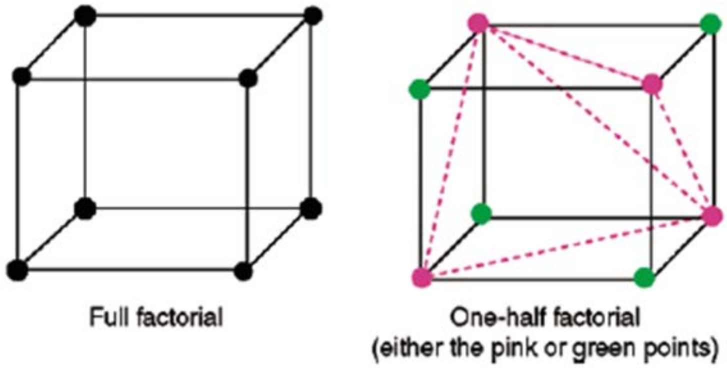


Figure 23. Full Factorial and One-Half Factorial in Three Dimensions (From Telford 2007)

Two types of commonly used design under Factorial Designs are namely 2^k Factorial Design (Coarse Grids) and m^k Factorial Design (Finer Grids). 2^k factorial designs sample at the vertices of a hypercube defined by the factors' low and high settings, whereas the m^k factorial designs reveal more factors interactions by sampling more of the spaces within the cube, which is otherwise known as having better space-filling properties. Despite the greater detail provided by the factorial designs, they are not good experimental designs due to massive data requirements (Sanchez 2005). As such, smarter and more efficient types of experimental designs is desired to achieve the end results of exploring the interactions among the factors of interest, yet keeping the experimental design simple.

Latin Hypercube (LH) is one design which offers flexibility of constructing efficient designs for quantitative factors, exhibiting some of the space-filling properties of factorial designs yet requiring orders of magnitude less sampling. Figure 24 shows the comparison on the degree of factor interactions between 2^k, m^k factorial designs and Latin Hypercube.

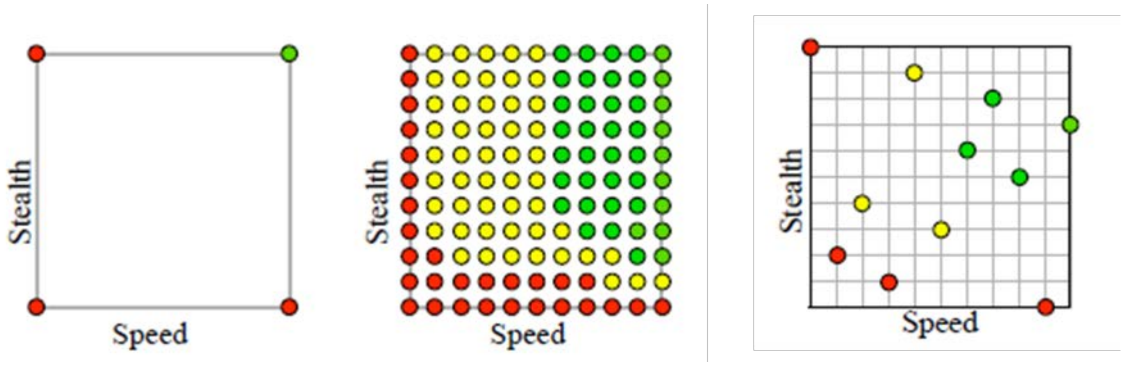
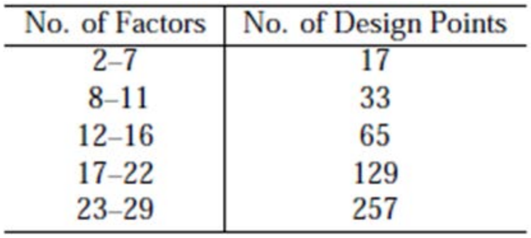


Figure 24. Degree of Factors Interactions between the 2^2, 11^2 and Random LH Designs (After Sanchez 2005).

C. NEARLY ORTHOGONAL LATIN HYPERCUBE (NOLH)

Latin hypercubes are good general-purpose designs for exploring complex simulation models when there is insufficient knowledge about the response surface (Sanchez 2005). Unlike the 2^2 factorial design where there is limited information in the center of the cube, and without the overwhelming details from the 11^2 factorial design, LH provides substantially accurate results at just a fraction of the sampling cost ($N = 11$ vs $N = 121$ of the 11^2 factorial design) (Sanchez 2005). In order to overcome the high pairwise correlation that exist for small LH designs where N is smaller than k, Cioppa and

Lucas 2005 developed tables that allow the so-called Nearly Orthogonal Linar Hypercube (NOLH) designs to exhibit good space-filling and orthogonality properties, even for small and moderate *k*, as shown in Table 4.



No. of Factors	No. of Design Points
2–7	17
8–11	33
12–16	65
17–22	129
23–29	257

Table 4. Data Requirements for NOLH (From Sanchez 2005)

Correspondingly, the space-filling property of the NOLH compares favorably with that of factorial design, and allows dramatically lesser design points to be investigated (see Figure 25).

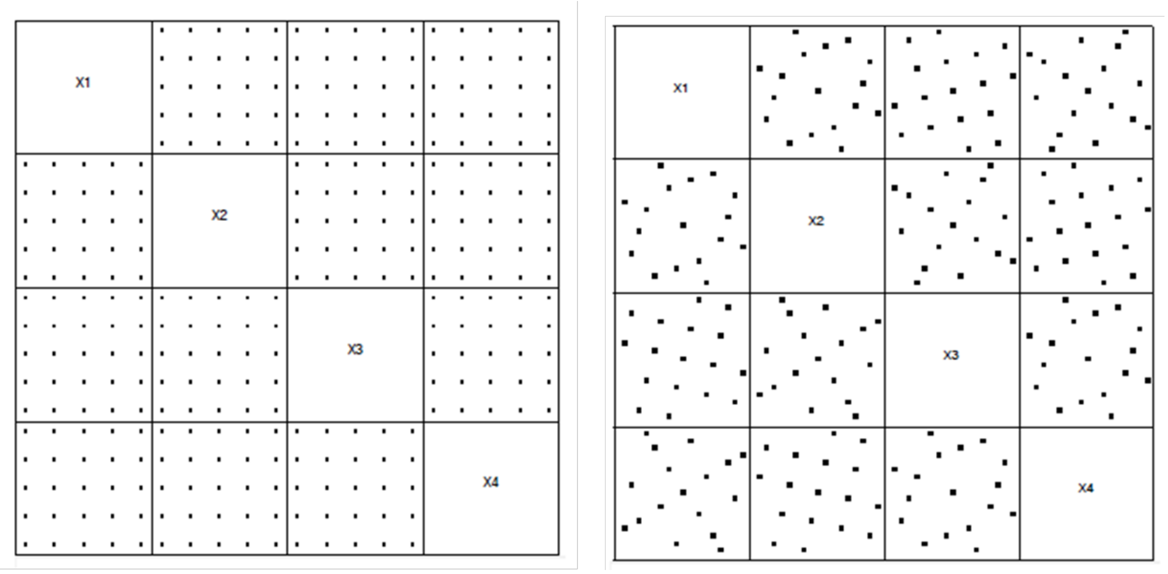


Figure 25. Scatterplot Matrix for a 54 Factorial Design (left) compared to a NOLH Design (right) with same four factors in 17 runs (After Sanchez 2005)

NOLH is used in this thesis to investigate the interactions between the identified ISR system parameters on the impact of unit survivability. The measurable outcome of the simulation Force Exchange Ratio (FER) will be determined for each run of the design points generated based on the desired number of factors. The FER will give an indication of unit survivability and the corresponding factors influencing it.

D. OPERATIONAL CONCEPT AND SCENARIO

The operational scenario is extracted from Major Treml's thesis, referenced against a division-level TRADOC scenario known as the Multi-Level Scenario MLS1.0 (Brown et al. 2009). The specific scenario used for the simulation refers to Phase II of the operation–International Border restoration. It shows the attack of a reinforced mechanized infantry company of the 7 HBCT (Heavy Brigade Combat Team) against parts of a mechanized battalion based on a fictitious scenario taking place in Colorado, United States. Figure 26 shows the tactical overview of the scenario.

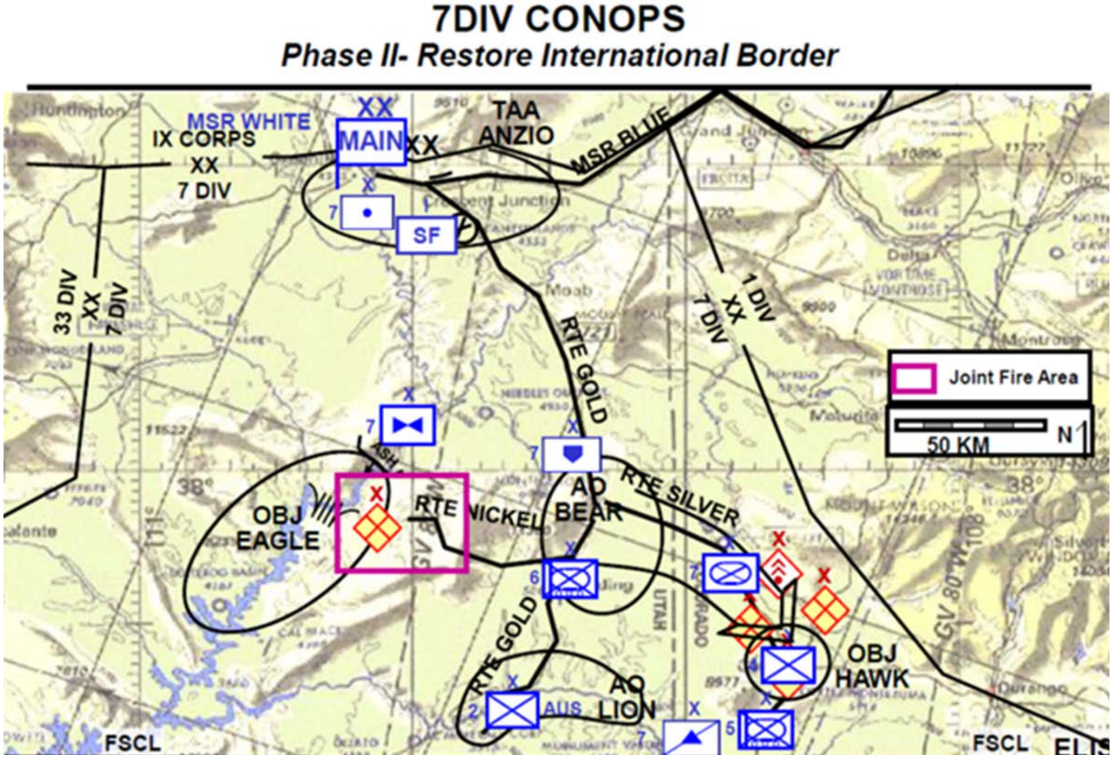


Figure 26. Division Level CONOPS of the chosen TRADOC Scenario (From Brown et al. 2009)

This scenario is chosen to illustrate a realistic battlefield environment that depicts a full spectrum of warfare. The diverse force structure of the scenario models closely the actual doctrine of a combined arms unit, with the most advantaged major ground vehicles and joint combat arms systems operationally deployed.

1. BLUE Force Concept of Operation

The mission of the BLUE force is to secure Objective 1, as a precursor for an attack by the Combined Arms Battalion (CAB) against Objective HAWK, as part of the overall main effort towards border restoration. Quoted from Capstone 2013, the BLUE force is attacking along a major highway 30km south towards Objective 1. With the BLUE force (comprising one mechanized platoon, one tank platoon) as the point company, it is the Battalion's main effort in securing the area and hence has task priority over indirect fire support from 155mm howitzer as well as priority on one medium UAV from the Battalion's UAV assets for intelligence gathering while enroute to the objective. The operational plan is shown in Figure 27.

Figure 27. BLUE Force Operational Plan From (Treml 2013)

2. RED Force Concept of Operation

The mission of the RED force is to deter and destroy the BLUE force from their fortified and concealed position with IEDs and mines. Its concept of operation is divided into three phases: ambush, hit and run and the main battle. Figure 28 shows the RED defense plan. The phases of the battle are described as follows:

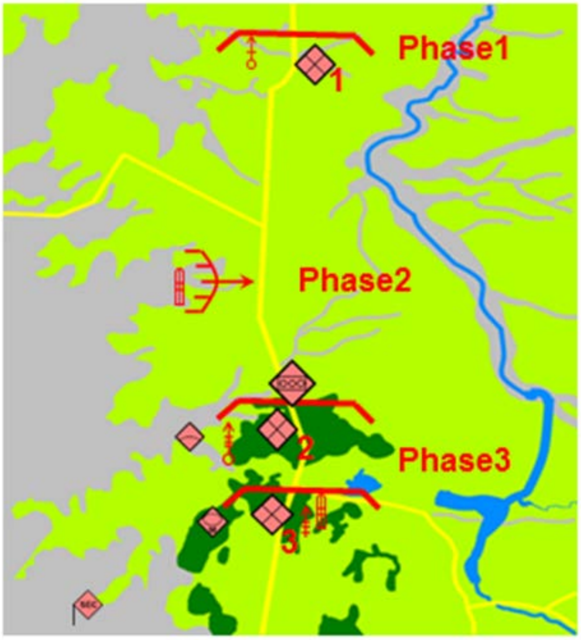


Figure 28. RED Force Defense Plan (From Treml 2013)

Phase I: Ambush – A form of attack by fire or other destructive means from concealed positions on a moving or temporarily halted enemy (Department of the Army 2001). In this scenario, the enemy does not have the firepower to defeat the BLUE force, due to BLUE having firepower superiority. Hence the aim of the ambush is to inflict casualties on the BLUE force as much as they can. The RED force is assumed to conceal very well despite the open terrain, while the BLUE force advances towards their objective with their main battle tanks first.

Phase II: Hit and run – This phase of battle entails engagement of long-range, precision attack of two RED MILAN anti-tank systems on the BLUE force. In continuation of Phase I, this is done to inflict more damages to the BLUE force and at the same time to create a psychological effect on the BLUE's morale.

Phase III: The Main Battle – This phase contains the main action. The RED fights from prepared, concealed positions with heavy mortars providing indirect fire support and their T90M tanks cutting the lines of advancement of the BLUE. Both the RED and the BLUE have complete lines of communication to their company headquarters and have access to continuous and updated common situation picture.

The simulation is modeled according to the three phases described in the RED defense plan. Such an approach is taken to simulate the different fighting tactics involved in a full spectrum of war all within one scenario, so as to eliminate the need to generate a variety of scenarios across the same set of parameters change. This keeps the DOE relatively simple and neat, since the intent of the simulation is to analyze the influence of system parameters change on the defined MOEs.

The main battle phase is the focus of the simulation, as it is usually the most critical phase of any battle. The BLUE force has suffered attrition during the first two phases of the battle and hence the real available forces and assets remaining during the main battle are crucial to the fight. During this phase, the sensors are deployed full force in providing critical intelligence updates to the ground troops. The capability of the ISR sensors will have a significant impact on the outcome of the battle and such outcome is often readily felt and will tilt the scale of the whole battle.

E. MEASURES OF EFFECTIVENESS

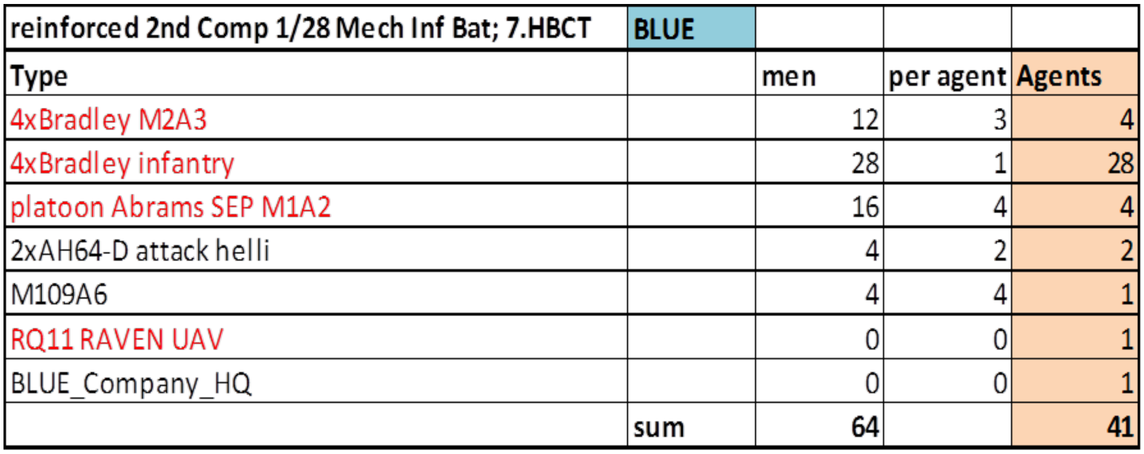
Measure of Effectiveness (MOE) is defined as "*operational measures of success that are closely related to the achievement of mission or operational objectives; i.e. they provide insight into the accomplishment of the mission needs, independent of the chosen solution.*" (Roedler 2005). Effectiveness measures are mission and scenario dependent, and hence for this chosen scenario, the operational goal of the ISR system is to provide enhanced situation awareness that leads to improved performance. Since mission performace involves friendly forces defeating enemy forces in ground combat, the primary MOE for this study is the Force Exchange Ratio (FER), which is considered to be the best measure for simple attrition analysis (Horn 2002). For this thesis, it is defined as the ratio of percentage RED loss to percentage BLUE loss, and therefore ratios greater than 1.0 implies a situation favorable for the BLUE. The formula for the FER can be computed as shown:

$$FER = \frac{NumberofREDkilled / TotalRED}{NumberofBLUEkilled / TotalBLUE} \tag{1}$$

Enhanced sensor capabilities and system integration should have a positive impact on the MOE (high FER). This implies well-integrated ISR systems are in place, and hence a well-networked environment. This allows battlefield information to reach the ground units and command HQ efficiently, which is critical especially during the main battle phase, where the fight and firepower is mainly concentrated.

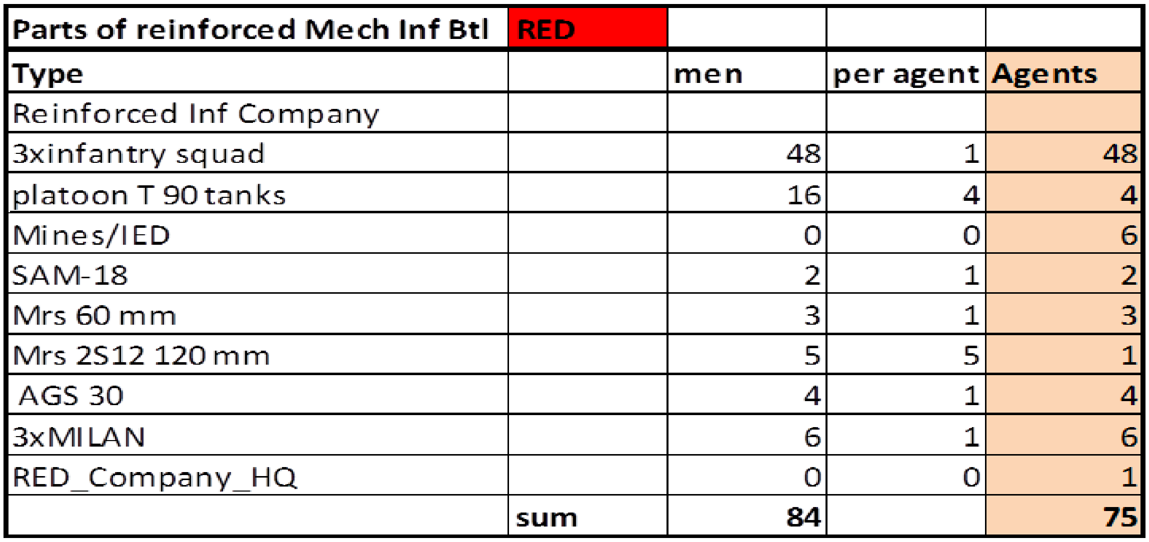
F. BASELINE MODEL

This thesis uses the baseline model, developed by Major Treml, as a starting point for subsequent parameter modification to suit the objectives of this study. Parameter change relating to ISR systems is introduced to determine the impact on situation awareness of the battlefield. The following tables show the agents make-up of the baseline model, designed by Major Treml, to achieve a 30%-50% BLUE loss while achieving some RED victories. The types of agents remained unchanged throughout the simulation and the quantity reflected in the tables serves as the start state for the simulation study. The figures are expected to change once the simulation starts to run from Phase I through to Phase III of the battle.



reinforced 2nd Comp 1/28 Mech Inf Bat; 7.HBCT	BLUE			
Type		men	per agent	Agents
4xBradley M2A3		12	3	4
4xBradley infantry		28	1	28
platoon Abrams SEP M1A2		16	4	4
2xAH64-D attack helli		4	2	2
M109A6		4	4	1
RQ11 RAVEN UAV		0	0	1
BLUE_Company_HQ		0	0	1
	sum	64		41

Table 5. BLUE Force Composition (From Treml 2013)



Parts of reinforced Mech Inf Btl	RED			
Type		men	per agent	Agents
Reinforced Inf Company				
3xinfantry squad		48	1	48
platoon T 90 tanks		16	4	4
Mines/IED		0	0	6
SAM-18		2	1	2
Mrs 60 mm		3	1	3
Mrs 2S12 120 mm		5	5	1
AGS 30		4	1	4
3xMILAN		6	1	6
RED_Company_HQ		0	0	1
	sum	84		75

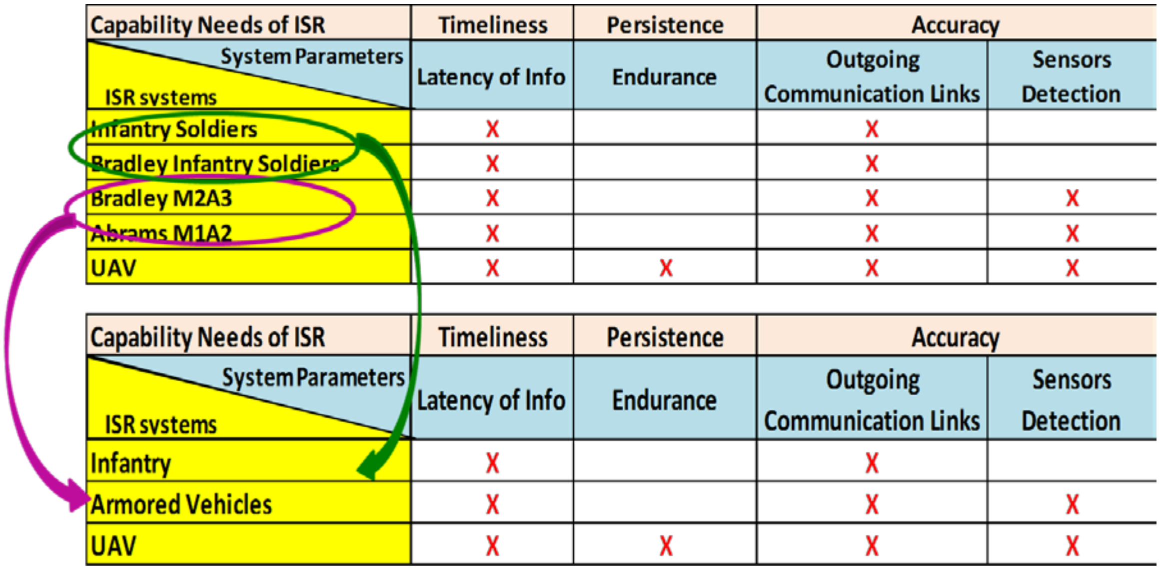
Table 6. RED Force Composition (From Treml 2013)

In MANA modeling language, the same type of agents can be grouped into different squads of a given properties. For the purpose of this study, the properties of the agents under the various squads remain largely unchanged from the baseline model, less those agents highlighted in red in Table 5. These BLUE agents form up the ISR system in the combined arms unit, and are therefore the study interest of this thesis.

G. THESIS MODEL AND PARAMETERS

1. ISR System Requirements

Highlighted earlier in Chapter IV, a well-integrated ISR system enhances battlespace awareness and facilitates decision making. The capability requirements of the ISR sensor platforms need to be (1) timely in intelligence acquisition, (2) accurate in information processing and (3) persistent in monitoring activities (see Table 7), to achieve comprehensive and holistic situation picture of the battlefield, hence providing force protection and system survivability.



Capability Needs of ISR	Timeliness	Persistence	Accuracy	
System Parameters / ISR systems	Latency of Info	Endurance	Outgoing Communication Links	Sensors Detection
Infantry Soldiers	X		X	
Bradley Infantry Soldiers	X		X	
Bradley M2A3	X		X	X
Abrams M1A2	X		X	X
UAV	X	X	X	X

Capability Needs of ISR	Timeliness	Persistence	Accuracy	
System Parameters / ISR systems	Latency of Info	Endurance	Outgoing Communication Links	Sensors Detection
Infantry	X		X	
Armored Vehicles	X		X	X
UAV	X	X	X	X

Table 7. Aggregation of Parameters

Table 7 shows the specific units in the CAU being aggregated into a higher level for simulation purpose. Units similar in nature are grouped under the same category, as “Infantry” and “Armored Vehicles”. This helps to simplify the model by implementing the same degree of change between the different tanks within the same category. A range of values (minimum and maximum) is assigned for each design point generated using NOLH design. Table 8 shows the design factors with their respective ranges of values, representative of the sensor capabilities that are modifiable under MANA’s squad properties. The threshold values are referenced from literature and a brief description of the parameters is provided below.

Index	Variable Name	Metric	Minimum Value	Maximum Value	Modification in MANA
1	# of UAV	Quantity	1	5	# of agent
2	Data Latency of Infantry	Time (s)	10	120	inter squad latency under the outbound comms link
3	Data Latency of Ground (Armored) Vehicles	Time (s)	1	20	inter squad latency under the outbound comms link
4	Data Latency of UAV	Time(s)	1	8	inter squad latency under the outbound comms link
5	Persistency of UAV*	Fuel Endurance (mins)	60	110	fuel endurance of UAV
6	Outgoing Comms Accuracy Infantry	%	85	100	outbound comms link of Infantry
7	Outgoing Comms Accuracy Ground	%	85	100	outbound comms link of ground
8	Outgoing Comms Accuracy UAV	%	85	100	outbound comms link of UAV
9	Sensors Accuracy Ground	%	85	100	Sensor accuracy
10	Sensors Accuracy UAV	%	85	100	Sensor accuracy

Table 8. Design Factors and Threshold Values

Number of UAV–This factor determines the amount of information that can be collected as well as the coverage over the battlefield. Based on current doctrine, each Battalion has an organic asset of two UAVs, that can be flown singly or both at the same time depending on operational requirements and operation tempo. The study intends to determine whether by doubling the number of UAVs, the building of situation picture of the battlespace is more comprehensive due to larger coverage and longer persistence. In addition, the results can also determine the point where subsequent increase in the asset no longer has an impact on the overall value of intelligence required.

Data Latency of Infantry and Ground (Armored) Vehicles–This factor determines the time delay between collected and disseminated intelligence of the ground troops and the armored vehicles. Both are designed with different time latency due to the nature of the equipment that they are assigned. Infantry troops are usually equipped with just laser rangefinder or binoculars, and as such, once they spotted enemy related information, they will report back to HQ via their communication set. Time latency sets in between them spotting the enemy and the actual reporting due to ground constraint, such as finding a concealed area before reporting back to HQ. For the armored vehicles, since most of the tanks now are now equipped with a digital electronic architecture that incorporates an on-board subsystem monitoring, diagnostics/prognostics, and an Army Technical Architecture (ATA) compliant Command and Control software suite, the tank commanders are able to disseminate intelligence faster than the troops, if not real-time.

Data Latency of UAV–This factor determines the time delay between collected and disseminated intelligence of the UAV. While based on literature, the sensor latency can go to as low as 40ms, this simulation will arbitrarily fixed the latency from from 1 to 8s to model the impact of delay. In Major Treml's thesis, he used 300s as input latency for the UAV to illustrate the delay in information dissemination between the Battalion HQ and CAU HQ. The 300s latency involved data processing and information dissemination from the Battalion HQ down to the troops. For the purpose of this thesis, this man-in-the-loop processing loop is not considered; rather the study focuses on the delay in information dissemination from UAV to the Battalion HQ (the sensor loop only). The assumption made is that there is no latency between Battalion HQ and Company troops who need the information collected by UAV.

Persistence of UAV–This factor acts as a surrogate to the overall ISR system persistence for this scenario. By changing the fuel endurance level of the UAV, the persistence in monitoring the battlespace by the UAV will vary, hence influencing the amount of intelligence collected and comprehensiveness of the situation awareness.

Outgoing Communications Accuracy of UAV, Infantry and Armored Vehicles–Other than being timely, these factors determine the accuracy of the information disseminated to the required troops. Data links accuracy is important especially in a networked environment to ensure information and data get transpired accurately to the stakeholders for critical decision-making.

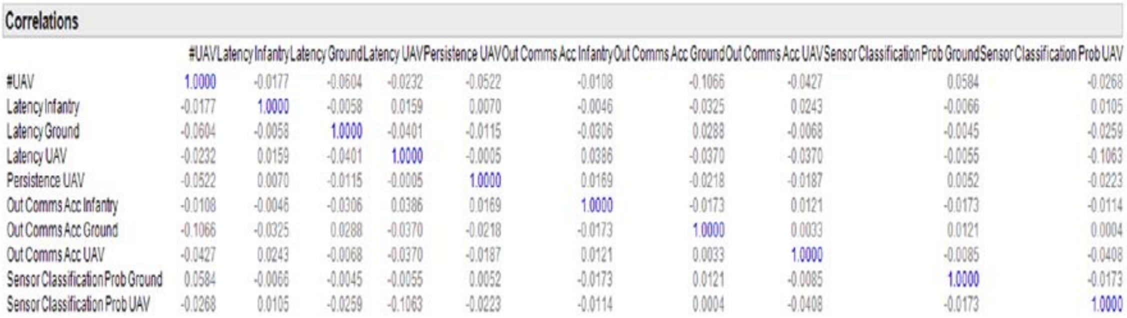
Sensors Accuracy–Sensor Detection and Classification Accuracy fall under this category of parameters that can be varied during the simulation. Sensor detection refers to the localization of target when a predetermined energy threshold of the sensor is exceeded, while sensor classification refers to the sensor's capability to accurately match the detected target against its database, to reflect the identity of the target. For this model, only sensor classification accuracy will be modified using the specified range. Sensor detection accuracy for all the sensors is not modeled, for they are fairly straight-forward, but classification accuracy is the one that is more complicated in design and hence determines the overall sensor capability. Without good classification capability, the intelligence generated will not meet the accuracy requirement despite having good detection capability.

2. Generation of Modeling Data

The model was evaluated using a 33 design point NOLH, based on Cioppa's designs (see Table 9). The correlation matrix and scatterplot results show well-dispersed design points, depicting a well-explored design space of the model. This DOE also has sufficiently low correlation between input variables, and good sampling of data points required to generate a fair model for study (see both Table 12 and Figure 30). It should be noted that a more exhaustive experimental design is recommended for future analysis, but time constraints prevented utilization of such a design for this study. A suggested design for follow on work is presented in Chapter V. The suggested design has improved space filling properties and decreased correlation between all variables.

	#UAV	Latency Infantry	Latency Ground	Latency UAV	Persistence UAV	Out Comms Acc Infantry	Out Comms Acc Ground	Out Comms Acc UAV	Sensor Classification Prob Ground	Sensor Classification Prob UAV
Minimium	1	10	1	1	60	85	85	85	85	85
Maximum	5	120	20	8	110	100	100	100	100	100
Metric	#	sec	sec	sec	sec	%	%	%	%	%
1	5	20	9	2	6240	94	95	92	100	95
2	5	120	3	4	4980	88	96	90	99	92
3	5	58	18	2	3720	94	96	85	90	100
4	5	13	10	3	5640	96	91	93	86	87
5	5	113	7	3	4920	88	87	98	85	93
6	4	62	19	3	3600	95	91	99	98	85
7	4	38	5	5	5760	90	85	88	94	94
8	4	82	6	6	4260	93	86	91	98	88
9	4	34	15	8	4620	86	87	87	91	94
10	4	89	13	8	5880	100	92	91	88	87
11	4	75	8	7	4080	93	99	96	89	97
12	4	31	17	7	4740	85	95	96	96	90
13	4	79	12	8	6060	99	93	95	97	96
14	3	106	20	4	6420	87	97	86	92	86
15	3	86	19	3	6300	89	88	100	93	99
16	3	27	5	5	5400	87	100	97	90	89
17	3	65	11	5	5100	93	93	93	93	93
18	3	24	1	5	3780	98	88	99	93	99
19	3	44	2	6	3900	96	97	85	92	86
20	3	103	16	4	4800	98	85	88	95	96
21	3	99	4	2	5460	100	90	89	89	95
22	2	72	3	7	6480	91	89	100	95	85
23	2	68	2	6	6600	90	94	86	87	100
24	2	93	16	4	4440	95	100	97	91	91
25	2	48	15	3	5940	92	99	94	87	97
26	2	96	6	1	5580	99	98	98	94	91
27	2	41	8	1	4380	85	93	94	97	98
28	2	55	13	2	6120	92	86	89	96	88
29	2	51	9	1	4140	86	92	90	88	89
30	1	110	12	7	3960	91	90	93	85	90
31	1	10	18	5	5220	97	89	95	86	93
32	1	117	11	6	4560	89	94	92	99	98
33	1	17	14	6	5280	97	98	87	100	92

Table 9. NOLH Design Space for ISR Model for 33 Design Points


Correlations

	#UAV	Latency Infantry	Latency Ground	Latency UAV	Persistence UAV	Out Comms Acc Infantry	Out Comms Acc Ground	Out Comms Acc UAV	Sensor Classification Prob Ground	Sensor Classification Prob UAV
#UAV	1.0000	-0.0177	-0.0604	-0.0232	-0.0522	-0.0108	-0.1066	-0.0427	0.0584	-0.0268
Latency Infantry	-0.0177	1.0000	-0.0058	0.0159	0.0070	-0.0046	-0.0325	0.0243	-0.0066	0.0105
Latency Ground	-0.0604	-0.0058	1.0000	-0.0401	-0.0115	-0.0306	0.0288	-0.0068	-0.0045	-0.0259
Latency UAV	-0.0232	0.0159	-0.0401	1.0000	-0.0005	0.0386	-0.0370	-0.0370	-0.0055	-0.1063
Persistence UAV	-0.0522	0.0070	-0.0115	-0.0005	1.0000	0.0169	-0.0218	-0.0187	0.0052	-0.0223
Out Comms Acc Infantry	-0.0108	-0.0046	-0.0306	0.0386	0.0169	1.0000	-0.0173	0.0121	-0.0173	-0.0114
Out Comms Acc Ground	-0.1066	-0.0325	0.0288	-0.0370	-0.0218	-0.0173	1.0000	0.0033	0.0121	0.0004
Out Comms Acc UAV	-0.0427	0.0243	-0.0068	-0.0370	-0.0187	0.0121	0.0033	1.0000	-0.0085	-0.0408
Sensor Classification Prob Ground	0.0584	-0.0066	-0.0045	-0.0055	0.0052	-0.0173	0.0121	-0.0085	1.0000	-0.0173
Sensor Classification Prob UAV	-0.0268	0.0105	-0.0259	-0.1063	-0.0223	-0.0114	0.0004	-0.0408	-0.0173	1.0000

Table 10. Correlation Table for the Design of Factors

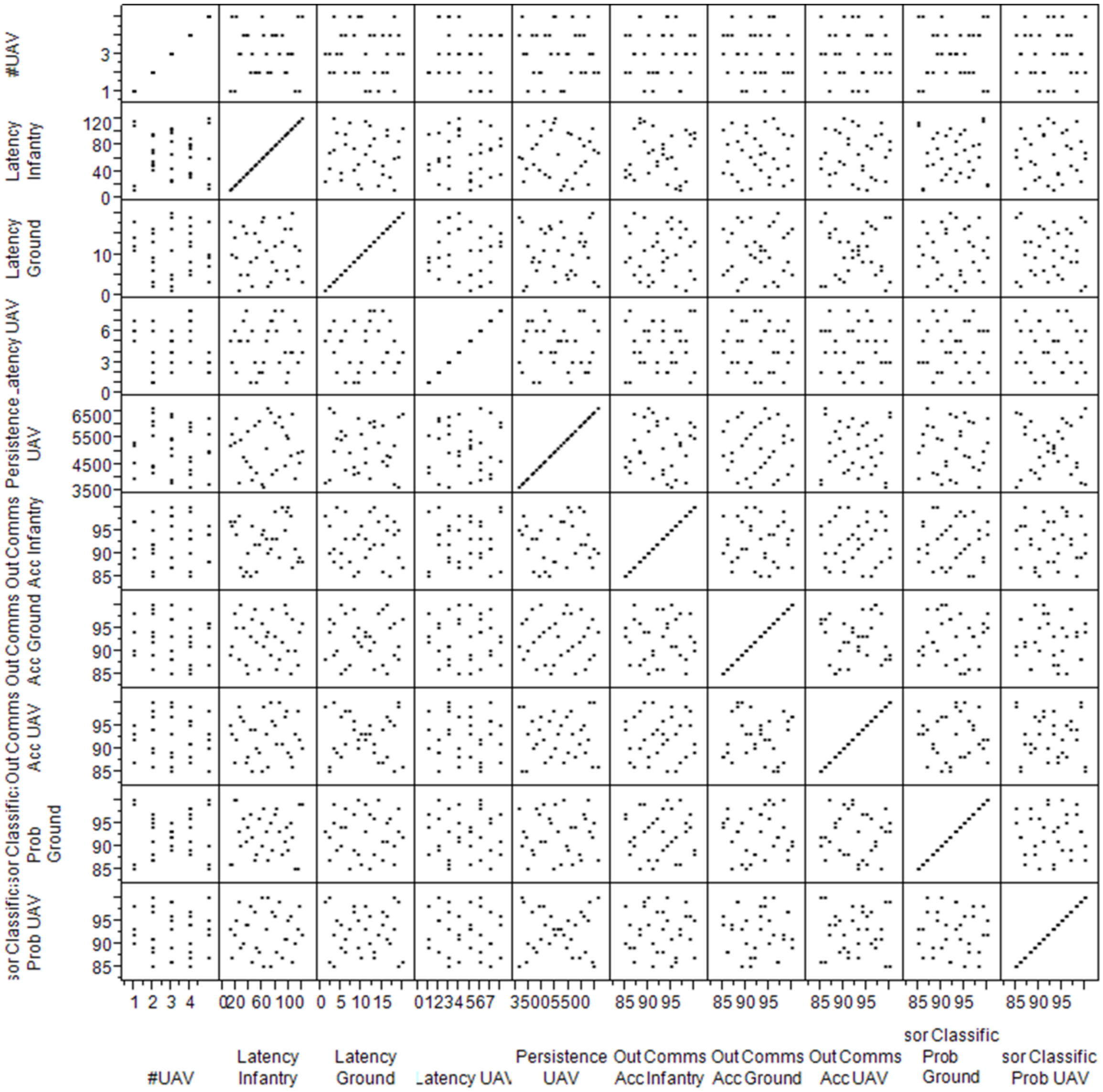


Figure 29. Scatterplot Matrix for 33 Design Points

H. ASSUMPTIONS

The following assumptions are made for this DOE in the defined scenario:

- Intelligence from HHQ has been circulated to the Battalion S2 prior to mission, hence predetermining the disposition and route of advancement of the BLUE troops
- The link from UAV to Unmanned Ground Station (UGS) and from UGS to Battalion HQ is treated as non-existent. In addition, the latency in information processing and dissemination from Battalion HQ to CAU HQ is also

disregarded. In this model, data latency of UAV results from discrepancy in collection and dissemination of the intelligence, down to CAU HQ and troops.

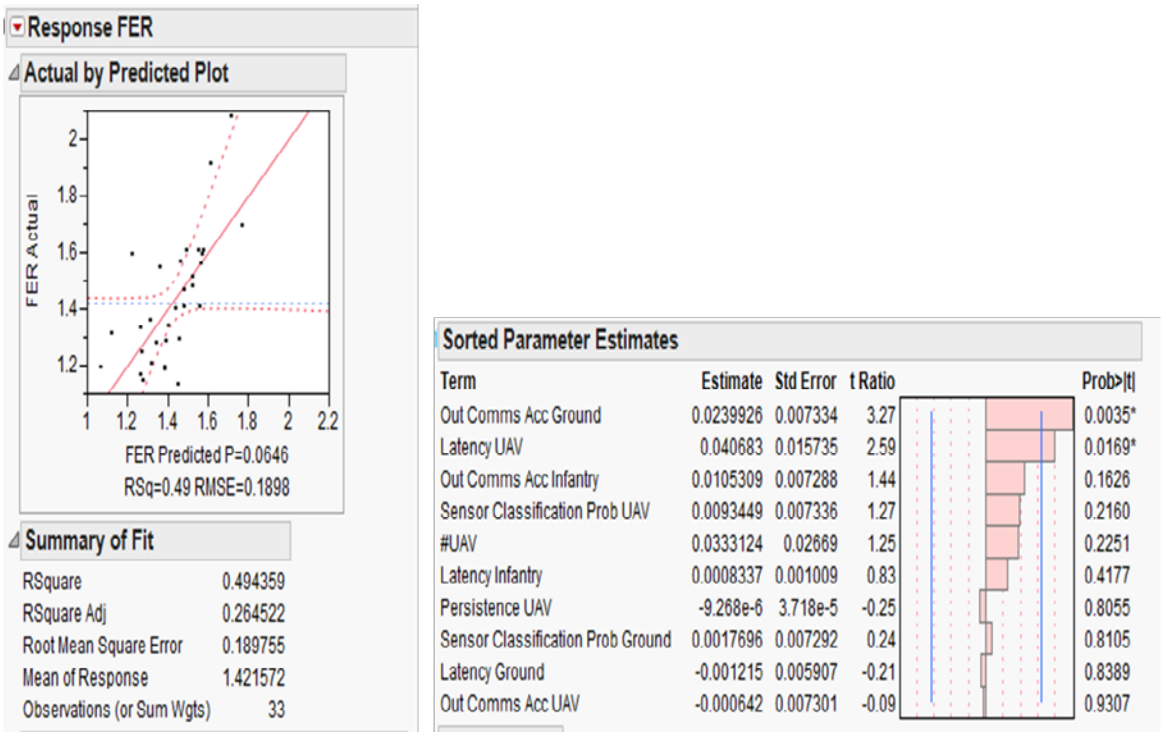
- All intelligence sent to individual agents' HQ is assumed to be updated to CAU HQ instantaneously
- Workload of the mechanized crew are not considered
- Fatigue level of the soldiers are not taken into consideration
- Payload of UAV is not varied throughout the simulation

V. RESULTS AND ANALYSIS

A. RESULTS

1. Main Effects Regression Model

The main effects regression model is first constructed to analyze the relationship between the ISR parameters and the FER. The low R^2 and Adjusted R^2 values, 0.494 and 0.265 respectively, reflect a small variability of the real data is being captured (see Figure 30). This means that the relationship between the parameters and FER is not linear; a more complicated relationship such as quadratic effects is present in the interactions among the parameters and FER. While this model is not appropriate for detailed analysis, it may provide initial insights that can inform the validity of future models. The initial analysis shows that the outgoing communications accuracy of the armored vehicles has a significant effect on the FER, as explained by the low p-value of 0.0035 (<0.05). The positive relationship shows that the FER increases as the communications accuracy improves. This is expected when communications accuracy of the BLUE force becomes better, since the FER is defined as the ratio of RED casualty to the BLUE casualty. The prediction profiler in Figure 31 further supports this analysis. As outgoing communications accuracy of the armored vehicles improves, better communication exist between the agents and therefore building better situation picture of the battlefield, enhancing the situation awareness of the BLUE troops.



Summary of Fit

RSquare	0.494359
RSquare Adj	0.264522
Root Mean Square Error	0.189755
Mean of Response	1.421572
Observations (or Sum Wgts)	33

Term	Estimate	Std Error	t Ratio	Prob>|t|
Out Comms Acc Ground	0.0239926	0.007334	3.27	0.0035*
Latency UAV	0.040683	0.015735	2.59	0.0169*
Out Comms Acc Infantry	0.0105309	0.007288	1.44	0.1626
Sensor Classification Prob UAV	0.0093449	0.007336	1.27	0.2160
#UAV	0.0333124	0.02669	1.25	0.2251
Latency Infantry	0.0008337	0.001009	0.83	0.4177
Persistence UAV	-9.268e-6	3.718e-5	-0.25	0.8055
Sensor Classification Prob Ground	0.0017696	0.007292	0.24	0.8105
Latency Ground	-0.001215	0.005907	-0.21	0.8389
Out Comms Acc UAV	-0.000642	0.007301	-0.09	0.9307

Figure 30. Main Effects Model for the Force Exchange Ratio (FER)

The prediction profiler also shows the number of UAVs, outgoing communications accuracy of the infantry troops and the sensor classification probability of the UAV are the other significant parameters in increasing the FER of the battle (see Figure 31, boxed in red). This is expected, since with more UAVs, wider area of the battlefield can be covered, giving more comprehensive situation picture. The high classification capability of the UAV will ensure the targets detected are identified correctly, allowing the commander to make correct decisions on the battlefield. Better outgoing communications accuracy of the troops will also allow better information flow within the network. These factors will lead to the BLUE force having better situation awareness of the battlespace and therefore increasing the RED casualty and hence FER.

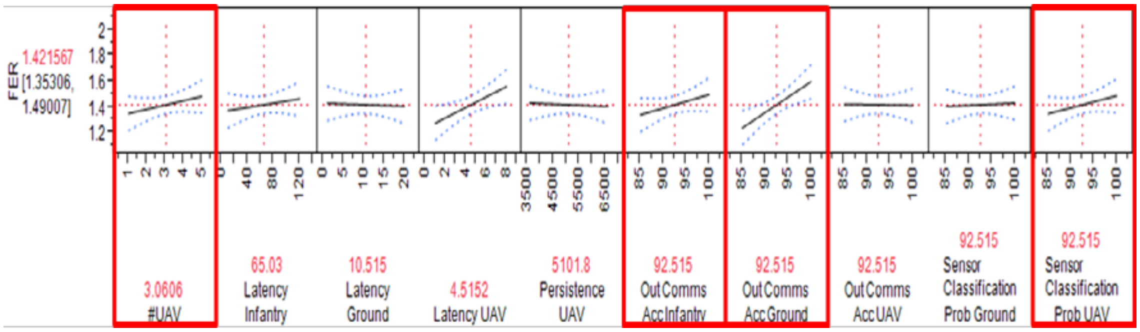
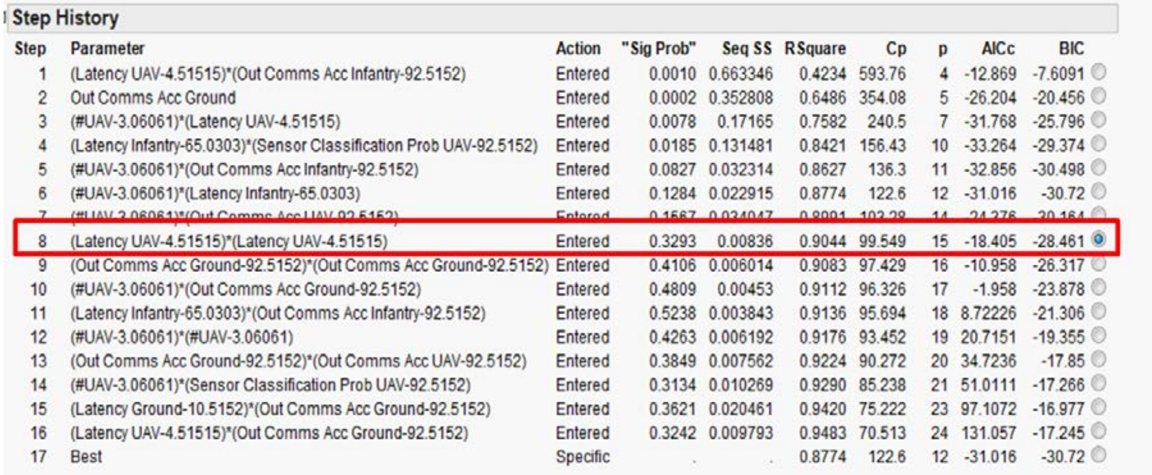


Figure 31. Prediction Profiler for Force Exchange Ratio (FER) – Main Effects Model

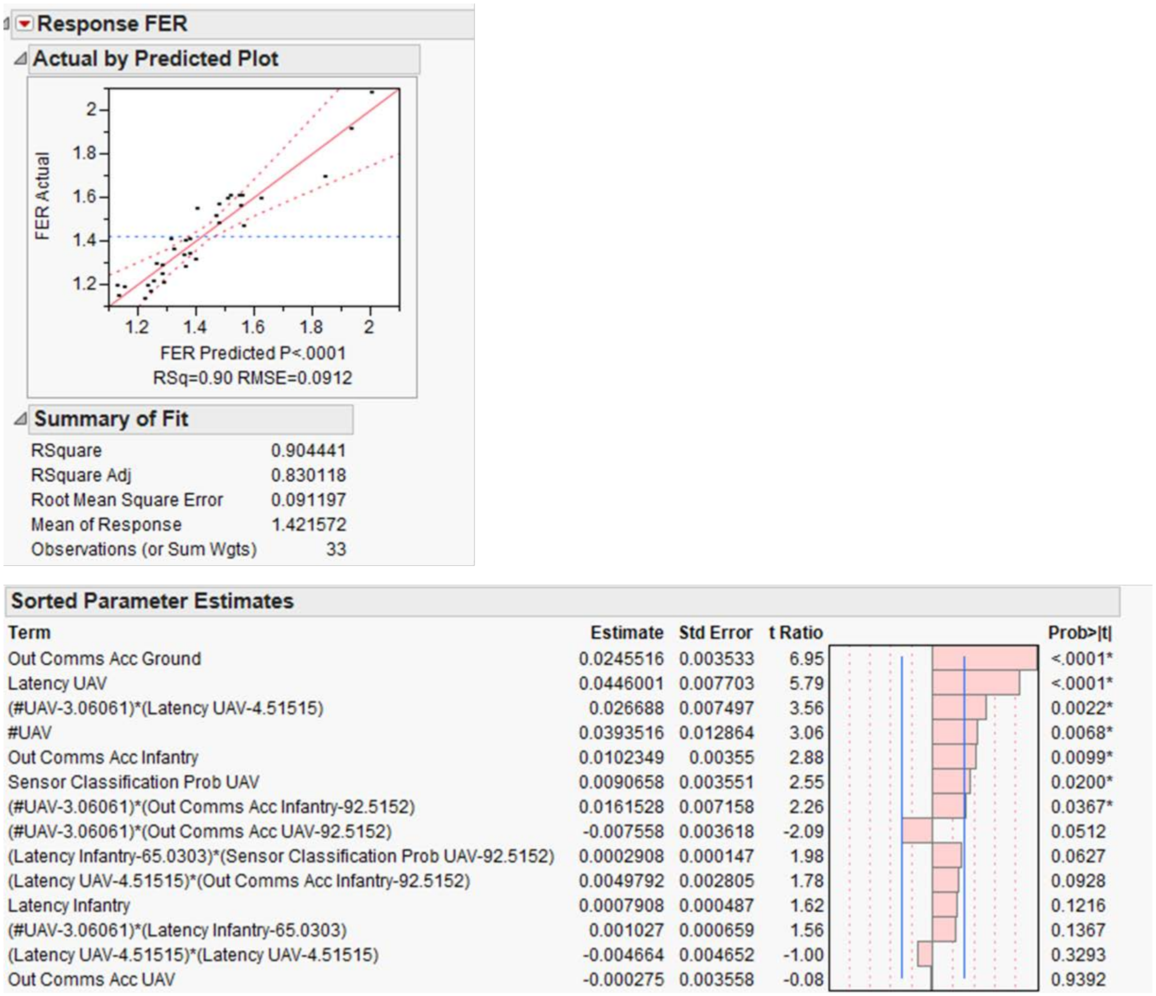
2. Interaction and Quadratic Regression Model

An expanded model is now considered, which allows for examination of the linear and quadratic effects of the ten design parameters on the FER. A stepwise analysis is first conducted to determine the significant factors in the model. They are subsequently used to produce the interaction regression model for analysis. The step history of the JMP stepwise regression tool shows candidate regression equations. Figure 32 highlights the selected regression equation; the model has a R^2 value of 0.9044 and is selected for regression analysis on the factors involved.


Step History

Step	Parameter	Action	"Sig Prob"	Seq SS	RSquare	Cp	p	AICc	BIC	
1	(Latency UAV-4.51515)*(Out Comms Acc Infantry-92.5152)	Entered	0.0010	0.663346	0.4234	593.76	4	-12.869	-7.6091	○
2	Out Comms Acc Ground	Entered	0.0002	0.352808	0.6486	354.08	5	-26.204	-20.456	○
3	(#UAV-3.06061)*(Latency UAV-4.51515)	Entered	0.0078	0.17165	0.7582	240.5	7	-31.768	-25.796	○
4	(Latency Infantry-65.0303)*(Sensor Classification Prob UAV-92.5152)	Entered	0.0185	0.131481	0.8421	156.43	10	-33.264	-29.374	○
5	(#UAV-3.06061)*(Out Comms Acc Infantry-92.5152)	Entered	0.0827	0.032314	0.8627	136.3	11	-32.856	-30.498	○
6	(#UAV-3.06061)*(Latency Infantry-65.0303)	Entered	0.1284	0.022915	0.8774	122.6	12	-31.016	-30.72	○
7	(#UAV-3.06061)*(Out Comms Acc UAV-92.5152)	Entered	0.1567	0.034047	0.8991	103.28	14	-24.276	-30.164	○
8	(Latency UAV-4.51515)*(Latency UAV-4.51515)	Entered	0.3293	0.00836	0.9044	99.549	15	-18.405	-28.461	●
9	(Out Comms Acc Ground-92.5152)*(Out Comms Acc Ground-92.5152)	Entered	0.4106	0.006014	0.9083	97.429	16	-10.958	-26.317	○
10	(#UAV-3.06061)*(Out Comms Acc Ground-92.5152)	Entered	0.4809	0.00453	0.9112	96.326	17	-1.958	-23.878	○
11	(Latency Infantry-65.0303)*(Out Comms Acc Infantry-92.5152)	Entered	0.5238	0.003843	0.9136	95.694	18	8.72226	-21.306	○
12	(#UAV-3.06061)*(#UAV-3.06061)	Entered	0.4263	0.006192	0.9176	93.452	19	20.7151	-19.355	○
13	(Out Comms Acc Ground-92.5152)*(Out Comms Acc UAV-92.5152)	Entered	0.3849	0.007562	0.9224	90.272	20	34.7236	-17.85	○
14	(#UAV-3.06061)*(Sensor Classification Prob UAV-92.5152)	Entered	0.3134	0.010269	0.9290	85.238	21	51.0111	-17.266	○
15	(Latency Ground-10.5152)*(Out Comms Acc Ground-92.5152)	Entered	0.3621	0.020461	0.9420	75.222	23	97.1072	-16.977	○
16	(Latency UAV-4.51515)*(Out Comms Acc Ground-92.5152)	Entered	0.3242	0.009793	0.9483	70.513	24	131.057	-17.245	○
17	Best	Specific	.	.	0.8774	122.6	12	-31.016	-30.72	○

Figure 32. Step History of the Selected ISR Parameters



Summary of Fit

RSquare	0.904441
RSquare Adj	0.830118
Root Mean Square Error	0.091197
Mean of Response	1.421572
Observations (or Sum Wgts)	33

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Out Comms Acc Ground	0.0245516	0.003533	6.95	<.0001*
Latency UAV	0.0446001	0.007703	5.79	<.0001*
(#UAV-3.06061)*(Latency UAV-4.51515)	0.026688	0.007497	3.56	0.0022*
#UAV	0.0393516	0.012864	3.06	0.0068*
Out Comms Acc Infantry	0.0102349	0.00355	2.88	0.0099*
Sensor Classification Prob UAV	0.0090658	0.003551	2.55	0.0200*
(#UAV-3.06061)*(Out Comms Acc Infantry-92.5152)	0.0161528	0.007158	2.26	0.0367*
(#UAV-3.06061)*(Out Comms Acc UAV-92.5152)	-0.007558	0.003618	-2.09	0.0512
(Latency Infantry-65.0303)*(Sensor Classification Prob UAV-92.5152)	0.0002908	0.000147	1.98	0.0627
(Latency UAV-4.51515)*(Out Comms Acc Infantry-92.5152)	0.0049792	0.002805	1.78	0.0928
Latency Infantry	0.0007908	0.000487	1.62	0.1216
(#UAV-3.06061)*(Latency Infantry-65.0303)	0.001027	0.000659	1.56	0.1367
(Latency UAV-4.51515)*(Latency UAV-4.51515)	-0.004664	0.004652	-1.00	0.3293
Out Comms Acc UAV	-0.000275	0.003558	-0.08	0.9392

Figure 33. Interaction Regression Model

The Adjusted R^2 of the corresponding set of parameters now exhibits a high value of 0.830 (see Figure 33). This means that 83% of the variability of the data is being captured by the interaction model, and the R^2 value of 0.9044 is not artificially inflated by the inclusion of a large number of terms in the model. As such, this is a fair model to be used for interaction study between the parameters and their corresponding response on the FER. The parameter estimates from Figure 34 highlight the following seven parameters and interactions that have significant impact on FER, with statistically significant p-values (<0.05):

- Outgoing communications accuracy of Armored Vehicles (p-value <0.0001)
- Outgoing communications accuracy of Infantry (p-value = 0.0099)

- Sensor classification probability of UAV (p-value = 0.0200)
- The number of UAVs (p-value <0.0001)
- Interaction between number of UAV and Outgoing communications accuracy of Infantry (p-value = 0.0367)
- Interaction between number of UAV and UAV latency (p-value = 0.0022)
- UAV latency (p-value <0.0001)

The first six factors are in line with the expectation that, when these parameters are improved, situation awareness of the battlefield is also greatly enhanced, thereby increasing the FER of the battlefield, which implied an increase in BLUE unit survivability. The only parameter that seem to deviate from norm is the UAV latency, as it is expected to show a corresponding drop in FER (decrease in RED casualty) when there is an increase in UAV latency. One possible explanation for this deviation from norm is the range where the UAV latency is being varied. The current range of 1 to 8 seconds might be too narrow for the model to simulate accurately the effect of UAV latency on the FER. From the prediction profiler in Figure 34, the UAV latency showed a concave behavior with FER, which may show a drop in FER if the range of this parameter is widened.

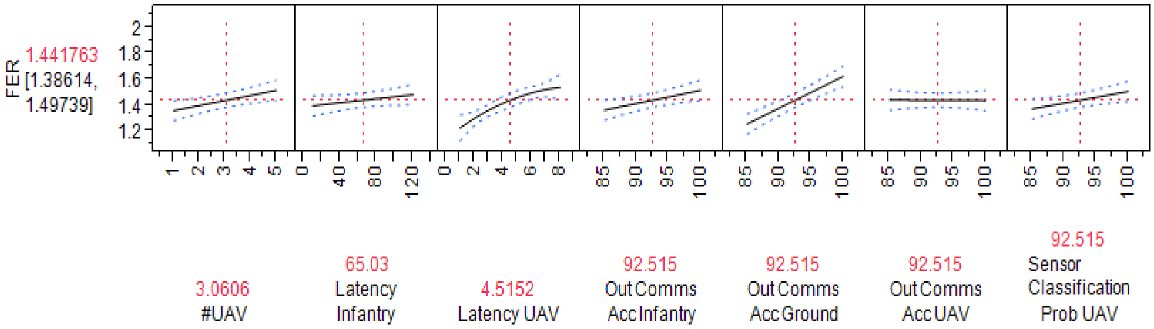


Figure 34. Prediction Profiler for Force Exchange Ratio (FER) – Interactions Model

Another way to study the eccentric behavior of UAV latency is to review the interaction plots between UAV latency and the number of UAVs. The interaction plot is shown in Figure 35. With reference to the interaction plot between the number of UAVs and the UAV Latency, when there is only one UAV, the increase in UAV latency does not seem to have much effect on the FER. However when UAVs are increased to five, the plot shows an increasing FER. This indicates that, when there are five UAVs present, increasing the latency of the UAV information actually increases the FER. Explicitly, this means that having information updates less frequently is good for the Blue Force. This seems counter intuitive, and may just be an artifact of the simulation. This requires explanation. In the simulation, a small latency and a large number of UAVs, means that each agent is getting information updated constantly. Because each agent must re-prioritize this information, it may be creating a delay in action based on this excess of information. This indicates that, at least in this simulation, too much information causes confusion. Future work can utilize a more detailed simulation to investigate whether this phenomenon is an artifact of MANA's communication structure, or whether this "information paralysis" can actually occur, and be accounted for in operations. Therefore, it emphasizes that there may be some "right amount" of information, and that having the absolute maximum amount of information possible may not be a good thing.

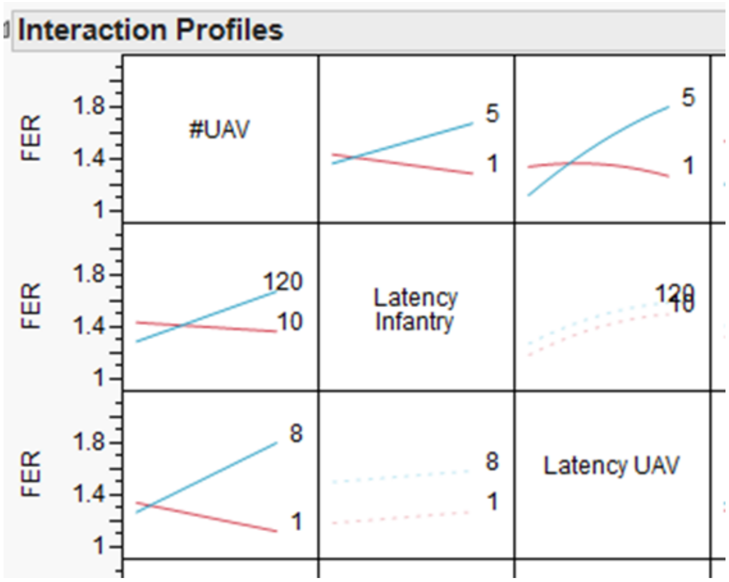
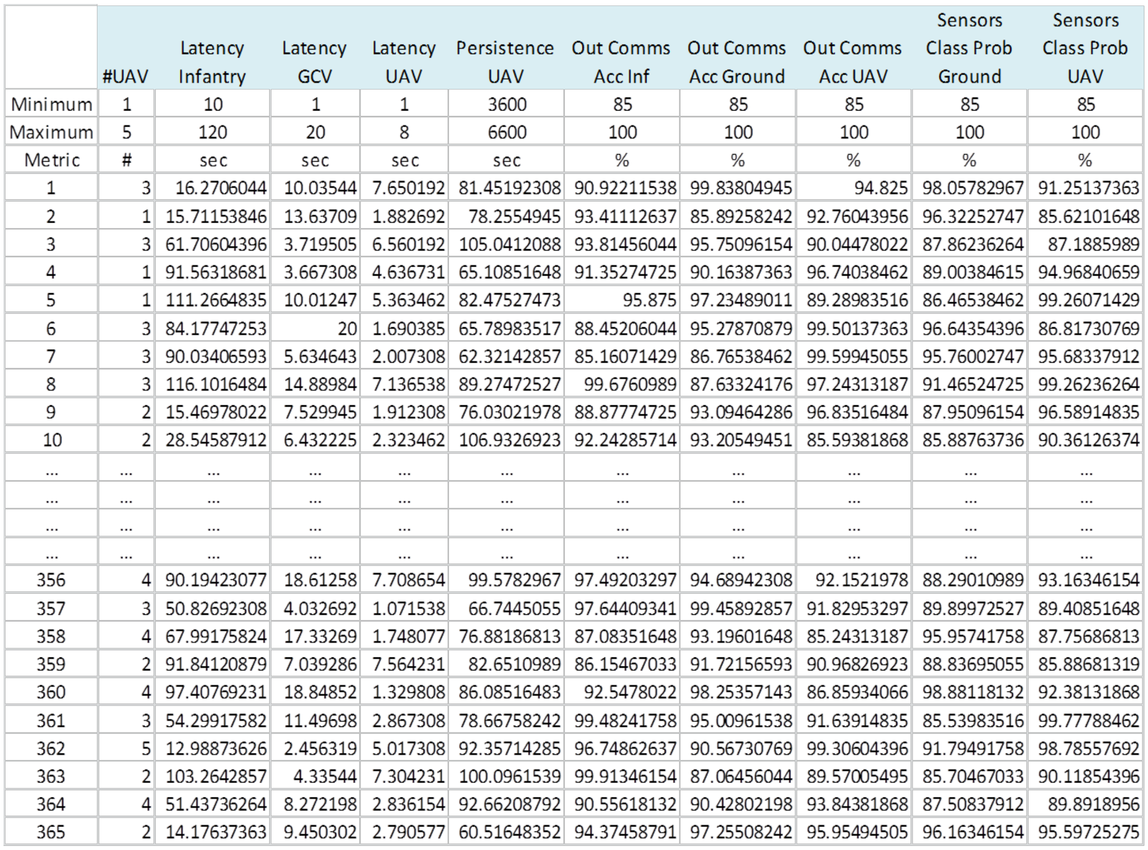


Figure 35. Interaction Plots of UAV Latency vs Number of UAVs

B. FUTURE EXPERIMENTAL DESIGNS

As noted in Chapter IV, a more exhaustive experimental design should be considered in future work (it was not possible for this work due to time constraints). Using the data in Table 8, nine continuous and one discrete (number of UAV) factors of design are generated using NOLH. A total of 365 combinations of the factors are generated. For this model, each combination is replicated 30 times to achieve randomization of the design space, amounting to a total of 10,950 runs. The NOLH design space for this model is show in Table 11.

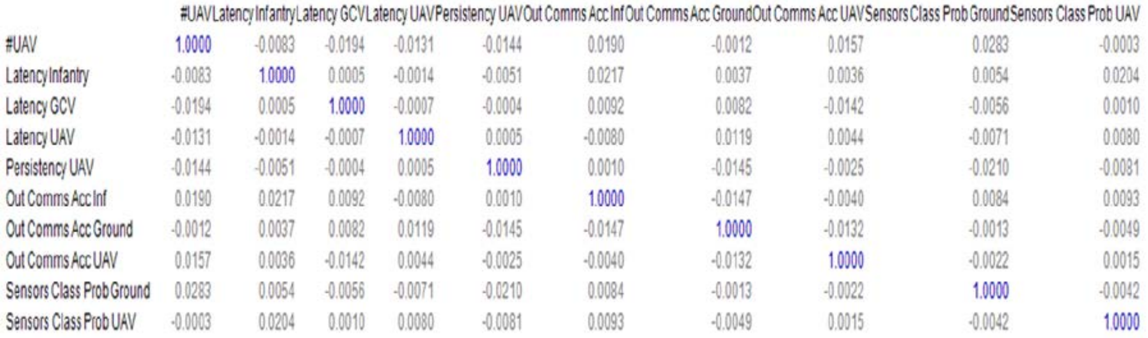


	#UAV	Latency Infantry	Latency GCV	Latency UAV	Persistence UAV	Out Comms Acc Inf	Out Comms Acc Ground	Out Comms Acc UAV	Sensors Class Prob Ground	Sensors Class Prob UAV
Minimum	1	10	1	1	3600	85	85	85	85	85
Maximum	5	120	20	8	6600	100	100	100	100	100
Metric	#	sec	sec	sec	sec	%	%	%	%	%
1	3	16.2706044	10.03544	7.650192	81.45192308	90.92211538	99.83804945	94.825	98.05782967	91.25137363
2	1	15.71153846	13.63709	1.882692	78.2554945	93.41112637	85.89258242	92.76043956	96.32252747	85.62101648
3	3	61.70604396	3.719505	6.560192	105.0412088	93.81456044	95.75096154	90.04478022	87.86236264	87.1885989
4	1	91.56318681	3.667308	4.636731	65.10851648	91.35274725	90.16387363	96.74038462	89.00384615	94.96840659
5	1	111.2664835	10.01247	5.363462	82.47527473	95.875	97.23489011	89.28983516	86.46538462	99.26071429
6	3	84.17747253	20	1.690385	65.78983517	88.45206044	95.27870879	99.50137363	96.64354396	86.81730769
7	3	90.03406593	5.634643	2.007308	62.32142857	85.16071429	86.76538462	99.59945055	95.76002747	95.68337912
8	3	116.1016484	14.88984	7.136538	89.27472527	99.6760989	87.63324176	97.24313187	91.46524725	99.26236264
9	2	15.46978022	7.529945	1.912308	76.03021978	88.87774725	93.09464286	96.83516484	87.95096154	96.58914835
10	2	28.54587912	6.432225	2.323462	106.9326923	92.24285714	93.20549451	85.59381868	85.88763736	90.36126374
...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...
356	4	90.19423077	18.61258	7.708654	99.5782967	97.49203297	94.68942308	92.1521978	88.29010989	93.16346154
357	3	50.82692308	4.032692	1.071538	66.7445055	97.64409341	99.45892857	91.82953297	89.89972527	89.40851648
358	4	67.99175824	17.33269	1.748077	76.88186813	87.08351648	93.19601648	85.24313187	95.95741758	87.75686813
359	2	91.84120879	7.039286	7.564231	82.6510989	86.15467033	91.72156593	90.96826923	88.83695055	85.88681319
360	4	97.40769231	18.84852	1.329808	86.08516483	92.5478022	98.25357143	86.85934066	98.88118132	92.38131868
361	3	54.29917582	11.49698	2.867308	78.66758242	99.48241758	95.00961538	91.63914835	85.53983516	99.77788462
362	5	12.98873626	2.456319	5.017308	92.35714285	96.74862637	90.56730769	99.30604396	91.79491758	98.78557692
363	2	103.2642857	4.33544	7.304231	100.0961539	99.91346154	87.06456044	89.57005495	85.70467033	90.11854396
364	4	51.43736264	8.272198	2.836154	92.66208792	90.55618132	90.42802198	93.84381868	87.50837912	89.8918956
365	2	14.17637363	9.450302	2.790577	60.51648352	94.37458791	97.25508242	95.95494505	96.16346154	95.59725275

Table 11. NOLH Design Space for ISR Model for 365 Design Points

Next, the correlation of the variables is investigated using a pairwise correlation matix (see Table 12). Ideally, the correlation between these design factors should be as low as possible, so that any change in one variable is independent of the other, therefore making the results easily interpreted. When there is strong correlation between any variables, the standard deviation of the regression coefficients become inflated, hence lowering the significance of the model the coefficients. This means the variables can be combined since they generate the same insight on the outcome of. For this model design, the degree of correlation between the variables is referenced against the “r” value of 0.1.

This threshold value has been used in the Cost Estimation lecture taught under the Systems Engineering Department in NPS. As a rule of thumb for determining multicollinearity, for r≤0.1, there is no issue. The generated pairwise matrix of the variables in Table 11 shows the largest r value of 0.0283. As such, the model is confident of delivering results that reflect accurately the impact of each variable change, independent of one another.



	#UAV	Latency Infantry	Latency GCV	Latency UAV	Persistency UAV	Out Comms Acc Inf	Out Comms Acc Ground	Out Comms Acc UAV	Sensors Class Prob Ground	Sensors Class Prob UAV
#UAV	1.0000	-0.0083	-0.0194	-0.0131	-0.0144	0.0190	-0.0012	0.0157	0.0283	-0.0003
Latency Infantry	-0.0083	1.0000	0.0005	-0.0014	-0.0051	0.0217	0.0037	0.0036	0.0054	0.0204
Latency GCV	-0.0194	0.0005	1.0000	-0.0007	-0.0004	0.0092	0.0082	-0.0142	-0.0056	0.0010
Latency UAV	-0.0131	-0.0014	-0.0007	1.0000	0.0005	-0.0080	0.0119	0.0044	-0.0071	0.0080
Persistency UAV	-0.0144	-0.0051	-0.0004	0.0005	1.0000	0.0010	-0.0145	-0.0025	-0.0210	-0.0081
Out Comms Acc Inf	0.0190	0.0217	0.0092	-0.0080	0.0010	1.0000	-0.0147	-0.0040	0.0084	0.0093
Out Comms Acc Ground	-0.0012	0.0037	0.0082	0.0119	-0.0145	-0.0147	1.0000	-0.0132	-0.0013	-0.0049
Out Comms Acc UAV	0.0157	0.0036	-0.0142	0.0044	-0.0025	-0.0040	-0.0132	1.0000	-0.0022	0.0015
Sensors Class Prob Ground	0.0283	0.0054	-0.0056	-0.0071	-0.0210	0.0084	-0.0013	-0.0022	1.0000	-0.0042
Sensors Class Prob UAV	-0.0003	0.0204	0.0010	0.0080	-0.0081	0.0093	-0.0049	0.0015	-0.0042	1.0000

Table 12. Correlation Table for the Design of Factors

The space-filling behavior of this DOE can be studied from the scatterplot matrix shown in Figure 36. The scatterplot matrix reflects the pairwise projections of the full design onto each pair of factors, and is a useful way to show the design’s space-filling characteristics (Sanchez 2005). Figure 36 shows well-dispersed design points within individual plot, depicting a well-explored design space of the model. This DOE has sufficiently shown low correlation, and good sampling of data points required to generate a fair model for study.

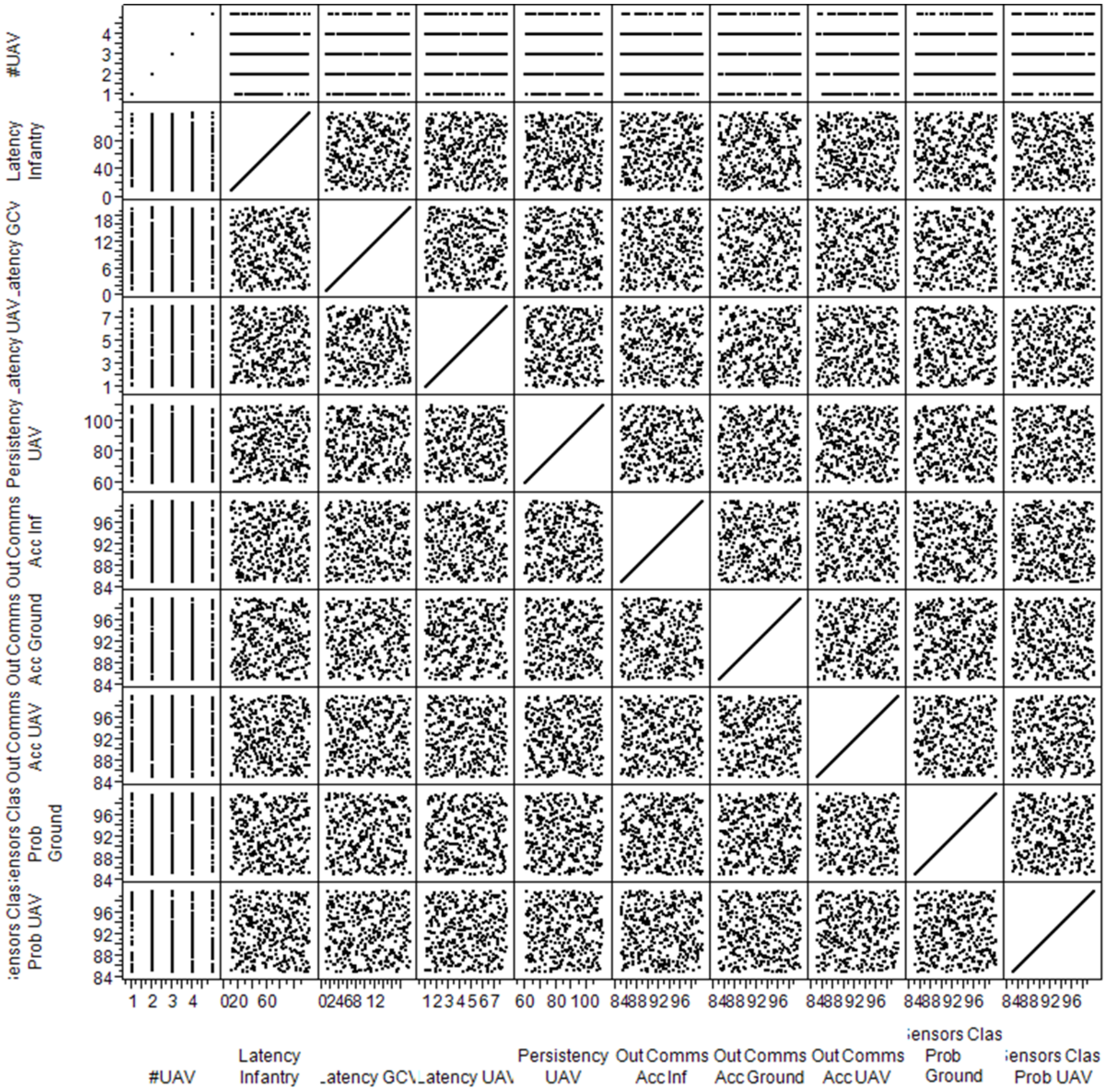


Figure 36. Scatterplot Matrix for 365 Design Points

C. ANALYSIS

Earlier in Chapter IV, two classes of variants are defined where the parameters affecting ISR system effectiveness and integration can be grouped into: Sensor effectiveness variant and the COP variant. The results from the modeling and simulation reveal the following parameters that have a significant impact on the overall unit FER and survivability, under the respective variant type:

Sensor Effectiveness Variant

- Outgoing communications accuracy of Armored Vehicles
- Outgoing communications accuracy of Infantry
- Sensor classification probability of UAV

COP Variant

- The number of UAVs
- Interaction between number of UAV and Outgoing communications accuracy of Infantry
- Interaction between number of UAV and UAV latency
- UAV latency

The sensor effectiveness variant looks at performance of sensors in generating information advantage for the BLUE force. As such, system parameters affecting ISR sensor accuracy in identifying and engaging the adversary are studied under this variant. The simulation results indicate outgoing communications accuracy of Infantry and Armored Vehicles, and the sensor classification accuracy of the UAV to have significant impact on ISR system operational effectiveness. When sensor classification accuracy of the UAV is enhanced, targets are identified with higher fidelity, thus enabling ground commanders to make decision with precision. Enhanced outgoing communications accuracy of the troops and armored vehicles allow information to be transpired without distortion, which inevitably builds better situation awareness of the battlefield. These factors give high FER, which reflects lesser BLUE force being annihilated during the battle, signifying accurate information flow among the agents and situation picture of the battlefield.

The COP variant is used as an approximation to study the outcome of sensor integration and the overall changes in situation awareness, by manipulating the timeliness and persistence involved in building up the operational picture. In the model, the effects of sensors integration and the overall changes in situation awareness of the combined arms unit are simulated through system parameters that affect the timing and building up of situation picture. The three functionalities identified earlier to have impact on COP variant are UAV persistence, the number of UAVs and latency of information from UAV, Armored Vehicles and Infantry.

The simulation results show the quantity of the UAVs has a significant influence over the build up of situation picture and its comprehensiveness. When information of interest on the monitored area(s) by the different UAVs are properly fused and shared among the units in the combined arms unit, enhanced situation awareness (high FER) is achieved, as evidently reflected via the COP variant. Coupled with UAV latency, which determines the timeliness of the information being disseminated to the respective units, these parameters show how connectivity and data sharing are achieved as part of system integration. This is discussed earlier in Chapter III under ISR System Integration Architecture, depicted by Figure 7: Enterprise Integration Architecture by Giachetti 2010. While the result from UAV latency remains inconclusive from this simulation, it does show that its strong influence over the integration of the sensors.

These seven parameters identified from the simulation results show ISR systems operational effectiveness and integration can be achieved, by enhancing sensor effectiveness, and building a more responsive and comprehensive situation picture, as part of enhancement to force protection and system survivability.

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VI. CONCLUSION

A. SUMMARY

Highlighted in the ISR-Integrated Capstone Strategic Plan (ICSP), DoD’s ISR capabilities will need to be melded into a system of systems that ties sensors, platforms, planners and shooters together in one global network in order to fight effectively. This network provides an overarching capability that will provide assured and actionable intelligence from single source and fused sensors by creating a fully integrated ISR SoS for effective collection, processing and dissemination within the global network (Corsano 2003).

In this thesis, work was done to determine impact of ISR system effectiveness and integration on the overall unit survivability, by analyzing their impact on the battlespace awareness. The parameters identified to influence the capability needs of any ISR systems are streamlined into sensor effectiveness variant and COP variant. Both variants are modeled, and with their FER response outcome analyzed and compared. Results from the simulation have proven that superior sensor effectiveness coupled with a number of sensors working together are indeed able to generate intelligence that greatly enhances the overall battlespace awareness, as compared to one lone sensor. This has proven that when data accumulated from multiple heterogeneous sensors are not able to be shared, the capabilities to fulfill missions are greatly reduced, if not limited (Essendorfer 2009).

Such ISR system effectiveness and integration is made possible with advanced technologies available today. As battlefield becomes more sophisticated, decision making anchors very much on the intelligence collected and therefore, the ISR systems of today are desired to be able to deliver intelligence that is timely, accurate and persistent. In this scenario of a combined arms unit, the deployment of capable assets such as the RQ-11 Raven UAV providing live video coverage and long flight endurance, the modernized Abrams tanks with digital data bus and radio interface unit that communicates a common picture among the rest of the M1A2s, as well as the System Enhancement Package (SEP) and the Improved Bradley acquisition system (IBAS) on the Bradleys that enhances situational awareness and improves target acquisition and target engagement, are indication of the importance of situation awareness in a battle. The enhancement in sensors effectiveness and system's architecture and design (modularity, connectivity and data sharing capability) are some of the materiel approaches to improve ISR effectiveness and system integration, across domains.

While this study shows with that enhanced sensors and properly integrated ISR system is able to achieve positive impact on the Force Exchange Ratio, and hence the overall battlespace awareness leading to overall unit survivability, the integration of such disparate array of sensor systems might be challenging, if without appropriate measures and policies in place. STANAGs, NIIA and the DCGS are some of the non-materiel approaches that provide the necessary framework in enabling system development to achieve interoperability. This is particularly crucial in today's context, since successful integration of an ISR system also means moving away from Service/platform-oriented collection operations, and toward capability needs operations, which provide a built-in agility and flexibility for collectors to response to the dynamic environment (Corsano 2003). This is also the future of how war will be fought as weapon systems and technology gets more advanced and sophisticated. Therefore, non-materiel approaches guide ISR system integration, in particular cross-domain systems, which span across different operational users and stakeholders. As such, both materiel and non-materiel approaches discussed above have significant influence over ISR system effectiveness and integration; maximizes force protection and survivability, by deploying appropriately and accordingly to operational needs and requirements.

B. FUTURE RESEARCH

The value of a warfare (or combat) simulation is directly related to the credibility of its representations of real-world military operation; equipment and systems; and environmental factors (Andrew J. Duck n.d.). As of today, systems acquisition is usually done based on the Services' operational needs and identified capabilities gaps. With that, new capabilities are developed and if needed, integrated to existing systems as part of a larger System of Systems interoperability framework. However, existing Army capabilities to model ISR systems are not suited to examine Army ISR related issues, such as the assessment of the overall value of such integration effort and whether the money spent on the newer capabilities is worthwhile. While there are existing studies on simulation related to ISR sensor systems, the domain is limited. One such research that came across was on “Assessing the Impact of C4ISR Alternatives with The Joint Warfare System” by Horn (2002). This study uses the Joint Warfare System (JWARS), an emerging set of modeling and simulation tools that provides multi-sided and balanced representation of the Joint Theater warfare, to model the C4ISR concepts in the area of C2, enhanced ISR operations and network-centric warfare (Horn 2002). Such tools can be used to model the ISR system parameters on their impact on situation awareness, using the same scenario in this thesis, at the combined arms level, instead of Joint Warfare level.

As with Major Treml’s thesis where MANA can be used to evaluate the system specifications in the overall capability framework before actual acquisition starts, the same concept can be applied to the ISR arena. Simulation tools such as MANA and JWARS can be used to assess the intelligence value of existing ISR assets of a given combat unit. The results from the simulation will facilitate decision makers in fine-tuning the capabilities desired to fill the identified needs or gaps. Such modeling tools are also able to evaluate the effectiveness on the level of integration and interoperability of the ISR assets owned by the Service or combat units. This can be done by scaling the level of operations accordingly, as well as depending on the aspects of ISR architecture and integration that require such study.

In this thesis, one component of the ISR system is not modeled: human-sensor interaction. This thesis focuses mainly on the capability of the sensors present in the CAU and their impact on unit survivability. One possibility for future work is to include modeling efforts that involves ISR systems that look to decision-making process between the human operator and the ISR asset he is operating (Veverka 2005). This can be done by adding the 300s from UAV data latency in Major Treml’s model to the sensor latency variation used in this thesis. This gives a more holistic sensor data latency study as part of the overall ISR framework. In addition, it is also recommended to widen the range of the

UAV latency than what is currently being modeled, so as to have better clarity on its behavior with respect to the unit FER.

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