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Modeling control in computer simulations

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

MODELING CONTROL IN COMPUTER
SIMULATIONS

by

Robert A. Claflin

September 1994

Thesis Advisor   Samuel Parry

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13. ABSTRACT (Maximum 200 words)

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MODELING CONTROL IN COMPUTER SIMULATIONS

by

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Submitted in partial fulfillment
of the requirements for the degree

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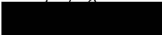
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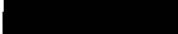
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ABSTRACT

This study outlines the design, implementation, and testing of the General Control Model as applied to the Future Theater-Level Model (FTLM) for the control of Joint and Allied Forces for all operational sides. The study develops a notion of battlefield control and describes the characteristics necessary to represent this notion of control in a computer simulation. Central to the implementation of the General Control Model is the robust capability for the user-analyst to describe any control relationship of research interest and to do so without having to alter the programming code. The user-analyst is provided the capability to determine the cause and effect relationship of different control representations in a simulation. A full description of the model is complimented by an explanation of the implementation to facilitate the use of the General Control Model. A discussion of the initial test results leads to a more rigorous test which confirms the intended behavior of the General Control Model in FTLM. Lastly, recommendations for future improvements to the General Control Model and FTLM are outlined to assist future research endeavors.

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EXECUTIVE SUMMARY

The impetus for this study was the requirement of the United States Military Training Mission to demonstrate the cause and effect relationships associated with different joint control representations for the Kingdom of Saudi Arabia. This study develops a General Control Model using a described notion of control and implements this model in the Future Theater Level Model (FTLM). The General Control Model will serve as a robust analytic tool capable of presenting any control representation of interest. This analytic tool is intended to assist in the development of the Saudi Arabian Armed Forces control structure and in turn provide a control structure foundation for the Saudi Arabian computer simulations capability at the Saudi Arabian Command and General Staff College. The Saudi Arabian Armed Forces control structure must be sensitive to unique Saudi Arabian political, cultural, and military control requirements while being capable of providing the most lethal use of military assets.

The research goal was to develop and implement a control model in a perception based computer simulation capable of representing joint and allied forces. The product must be robust to ensure that the user-analyst can describe any control representation and do so without changing the programming code of FTLM. Furthermore, the use of FTLM naturally provides the capability to audit each simulation run and trace the origination of information generated by sensors through the passing of that information between units according to the described control representation. The audit process, the ability to compare unit perceptions, and the ability to compare unit perception to simulation ground truth provide an analytic tool capable of meeting the needs of researchers interested in understanding the effects of various control representations within a computer simulation.

The General Control Model provides eight components to represent a control structure. These eight components are:

1. the capability for units to maintain their own, individual perception of the battlefield environment and the corresponding enemy course of action, as denoted by Π_i;

2. the capability to describe unit ownership of sensor assets and specify the sensor characteristics commensurate with the hierarchical level of the unit;

3. the capability to restrict a unit to acquire sensor observations from geographic locations within the unit's area of influence;

4. the capability to describe sensor-to-unit and unit-to-unit relationships due to the enabling technologies infrastructure, called the control architecture and denoted by an arrow;

5. the capability to describe sensor-to-unit and unit-to-unit relationships as prescribed by doctrine, called the control doctrine and denoted by an arrow;

6. the capability to describe a stochastic time delay of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $TD(\mu_{ij}, \sigma_{ij})$;

7. the capability to describe a stochastic probability of receiving a message to simulate the loss of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted by $PR(\rho_{ij})$; and

8. the capability to describe a staffing ability multiplier that is a characteristic of an individual unit and indicative of the unit's ability to perform the staff function of processing information, denoted as $SAM(\alpha_i)$.

All eight components were implemented in FTLM and six control representations were developed to test the General Control Model. The testing of the General Control Model was divided into four sets of tests. The first set of tests consists of simulation runs where two units maintain individual perceptions for each of the six control representations. The second set of tests consists of simulation runs where eleven units maintain individual perceptions for each of the six control representations. The third set of tests consists of four parameter sets. Each parameter set varies the characteristic values associated with the previously described components using the first control representation as a basis for comparison. The fourth set of tests consists of two excursionary simulation runs to show the increased computing resource required when increasing the number of units with

individual perceptions and to confirm the flexibility of representing different control structures using the General Control Model.

Test runs were analyzed using the audit process, the ability to compare unit perceptions, and the ability to compare unit perception to simulation ground truth. Each tested control representation behaved in a realistic manner as intended. Results verified that the General Control Model as implemented in FTLM provides a robust means to represent control in a computer simulation.

The study pointed to several areas still needing additional research. First, a portion of the course of action update warrants verification. Second, a historical base of parameter values which describe components of the General Control Model would increase the believability of the model and the simulation accuracy of the units the model represents. Continuing research will provide further refinement to the capabilities offered by the Future Theater Level Model.
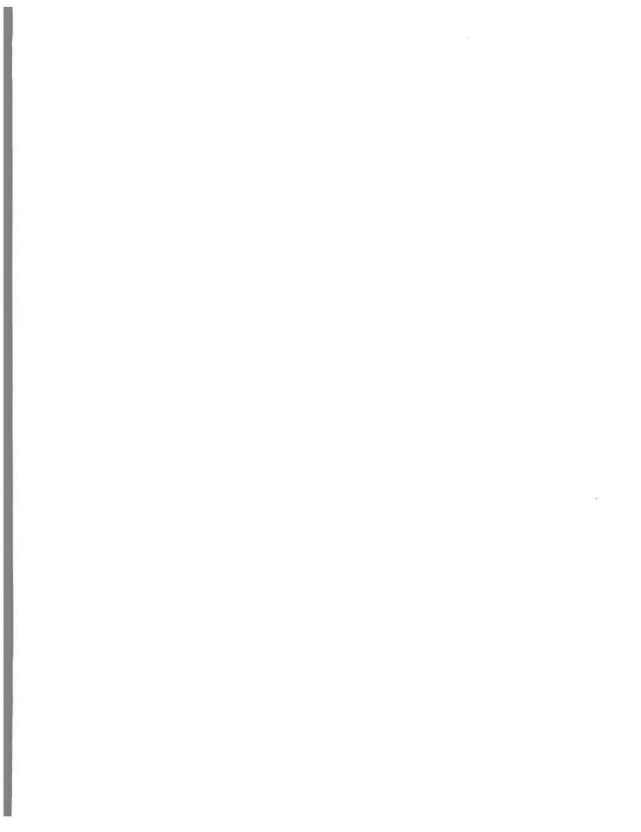
I. INTRODUCTION AND PROBLEM DEFINITION

A. OVERVIEW

This thesis develops a general approach to representing military control in perception based war game simulations. The thesis then applies the general control model to the Future Theater Level Model (FTLM) as a vehicle to determine cause and effect relationships between various control representations. The relationships of interest include who wins, the similarity of perceptions of the battlefield amongst subordinate units of an operational side, timeliness of attaining a similarity of perceptions if attained, and with what necessary commitment of forces through the selection of a common course of action against the enemy side. The control representations used for this analysis will include variations on the notions of centralization of information dissemination, decentralization of information dissemination, and ownership of sensor assets. The impetus for researching this growing area of interest is the United States Military Training Mission (USMTM) to the Kingdom of Saudi Arabia's need to provide an analytic tool to aid the Saudi Arabian Ministry of Defense and Aviation (SAMODA) such that SAMODA can improve their military control architecture and doctrine.

The general approach requires the development of mathematically modeled unique identities for individual units within a given computer war game simulation. The requirement for unique identities allows individual units to hold their own perception of the battlefield. These perceptions may vary between sister and/or senior units on the same operational side of the conflict. Unique perceptions by sub-units and the ability to describe control relationships as expressed in this thesis will eventually lead to flexible and dynamic branching within a set of courses of action to be followed by sub-units at critical decision points using future developed artificial intelligence decision set theory rather than a common, scripted course of action currently used in FTLM. Control representations will describe any military control architecture and doctrine of interest and will allow the analyst to specify who can talk to whom on the battlefield (control architecture), who

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chooses to talk to whom (control doctrine), and what individual headquarters do with information. The control model envelopes the idea of ownership of sensor assets by describing reporting hierarchies and limiting sensor readings to the area of interest controlled by the owning unit, sensor-to-unit and unit-to-unit reporting hierarchies and the associated real world representations of information time delays within units, the probability of successfully receiving information associated with communications hardware, and a staff's ability to process new sensor information based upon the staff's level of training.

B.   HISTORICAL BACKGROUND AND PERSPECTIVE

Culturally, Saudi Arabia is a closed and cautious society. Western ideas and day-to-day practices are opposite to Saudi beliefs and are considered eroding to the health of the Kingdom. Information is held as a precious commodity of power and not freely disseminated even when it would appear logical, from a Western viewpoint, to share the information in order to better achieve common goals.

With the advent of the Kingdom of Saudi Arabia under the Saud Family and the historically recent wealth derived from Saudi Arabia's vast and rich oil basins, government imposed restrictions exist today which separate the military services. This separation precludes any formidable government opposition while it potentially limits the defense capability of the armed forces. Over the years, the royal family has solidified power and the Kingdom has become more stable as a nation. Meanwhile, the Middle East region has become increasingly unstable. Saudi Arabia finds itself potentially requiring its full and optimal military ability to defend its territories. The possibility of a regional conflict, as dramatically evidenced by the Gulf War with Iraq, illustrates the potential need for Saudi Arabia to be fully capable to defend against aggressors. During the Gulf War, Saudi Arabia committed military forces to protect its northern border against Iraq. The Chief of Joint Section, USMTM, was a principal advisor to the Saudis during the war in the North. He witnessed noticeable difficulties within the Saudi command and control structure, as

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well as the Saudi inability to operate as an effective joint force. The inability to smoothly integrate the Saudi services initiated a process at Joint Section to investigate ways to better develop the Saudi Arabian Armed Forces (SAAF) command and control systems. Joint Section, USMTM, found that not only were communication links between services incompatible or nonexistent, but doctrine in use during training exercises and during conflict did not include any joint service capability.

USMTM began a dialogue with the Commandant of the Saudi Arabian Command and General Staff College (SACGSC) to begin understanding command and control, as taught and practiced within the Saudi Arabian Armed Forces. The primary goal of the designated Saudi committee was to develop the SACGSC simulation capability. The committee's focus centered on an integrated joint simulations capability. Their immediate requirement is to develop a new control structure and doctrine to better defend the Kingdom with the Saudi Arabian Armed Forces acting as a joint force. Their hope is to then use this new control structure and doctrine as a basis for their own war game simulation capability. It is important to the SAAF to develop a control structure that is effective while being considerate of the unique Saudi culture. Adopting the United States control structure and doctrine is impractical since it is not sensitive to Saudi Arabia's unique cultural heritage. This realization by MODA marked an important first hurdle. Leadership within the SACGSC recognized a control deficiency during the Gulf War and decided to correct the shortfall. They did not blindly copy what the U.S. was doing, but decided to create a blended control system representative of their culture, political requirements, and mostly U.S. weapon systems. They decided to use simulations and operations research as a vehicle to assist in convincing decision makers to make appropriate change.

C.   UNITED STATES MILITARY TRAINING MISSION

The purpose of the United States Military Liaison Mission to the Kingdom of Saudi Arabia is two fold. First, the USMTM advises Saudi Arabia in the training and

doctrinal use of equipment and forces. Secondly, they provide the formal link for foreign military sales of equipment between the United States and the Saudi governments. USMTM comprises senior officers and non-commissioned officers from each branch of service and works as a joint command under the leadership of a two star general. USMTM currently operates in the capital city of Riyadh with the Ministry of Defense and Aviation (MODA); the Joints Chief of Staff equivalent, and with each of the service departments to include Army, Navy, Air Force, and Air Defense. Joint Section, USMTM, is tasked to advise the Saudi Arabian equivalent of the Joint Chiefs of Staff, MODA. Although MODA, in theory, is the senior agency to each of the services, each service has an autonomy associated with it and often operates independently.

D. U. S. INVOLVEMENT

Change does not occur quickly in Saudi Arabia. Consensus is required for each decision and is often difficult to obtain. The Ministry of Defense and Aviation (MODA) must be convinced that a better alternative exists in the area of control to warrant change. The United States Military Training Mission began assisting MODA and SACGSC with the development of the SAAF war game simulation capability and concurred that simulations would be an appropriate vehicle to aid MODA's decision making process in the development of a control structure capable of joint operations.

The cultural differences between the Kingdom of Saudi Arabia and the United States dictate the currently adopted and practiced control structures. USMTM strongly believes that it does not provide the most lethal force given the mostly U.S. designed and made military assets of Saudi Arabia. U.S. interests reside with a strong Kingdom of Saudi Arabia in the Middle East. USMTM is committed to advise Saudi Arabia such that Saudi Arabia has the most effective force possible in that critical region. Fortunately, and concurrent to U.S. interests, senior Saudi leaders at the Saudi Arabian Ministry of Defense and Aviation (MODA) are working to make progressive change throughout the Saudi Arabian Armed Forces (SAAF). These senior leaders envision the use of analytic tools

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and quantitative studies as a strong and persuasive tool to provide current decision makers. They hope to begin a more pragmatic and analytic approach to decision making, rather than a cultural one. The first steps have been taken to develop an operations research department within MODA.

Operations research as a decision aid tool for the SAAF has only been introduced on the most basic level. Although the Petroleum University in Dhahran and the King Faud University in Riyadh teach operations research, their focus has exclusively been towards business applications. Only in recent years has a bridge been built by Colonel Al-Otaibi of the Royal Saudi Army to introduce operations research as an important decision aid tool for the military through the publication of the first military operations research text. (Al-Otaibi, 1993)

E. SPONSOR'S PROBLEM

The current military control structure and control doctrine of Saudi Arabia do not provide the most advantageous and lethal use of assets. USMTM requires an easily understood and flexible analytic tool, using operations research techniques, to assist in MODA's decision for a more lethal control structure for the Saudi Arabian Armed Forces (SAAF). A computer simulation model which can specifically show the effects of various control structures and control doctrines is required. The model must be general in scope and capable of being custom tailored by the user/analyst for national security reasons.

The end product of this research will be a computer simulation integrating the general control model and capable of showing the effects of control within an analyst specified military organization. Proof of principle of the control model within FTLM will consist of a comparison of six different control representations and will primarily show how individual units perceive the enemy's ground truth course of action. Not only will the accurate perception of the correct enemy course of action be an issue, but also the timeliness to achieve the correct perception of the enemy's selection of its course of action. USMTM, or any military organization, will be able to take a given scenario in

FTLM and produce results for each control representation of interest and determine which control representation is best to achieve success on the battlefield.

The analyst will be able to specify the details of any control representation of interest. These details will include specifying the hierarchy of information flow between individually specified units; specify ownership of sensor assets by individually specified units; specify sensor and communication link mean time delays of information and the associated standard deviation; and specify the probability of successfully receiving the information being communicated. Furthermore, the analyst will be able to specify the staff's ability to clarify or confound information based upon its level of training and experience. A mapping function using human factors to develop a staffing ability multiplier is proposed for future research.

The simulation integrated control model is intended to be a persuasive decision aid for commanders and staffs on how best to control diverse and numerous forces and sensor assets engaged in peacetime and wartime operations.

II.   LITERATURE REVIEW AND RELEVANT FACTORS

A.   IMPORTANCE OF STUDYING MILITARY CONTROL

Extensive work has been done in the area of Command, Control, and Communications (C3) as a grouped set of operational concepts. Typically, C3 is regarded as a single entity with the scientific focus on the tangible qualities of communications and the supporting enabling technologies. Most military schools regard the first C, Command, as an operational art and not a science. Command cannot be broken down into an algorithmic discipline, but is rather a complex series of judgments, with moral and ethical bases, logical rationale, and personal experience all playing their respective and weighted parts in the decision making process. The second C, Control, has often been ignored or wrapped up with the either the first C or the third C, Communications.

Control is a structure or architecture which the commander envisions as the critical paths for the sharing and processing of information before, during, and after the decision making process to achieve his intent. Control encompasses not only the plan to pass information to specified units on the battlefield, but also what those units do with the information and how well and quickly they do it. Control further encompasses the truth in information and the planned deception of the enemy through the passing of misinformation.

Communications acts as the enabling technology, or the highway over which this information is passed. Communications is often dealt with as a directed path between two or more units. Volumes of work have been done on optimizing the enabling technology infrastructure. The intricacies of communications is not the purpose of this general control model representation. Although communications is far more tangible than control, understanding necessary control relationships is the fundamental first step before the creation of the communications infrastructure.

Joint Pub 1-02 (AFSC, 1993) defines Command and Control as:

The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission.

It further defines Command and Control Systems as:

The facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations of assigned forces pursuant to the missions assigned.

and Command, Control, Communications, and Computer Systems (C4 Systems) as:

Integrated systems of doctrine, procedures, organizational structures, personnel, equipment, facilities, and communications designed to support a commander's exercise of command and control through all phases of the operational continuum.

All three definitions include the term control and are closely related. There are numerous definitions for command and control and an equal number of paradigms representing the C3 process (Johnson, 1988). This paper will use the Joint Pub definition as the basic reference for defining command and control in an operational context.

Keep in mind that the research aim is to define, within a computer simulation, the "arrangement of personnel, equipment, communications, facilities, and procedures employed" by permitting the analyst to specify the "doctrine, procedures, and organizational structures." The equipment naturally must be considered for the communications to flow.

The March 1993 edition of PHALANX, The Bulletin of Military Operations Research, contains an article by LTG Wilson A. Shoffner entitled Future Battlefield Dynamics and Complexities Require Timely and Relevant Information. (Shoffner, 1993) General Shoffner addresses the importance of C2 and pulls the acronym apart to form two separate terms; command and control. He states that "each word is different and carries with it significantly different meanings, ideas and responsibilities." He further states that

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"Our future leaders must understand this difference, especially as it applies to tactical decision making." General Shoffner defines control as:

> a science of regulating forces and functions on the battlefield to execute the commander's intent. Control is a more precise means through which staffs support their commander's intent and work with other staffs. Control performs the functions shown in this figure and is primarily the staff's business. Commanders anticipate change and staffs project change.

Figure 1 is a reproduction of General Shoffner's control diagram from the March 1993 edition of PHALANX.
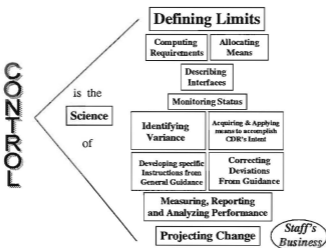
Figure 1. "LTG Shoffner's Control Diagram From Ref. (Shoffner, 1993)."

The top block of Figure 1, labeled "Defining Limits," implies the area of interest and the control doctrine which provides general guidance. It provides the answer to who chooses to talk to whom. This also suggests the procedures of sending information that may exist due to a hierarchy or to an alert channel. The block labeled "Allocating Means" implies ownership. Not only does this address chain of command relationships between units, it also includes which sensors belong to whom. The block labeled "Describing

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Interfaces" implies the control architecture. It provides the answer to who can to talk to whom. Associated with the communications hardware are the realities of time delays and the loss of information. The remainder of the blocks represent the human-performed staff process within the headquarters.

The December 1993 edition of PHALANX, The Bulletin of Military Operations Research, contains an article by Col. Thomas A. Cardwell III, Ph.D.. The article entitled Theater Air C3 Analyses - Future Needs further discusses LTG Shoffner's article in terms of the needs of the Air Force. (Cardwell, 1993) Col. Cardwell asserts that the military community should be "able to dissect control, study it, and put it back together again so that it provides the commander with maximum force effectiveness." Col. Cardwell believes that levels of control elements exist and that there is a "unifying theme that ties them together and allows us to systematically examine control so that we may optimize its development."

B. RESEARCH IN MILITARY CONTROL AND RELATED SYSTEMS

Work done in the field of command and control has focused either on representing the decision making process associated with information systems or on the specific performance specifications of the information system itself. (Alexander, 1974) The Lawson Model is a common representation of the C2 decision making process. The diagram in Figure 2 best describes the model.

The Lawson Model (c. 1980)
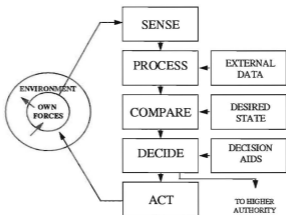
Figure 2. "The Lawson Model From Ref. (Johnson, 1988)"

The top block labeled "SENSE" parallels the use of sensors to achieve a snapshot picture of some portion of the environment. This information is sent to a headquarters where it is processed and combined with previous external data. A comparison of the perceived current condition of the environment and the desired state is made. A decision is made on what to do to either correct the perceived current condition of the environment or sustain it, if desired. Decision aids are used in the decision making process. Orders are issued and a subordinate unit (one's own force) acts upon the environment to affect necessary change. The process repeats itself until some end state is reached. The end state could be that the environment matches our desires, our ability to act upon the environment is depleted, or that our desires have changed to match the current environment (Johnson, 1988).

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C. REPRESENTING MILITARY CONTROL IN SIMULATIONS

Representing military control in simulations and war games typically suggests the paths along which information is sent between entities on the battlefield. No explicit documentation exists which reflects the ability for an analyst to represent various control architectures and control doctrines in a simulation (Youngren, 1994). Consequently, this thesis researches an important capability; to represent military control in computer simulations and be able to conduct cause and effect analysis to determine control differences between analyst specified control structures.

Defining military control mathematically is not readily apparent. The following definition provides a list of characteristics which a control model will need to describe mathematically. An integral step is to determine which current functions within a war game simulation can be adapted or augmented to model control and which functions must be added. The characteristics of control which the methodology of design will address are posed as the critical questions which the model must address:

1. How well do subordinate units share the commander's intent based upon the control architecture and control doctrine? (Inter-service and joint operations)

2. When subordinate units share similar perceptions of the commander's intent (similar or supporting Course of Action), how well does the force achieve the mission given the control architecture and control doctrine?

3. When subordinate units do not share similar perceptions of the commander's intent (dissimilar Courses of Action), how well does the force achieve the mission given the control architecture and control doctrine?

4. How does the commander's intent (most likely Course of Action) compare to ground truth? (Would it have had any effect on 2 or 3 above in any case?)

5. How do variations in the control architecture, control doctrine, and the associated parameterized characteristics, affect the sharing of similar or supporting perceptions and subsequent battle outcomes? (Which units talk to which other units and which sensors belong to which units?)

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D.   FUTURE THEATER LEVEL MODEL (FTLM)

The Future Theater Level Model (FTLM) was chosen as the platform simulation for two reasons. First, FTLM is a perception based simulation. This quality permits the concepts of individual identities and decisions based upon the perceptions of those individual identities. Secondly, FTLM is an easy to use, personal computer based simulation that has been developed for rapid analysis. It provides a complete audit trail of all functions within the simulation. Adapting a control model to FTLM is a natural progression in the development of FTLM as an analysis tool.

Once the general control model has been integrated into FTLM, comparative analysis between the various control representations of interest will determine if the control model adequately represents reality. The basic design of FTLM permits the analyst to compare unit-to-unit commonality of selected courses of action. As a unit's perception of the battlefield is updated, the unit's selection for a course of action is updated. Subsequently, the selected course of action can be compared to the enemy ground truth and since courses of action for each side must correspond one-to-one, a determination can be made whether the correct course of action has been selected. The analyst specifies which scripted course of action the enemy is taking. The friendly side's perception of the appropriate course of action over time and the critical point where the friendly side commits to a course of action can be traced and is dependent upon obtaining sensor information of the environment. The friendly selection of a course of action can then be compared to the selected, scripted enemy course of action to determine if the friendly side perceived the environment correctly when compared to enemy ground truth. The analyst is able to compare all friendly unit perceptions for any commonality of a selected course of action. Deviations between units can be recognized and the associated chaos of control due to dissimilar perceptions can be determined.

FTLM provides an audit trail at each time interval to include the unit's current perception and course of action, to include the associated probabilities. Secondly, each unit's perception and chosen course of action can be compared to ground truth within the

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model as well as to other units on the same operational side. A measure of performance to reflect deviations from ground truth will be applied. A visual plot of each unit's associated probability that the unit perceives the selected ground truth enemy course of action, plotted on the y axis, over time on the x axis, will provide a quick check of whether a unit's perception of the environment is correct. As a unit's probability of perceiving the enemy ground truth course of action approaches one, that unit is more accurately perceiving its environment. Plotting several units on the same chart will visually indicate the level of similarity in perceiving the environment. Unit plots should be roughly similar when perceptions are shared and similar. Again, deviation from ground truth can be audited to the time step when the deviation occurred by examining the sensor observations history files.

Although all possible combinations between units and ground truth could be considered for comparison, it is more practical to limit initial comparisons between units for the recognition of similar or dissimilar perceptions and common courses of action. Only after it is determined that an operational side shares a common perception is the question of comparison to ground truth relevant. Comparison to ground truth at this point is important since it will allow the analyst to know the difference between an operational side which shares similar perceptions while it follows the correct course of action and an operational side which shares similar perceptions while it follows an incorrect course of action.

Currently in FTLM, sensor reports consist of a "bean count" of assets on a node by asset type. This information is provided to a Bayesian update cycle along with the ground truth mean for that asset type, the variance associated with the sensor, and the prior from all previous sensor observations for that asset type. The update maps into a probability associated with the possible courses of action which the enemy may choose.

As an artifact from the original versions of FTLM, a detection model exists which acts as the trigger to schedule a sensor. This step is vital to the integration of the sensor model within FTLM. One would not send out a scarce asset such as a sensor unless one

had some provocation. However, the detection also contributes to the course of action perception update. Essentially, the course of action perception update is affected twice by the same acquisition, but in two distinct ways. Two components are responsible for the course of action perception update, a detection component and a sensing component.

Semantically, these two components appear to mean the same thing; however they do not. A detection is merely the acquisition of some potentially significant item at a known location. A sensing provides quantification of the item at a known location; say two tanks and three howitzers. The level of information increases from a detection to a sensing. To be able to reduce the analysis to the effects of a control model of quantified information, the detection component of the course of action perception update must be eliminated. This is reasonable since the sensing already inherently includes the fact that a detection occurred. A sensing would never take place unless a detection had triggered it. It appears that the detection component is redundant with the advent of the sensor model within FTLM. An opinion would not have been formed unless the gatherer had some quantifiable level of information, which is exactly what the sensor is providing. Future research may involve treating the detection as a separate and weighted piece of information to be shared between units within FTLM. This will result in a study of the magnitudes of weights associated with the various levels of information when they are combined into a single function.

Another design feature of FTLM is that the possible courses of action for both friendly and enemy sides are prescribed in detail and must correspond one-to-one. This ensures that if the enemy is pursuing a course of action, the correct friendly course of action is the one-to-one corresponding friendly course of action prescribed to defeat the enemy course of action. Each operational side now perceives, in the form of a probability, which course of action it believes the opposing operational side is pursuing. This process occurs for an operational side as a single entity, regardless of the quantity and type of units composing the operational side. When a sensor has information to report, the simulation update process provides an instantaneous and shared perception of the battlefield to all

units of the operational side in question on a periodic basis. This perception is maintained as a single Bayesian update cycle. The simulation acts as if each unit gets the same information and that they do so without interruption or delay. This does not represent the true flow of information on the battlefield.

FTLM does not currently account for the effects of control explicitly. The general control model developed in this thesis will provide a more realistic representation of units and sensors and how they interact through the passing of information. Implementation of the control model will be applicable to both operational sides and introduce realism into the control of forces. Furthermore, the control representation will be flexible and allow different variations of control to permit cause-and-effect analysis. The control representation model will provide a foundation for future artificial intelligence endeavors in FTLM and hopefully allow a meaningful use of individual decision sets for sub-units. This will enable sub-units to make critical decisions according to the described decision set theory. The eventual introduction of artificial intelligence into FTLM will eliminate the requirement for courses of action in FTLM to be described and fixed. Courses of action will become dynamic, less rigid, and contain multiple branches at any given critical decision point at the sub-unit level.

For a complete description of FTLM, refer to the thesis by Karl M. Schmidt, entitled Design Methodology for FTLM (Schmidt, 1993).

E.   RESEARCH OBJECTIVES

The primary objective is to design and integrate a control model into a theater level simulation. This will allow an analyst to study the effects of different control representations within the context of an operational situation. The model will provide an analytic method to study different control structure alternatives. The analyst will better understand the sensor-to-unit and unit-to-unit relationships of control on the battlefield. Additionally, control's relationship with battle outcomes will become more apparent. This

can be extended to any military organization that can specify their current control architecture and control doctrine.

Doctrine is addressed since it reflects the general path to a goal. For an example, U.S. doctrine states that the Army and the Air Force will fight joint. The procedures to do so are important, but they would not exist without the vision which the doctrine sets forth on the conduct of joint operations. Control doctrine in the context of this thesis includes being capable of describing important information exchange relationships between services and allies, sensors and units, as well as describing procedures to achieve the doctrinal intent. The Doctrine Control Matrix specified in Chapter III describes mathematically the doctrinal relationship of units. It may, on the surface, appear redundant with the Architecture Control Matrix discussed in Chapter III, however its purpose is to delineate between whether an operational side cannot form a specific information exchange link or whether it chooses not to form that link. The difference is subtle, but will allow the analyst to show the using military organization whether a change is needed in terms of hardware procurement or doctrinal text. The doctrine specifies whether or not the Army will work with the Air Force. The same matrix may specify the procedures; that is, it may state that the Army must first talk to the Joint Command as a conduit for talking to the Air Force.

The using military organization can run the simulation with their identified control structure alternatives and conduct comparative analyses against various other control architectures and control doctrine.

F.   INITIAL CONTROL MODEL

The diagram in Figure 3 depicts an initial model of the interactions that occur at a unit headquarters with regards to the receipt, processing, and passing of information.

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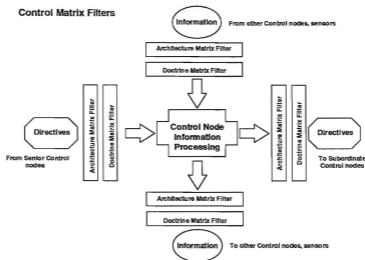
Figure 3. Nodal Control Model

The Architecture Matrix Filter addresses the communication hardware realities that exist between nodes. Information can only be permitted to flow if a link exists. If a link does exist, the passing of information is possibly delayed and/or perturbed. The Doctrine Matrix Filter addresses doctrinally and procedurally which nodes pass information. Although the Architecture Matrix Filter may have a possible link between two nodes, the doctrine may prohibit the link or may not address two nodes communicating together. This allows the analyst to identify if an improvement can be made non-materially, or if new hardware is required to improve control. The control node is where the information is processed, otherwise referred to as a "unit" in this thesis. The information is added to the current external data and the picture of the battlefield is refined as described by the Lawson Model. The control node addresses the capability of the staff to separate the wheat from the chaff by either being able to refine the new sensor information or by being mislead significantly and increasing the variance of the current estimate.

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G.   ASSUMPTIONS

The underlying premise for this research is the notion of organizational control. Organizational control is the degree of consensus within the organization to meet the stated objectives. An organization which holds similar perceptions and behaviors (courses of actions) acts in concert and is said to have a high degree of control. An organization which holds dissimilar perceptions and behaviors (courses of actions) acts in chaos and is said to have a low degree of control. An important assumption is that an organization acting in concert with a higher degree of control probabilistically provides better performance outcomes, while an organization acting in chaos probabilistically provides poorer performance outcomes.

This control model concept is based upon a distributed network allowing perceptions and courses of actions (COAs) at each node to be similar or dissimilar to the encompassing family of nodes to which it belongs. A node is defined as any operational unit where information and directives are processed to result in subsequent action (COA selection). Subsequent actions may also include directives and passing information to subordinate, adjacent and superior headquarters. Similar or dissimilar perceptions at a node are possible when the encompassing set, say friendly units, possess a unique and exclusive set of sensor sources that are owned by specified units. However, the sensor information, when and if passed to and interpreted at each unique friendly subordinate headquarters, may result in dissimilar perceptions of the battlefield. The same will be true for the opposing force. Furthermore, the network acts as a security network where access, both ingress and egress, may be open, interrupted, or closed between specified nodes for reasons of doctrine and/or capabilities (enabling technologies).

The Bernoulli distribution with a single mean probability parameter, ρ, is used to provide the analyst the ability to represent a successful or an unsuccessful receipt of a sensor-to-unit communication or a unit-to-unit communication.

The Lognormal distribution with a mean and a standard deviation parameter, μ and σ, is used to provide the analyst the ability to represent the positive time delay of a sensor-to-unit communication or a unit-to-unit communication.

The Staffing Ability Multiplier, α, provides the analyst a means to influence the variance associated with a sensor report as if the staff were able to confound or clarify the incoming report during the intelligence process.

H.   LIMITATIONS

Increasing the number of units with individual Bayesian update cycles which permit unique sub-unit perceptions increases the computing burden on the computer system hardware and subsequently increases the time for each replication. A replication with just one unit maintaining a perception may take 10 minutes, whereas a replication with thirty units maintaining individual perceptions may take longer than 48 hours depending upon the control architecture. Control architectures which allow all sensor reports to eventually reach all units are more computationally time intensive than control architectures limiting sensor reports to certain units.

Logistic units in the scenario no longer contribute to the perception update cycle after the time until attack and time until reinforcement are determined. This allows the simulation to process the combat unit sensor data in a more reasonable time with the associated decrease in memory allocation for the logistic units. Although this provides a lack of realism, since logistic units are not contributing to an opposing side's perception for the entire replication, the savings in time to run the replication justify the limitation when logistic units are not the immediate subject of interest.

I.   SCOPE

Six alternative control representations will be run to verify the control model. These alternatives will represent centralized information dissemination and decentralized information dissemination and sensor ownership. The base case, which reflects the current FTLM and a single perception for each operational side, will be the point of reference. An important note is that Case 5 produces the same theater perception that the base case produces. The base case is represented in Figure 4.

Information Flow
Base Case

Theater Unit $_1$ ← Sensor $_1$

Divisional Unit $_i$

(No Sub-unit Perceptions)

i = {Set of Divisional Units}
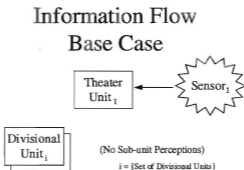
Figure 4. Base Case Control Representation

1.   Case 1

Case 1 consists of each divisional unit possessing a sensor defined to be capable of making observations restricted to the divisions corridor. The division in turn passes all sensor reports to the theater. The theater then sends the report from a division to each of the other divisions described on that operational side. The theater also possesses a sensor defined to be capable of making observations anywhere in the theater and sends each report to each of the divisions. The flow of information is two way, lower-to-higher and higher-to-lower. This alternative represents the greatest possibility of sharing information and the luxury of affording sensors to each divisional unit and above. Figure 5 depicts Case 1.

Information Flow
Case 1

$i = \{\text{Set of Divisional Units}\}$
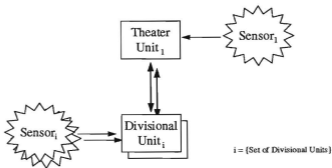
Figure 5. Case 1 Control Representation

2. Case 2

Case 2 consists of each divisional unit possessing a sensor defined to be capable of making observations restricted to the division's corridor. The division does not pass any sensor report to the theater. The theater also possesses a sensor defined to be capable of making observations anywhere in the theater and sends each report to each of the divisions. The flow of information is one way, higher-to-lower. This alternative represents a centralized structure of control while maintaining the luxury of affording sensors to each divisional unit and above. Figure 6 depicts Case 2.

Information Flow
Case 2
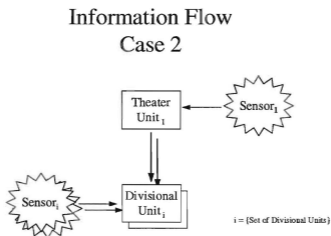
Figure 6. Case 2 Control Representation

3. Case 3

Case 3 consists of each divisional unit possessing a sensor defined to be capable of making observations restricted to the division's corridor. The division in turn passes all sensor reports to the theater. The theater is capable of accepting information from subordinate units, but does not send information back to the subordinate units. The theater also possesses a sensor defined to be capable of making observations anywhere in the theater but, again, does not share sensor reports with the divisions. The flow of information is one way, lower-to-higher. This alternative represents a centralized structure of control while maintaining the luxury of affording sensors to each divisional unit and above. Figure 7 depicts Case 3.
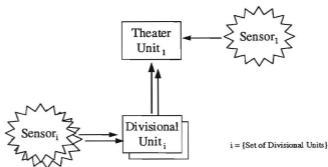
Figure 7. Case 3 Control Representation

4.   Case 4

Case 4 consists of each divisional unit possessing a sensor defined to be capable of making observations restricted to the division's specified corridor. The division in turn passes all sensor reports to the theater. The theater is capable of accepting information from subordinate units, but does not send information back to the subordinate units. The theater does not possess a sensor. The flow of information is one way, lower-to-higher. This alternative represents a centralized structure of control while maintaining the luxury of affording sensors to each divisional unit but not to the theater. Figure 8 depicts Case 4.

Information Flow
Case 4

$i = \{\text{Set of Divisional Units}\}$
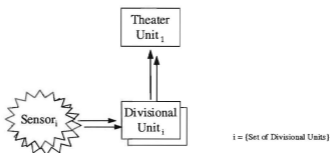
Figure 8. Case 4 Control Representation

5.   Case 5

Case 5 consists of the theater possessing a sensor defined to be capable of making observations anywhere within the theater. The theater is capable of passing information to each subordinate unit. The divisional units do not possess sensors. The flow of information is one way, higher-to-lower. This alternative represents a centralized structure of control with only one sensor. Figure 9 depicts Case 5.

Information Flow
Case 5

Theater Unit$_1$ → Sensor$_i$

Divisional Unit$_i$

$i = \{Set\ of\ Divisional\ Units\}$
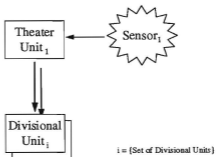
Figure 9. Case 5 Control Representation

6. Case 6

Case 6 consists of each divisional unit possessing a sensor defined to be capable of making observations anywhere along the division's corridor. The division does not pass sensor reports to the theater. The theater is not capable of accepting information from subordinate units. The theater also possesses a sensor defined to be capable of making observations anywhere in the theater but, again, does not share each report to each of the divisions. The flow of information does not exist beyond the reports provided by sensors owned by the receiving unit. This alternative represents an unconnected structure of control while maintaining the luxury of affording sensors to each divisional unit and above. Figure 10 depicts Case 6.

Information Flow
Case 6

$i = \{\text{Set of Divisional Units}\}$
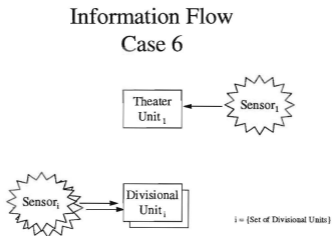
Figure 10. Case 6 Control Representation

J.   TEST DESIGN

The testing of the general control model as implemented in FTLM will require an operational context in which to conduct the test. The operational context will be the Korean Peninsula. The test run will be conducted in three parts. The first part will be to run replications using the six previously defined control representations, Case 1 through Case 6, while holding the parameters fixed. The second part will be to run the Case 1 control representation and varying the previously defined parameter sets.

1.   Test Scenario

The Korean peninsula scenario, currently in use by the FTLM research team and developed by CPT Greg Brouillette (Brouillette, 1994) and LT Mike Fulkerson (Fulkerson, 1994), is the operational context for the integrated control model analysis. The scenario consists of two opposing sides; the North is called Red and the South is called Blue. Both sides are composed of Army, Navy, Air Force, and Marine units. The general scenario consists of a logistics build-up in North Korea and the early entry required by U.S. forces to augment South Korean forces and already emplaced U.S. forces. An estimated attack time is calculated for the North Korean forces and the Southern forces prepare to defend according to that estimate. Once the attack is launched by the North, the battle commences until either North or South win.

There are three courses of action defined in the scenario data file. The three courses of action, from which the simulation must assign probabilities, possess similarities which will provide a more rigorous test than having three courses of action which possess no similarities; and which are thereby easier to determine as ground truth by simple elimination.

For example, if three courses of action follow three distinct and unique corridors which share absolutely no nodes or transit nodes, any sensor report on any node or transit node will immediately point to a unique and corresponding course of action. The remaining two courses of action will be eliminated and the prior to the Bayesian update cycle will be represented by 1.0 for the ground truth course of action. To ensure that the

prior can never reach 1.0, and thereby permit the Bayesian update cycle to be capable of being changed from the currently held perception when new sensor reports are generated, a number close to 1.0, but not 1.0, will always replace a prior of 1.0, if attained. For practical purposes of affording the Bayesian update a chance to change when conditions are such that the prior becomes absolutely certain of a course of action, this change is necessary and reasonable. The Bayesian update cycle will be discussed further in Chapter III.

The test runs will all use course of action one as the opposing force, or Enemy, ground truth course of action. For a complete description of the courses of action and the operational scenario, refer to the thesis by CPT Brouillette (Brouillette, 1994) and the thesis by LT Fulkerson (Fulkerson, 1994). The scenario and the ground truth course of action will remain the same for all replications.

2. Control Representation Test Runs

For the first part, two sets of replications will be made for each of the control representation case alternatives. The first set of replications will consist of a simple test run using just two units with individual perceptions, the theater and a divisional combat unit. This will provide a fundamental check that the assertions of the general control model are behaving in a manner commensurate with the intent of the design.

The second set of replications will consist of a rigorous test run using eleven units with individual perceptions; the theater, six combat units, three naval units, and an airbase. This will provide a second check that the assertions of the general control model are behaving in a manner commensurate with the intent of the design. Each run will be analyzed for general trends.

Parameters for the mean and variance of the time delay, the probability of a successful receipt of a transmission, and the staffing ability multiplier will all be fixed to a set of values to ensure that these parameters do not confound the comparison of control representations. Table 1 shows the base set of parameter values which will be used for the first part of the analysis, with time parameters given in minutes.

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	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ^2)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	1.0	1.0	1.0	1.0

Table 1. Parameter Set 1

3.   **Parameter Set Test Runs**

For the second part, the parameters will be varied to determine the effect they cause during the course of a replication and their propensity to reflect realism of the characteristics they intend to model. General trends will be drawn from the replications and the sets of parameters. The general trends will be discussed as to whether they follow a common sense representation of reality and if the model is capable of providing a usable model for the described research objectives.

The following descriptions of the parameter sets will be used for the second part of the analysis. Table 1 consists of the parameter values used in the first part of the analysis. This set will serve as the initial base case for comparisons between the subsequent parameter sets. Table 2 shows Parameter Set 2. Parameter Set 2 decreases the Bernoulli parameter (ρ). All other parameters remain the same as in Parameter Set 1.

	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ²)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	0.90	0.90	0.90	0.90
Staffing Ability Multiplier (α)	1.0	1.0	1.0	1.0

Table 2. Parameter Set 2

Table 3 shows Parameter set 3. Parameter Set 3 increases the Lognormal delay time mean (μ) and variance (σ²) parameters.

	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	30	30	120	60
Delay Time Lognormal variance (σ²)	5	5	30	15
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	1.0	1.0	1.0	1.0

Table 3. Parameter Set 3

Table 4 shows Parameter set 4. Parameter Set 4 increases the Staffing Ability Multiplier. All other parameters remain the same as in Parameter Set 1.

	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ²)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	5.0	5.0	5.0	5.0

Table 4. Parameter Set 4

Table 5 shows Parameter set 5. Parameter Set 5 decreases the Staffing Ability Multiplier. All other parameters remain the same as in Parameter Set 1.

	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ²)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	0.8	0.8	0.8	0.8

Table 5. Parameter Set 5

4. **Excursion Test Runs**

The third part will be an excursion to determine the limitations associated with increasing the number of units with individual perceptions and the amount of time required

to run the replication, and a composite case with the control representation shown in Figure 11 depicts the Composite Case.
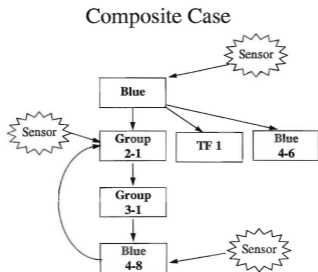
Composite Case

Figure 11. Composite Case Control Representation

III.   GENERAL CONTROL MODEL METHODOLOGY AND FUTURE THEATER LEVEL MODEL IMPLEMENTATION

A.   DEFINITION OF UNIT PERCEPTION

Central to the development of the general control model is the ability for a unit to maintain a perception (Π) of its environment within a computer simulation. Webster's New Collegiate Dictionary defines perception as "a mental image or awareness of the elements of environment through physical sensation." For the general control model, a unit perception embodies the commanders opinion of the enemy units he is facing and the enemy course of action being pursued, thus providing the commander a basis of knowledge from which to decide upon an appropriate counter-measure. Note the use of the word opinion. Webster's defines opinion as " a belief stronger than impression and less strong than positive knowledge." Decisions are rarely made with perfect knowledge. A unit's perception represents an accumulation of the available sensor knowledge and does not necessarily reflect omniscience or ground truth. A perception represents a body of knowledge consisting of what is believed to be the best available information.

The definition of a unit perception for the general control model is what the commander believes to be the current number, type, and composition of enemy units, referred to as the order of battle, and the current course of action the enemy is most likely to pursue. The unit perception of both order of battle and enemy course of action is based on sensor information in the form of counts of enemy soldiers, vehicles, and weapon systems and the location of these quantifiable attributes. The perception of both enemy order of battle and enemy course of action is the unit's belief of the relative likelihood of the possible unit numbers, types, and combinations and the possible course of action alternatives. A unit perception is further defined to be a probability vector of the possible number, types, and combinations of enemy units and the possible enemy courses of action.

This definition of unit perception provides the framework for the general control model.

B.   GENERAL CONTROL MODEL

The general control model is composed of eight major components.   The components are:

1. the capability for units to maintain their own, individual perception of the battlefield environment and the corresponding enemy course of action, as denoted by Π_i;

2. the capability to describe unit ownership of sensor assets and specify the sensor characteristics commensurate with the hierarchical level of the unit;

3. the capability to restrict a unit to acquire sensor observations from geographic locations within the unit's area of influence;

4. the capability to describe sensor-to-unit and unit-to-unit relationships due to the enabling technologies infrastructure, called the control architecture and denoted by an arrow;

5. the capability to describe sensor-to-unit and unit-to-unit relationships as prescribed by doctrine, called the control doctrine and denoted by an arrow;

6. the capability to describe a stochastic time delay of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $TD(\mu_{ij}, \sigma_{ij})$;

7. the capability to describe a probability of receiving a message to simulate the loss of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $PR(\rho_{ij})$; and

8. the capability to describe a staffing ability multiplier that is a characteristic of an individual unit and indicative of the unit's ability to perform the staff function of processing information, denoted as $SAM(\alpha_i)$.

For example, given two units called Unit i and Unit j, where Unit i is not Unit j, and Unit i and Unit j belong to the set of all sensors and units described in the operational

scenario of the computer war game simulation, the eight components of the general
control model are applied in Figure 12.
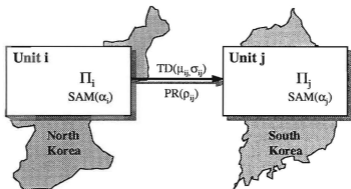
Figure 12. General Control Model with Major Components Applied to Two Units

Component 1 is represented by Π_i and Π_j where both Unit i and Unit j maintain
their own perception of the environment. Component 2 is represented by Unit i, which for
this example, is a sensor and is owned by Unit j. Unit j directly receives Unit i's sensor
information. Component 3 is represented as the geographic areas of North and South
Korea. Unit i, acting as a sensor, is restricted to only acquire sensor observations from
North Korea. The directed sensor-to-unit and unit-to-unit relationships due to
Component 4, enabling technologies, and Component 5, doctrine, are represented by the
arrow between Unit i and Unit j. If a sensor-to-unit or unit-to-unit relationship does not
exist because of either the control architecture, Component 4, or the control doctrine,
Component 5, the directed flow of information as represented by an arrow will not exist
and the sensor observation information may not flow directly between the two units.
Component 6, the time delay of sensor information, is represented in association with the
directed arrow between Unit i and Unit j as $TD(\mu_{ij}, \sigma_{ij})$. Component 7, the probability of
receiving a message, is represented in association with the directed arrow between Unit i

and Unit j as PR(ρ_{ij}). The Staffing Ability Multiplier, Component 8, is represented for both Unit i and Unit j as SAM(α_i) and SAM(α_j), respectively.

Figure 5 through Figure 10 depicted in Chapter II represent six general sensor-to-unit and unit-to-unit relationship structures. These six relationship structures will be used to test whether or not the general control model behaves in a realistic and analytically useful manner when coupled with a set of parameters for time delay, probability of receipt and the staffing ability multiplier.

It is important to recall that the general control model is designed to allow an analyst interested in understanding the effects of varying control structures within an operational context to describe, test, and analyze any control structure of interest for the set of sensors and units contained in the operational scenario. Any directed, linked relationship that can be described between a set of units is capable of being represented by the analyst. For example, an analyst can represent the flow of information in the following manner.

A theater owns a sensor which provides the theater sensor observations. The sensor-to-unit description specifies the sensor observation to arrive at a variable time in the future. It also specifies a variable chance of a successful and complete receipt of the observation. The theater, upon receipt of the sensor observation, processes the sensor observation while applying the theater Staffing Ability Multiplier. In turn, the theater passes the sensor observation onto two of six subordinate Army units, a Navy Battle Group, and an allied Air Force airbase as outlined by the unit-to-unit description with the unit-to-unit specified variable time delay and probability of receipt. Each unit, upon receipt, processes the sensor observation while applying its own specified Staffing Ability Multiplier. The two Army units send the sensor observation information to their respective two subordinate Army units. The Navy Battle Group sends the sensor observation information to the remainder of the group. The Air Force airbase sends the sensor observation to each of the subordinate wings.

Each subsequent unit receives the sensor observation according to the unit-to-unit description of time delay and probability of receipt parameters and processes the sensor observation while applying the associated unit Staffing Ability Multiplier. A description of the components of the general control model is given below.

1. Individual Perceptions

The first component of the general control model is the capability for units to maintain their own, individual perceptions of the battlefield environment and the enemy course of action (COA). This enables the realistic quality that different units may hold differing views of the enemy, and plan and potentially execute differing courses of action in the absence, or delay, of timely and accurate information. Different unit types may be represented to include Army, Air Force, Navy, Marine, and Allied units. Subordinate units of an operational side can be compared to each other and the hierarchically controlling unit to see if perceptions and the selected enemy courses of action are similar or supporting. Furthermore, if an operational side is determined to be pursuing a similar course of action as evidenced by all or a majority of the units contained on that operational side, the selected course of action can be compared to the enemy ground truth which is maintained in FTLM. This provides a means to determine if an operational side is working towards a common and accurate or inaccurate goal. Additionally, if an operational side is not working towards a common goal, and one or more units have differing perceptions of the battlefield and believe the enemy is pursuing different courses of action, the possible cause for the perception disconnect can be traced. Changes made to the control architecture, control doctrine, probability and/or timeliness of receiving the sensor observation information, the staffing ability multiplier, or any combination of these components will impact on the ability for an operational side to share a similar perception of the battlefield. The consequences of units sharing, or not sharing, the "commanders intent" can be determined with the foundation capability for units to maintain their own, individual perceptions of the battlefield environment and the enemy course of action (COA).

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2.   Unit Ownership Of Sensor Assets

The second component of the general control model is the capability to describe unit ownership of sensor assets and specify the sensor characteristics commensurate with the hierarchical level of the unit. Each sensor is of a type which is defined by the equipment types it can perceive and the sensor standard deviation by equipment type when perceiving that equipment type. A unit may own a sensor, meaning that when the unit makes a detection, the unit has the ability to send out a sensor to refine the information regarding the detection. The sensor observes the location where the detection occurred and reports back to the unit. For the analysis in this thesis, only one sensor type will be used to ensure that the effects due to different sensor types with different capabilities do not confound the results.

3.   Acquire Sensor Observations

The third component of the general control model is the capability to restrict a unit to acquire sensor observations from geographic locations within the unit's area of influence. Units will be defined according to the geographic area where they might possibly receive sensor observations. Not every unit will traverse every key geographic feature contained in the area of operations. Units can be restricted to a finite and listed set of geographic areas where they might possibly receive sensor observations.

The capability to restrict a unit to acquire sensor observations from geographic locations within the unit's area of influence presents a more realistic representation and prohibits a unit from receiving a sensor report from a geographic area outside of the unit's area of interest.

4.   Control Architecture

The fourth component of the general control model is the capability to describe sensor-to-unit and unit-to-unit relationships due to the enabling technologies infrastructure, called the control architecture. Table 6 represents the structure of the control architecture matrix and is used to conveniently show who can talk to whom.

	Sensor 1	Sensor 2	Theater A	Division 1	Division 2
Sensor 1	N/A	0	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	0	0
Sensor 2	0	N/A	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	0	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$
Theater A	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	N/A	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$
Division 1	0	0	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	N/A	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$
Division 2	0	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	1, $TD(\mu_{ij},\sigma_{ij})$, $PR(\rho_{ij})$	0	N/A

Table 6. Example of a Control Architecture Matrix

For this example, Sensor 1 can only communicate with Theater A, as indicated by the first entry identifier of "1". The second entry, $TD(\mu_{ij},\sigma_{ij})$, represents the stochastic time delay and the third entry, $PR(\rho_{ij})$, represents the stochastic probability of receipt. Entries with a "0" indicate that sensor-to-unit or unit-to-unit direct enabling technology does not exist. For example, Division 2 cannot communicate directly with Division 1. However, a path exists through Theater A for Division 2 to provide information to Division 1. This path has the potential to lengthen the time delay and decrease the probability of receipt.

Each of the potential sensor-to-unit and unit-to-unit links suffers from the consequences of a time delay associated with staff processing and the possible loss of the message associated with a probability of receipt, whether the loss occurs on the air waves or within a tactical operations center due to human neglect. In a broad sense, the control architecture, the time delay, and the probability of receipt represent the third C of C3; communications. Communication is addressed only as a foundation upon which control can be studied.

5.   Control Doctrine

The fifth component of the general control model is the capability to describe sensor-to-unit and unit-to-unit relationships as prescribed by doctrine, called the control doctrine. Figure 7 represents the structure of the control doctrine matrix and is used to conveniently show who chooses to talk to whom.

	Sensor 1	Sensor 2	Theater A	Division 1	Division 2
Sensor 1	N/A	0	1	0	0
Sensor 2	0	N/A	1	0	1
Theater A	1	1	N/A	1	1
Division 1	0	0	1	N/A	0
Division 2	0	1	1	0	N/A

Table 7. Example of a Control Doctrine Matrix

For example, doctrine prescribes that Division 1 may report information to the Theater A, but to no one else. The control architecture matrix indicated that enabling technology existed between Division 1 and Division 2 such that the two Division have the capability to communicate and can talk. However, since doctrine dictates that Division 1 may not talk with Division 2 directly, the associated directed flow of information represented by the arrow in Figure 12 and defined in the control architecture matrix is deleted and is no longer considered as a viable directed link. Recall that the control architecture and the control doctrine capabilities may appear, at first, to be redundant. Keeping these two components separate will allow the analyst to describe whether the enabling technology or the doctrine or both prohibit a sensor-to-unit or unit-to-unit directed link. Only when the control architecture and the control doctrine describe a sensor-to-unit or unit-to-unit link will a viable directed link exist with the associated time delay and probability of receipt.

The control doctrine represents the general path of achieving information flow as envisioned by doctrine and the commander. It establishes the procedures for the routing of that information. The general control model as implemented within FTLM provides a critical capability that USMTM requires to demonstrate potentially better, and consequently joint, control architectures and control doctrines to the Ministry of Defense and Aviation in the Kingdom of Saudi Arabia. The previous examples of a control architecture matrix and a control doctrine matrix indicate that Division 1 "technologically" can and "doctrinally" chooses to receive information only from Theater A. Division 2 may be an ally or represent a sister service; such as an Army division, a Marine division, an Air Force wing, or a Navy group where either enabling technology limitations and/or doctrine prohibit the transmission of information directly from Division 1 to Division 2 and must first pass through Theater A. The analyst will be able to create or delete the directed sensor-to-unit or unit-to-unit links to determine a sufficient or optimal control structure given limited resources to obtain a similar perception of the battlefield among units on an operational side.

6.   **Time Delay Of Sensor Information**

The sixth component of the general control model is the capability to describe a stochastic time delay of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $TD(\mu_{ij}, \sigma_{ij})$. Time delays are represented using a Lognormal distribution with scale parameter μ, the mean, and shape parameter σ, the standard deviation. The Lognormal distribution is often used to simulate the time to perform some task and ensures non-negative values. (Law, 1991) A Monte Carlo process is used to stochastically vary the time a sensor observation spends being processed at the receiving unit before it can be passed to subsequent units. The analyst specifies the mean and standard deviation associated with each directed sensor-to-unit and unit-to-unit link. The mean and standard deviations units are in minutes. Future development of the control model can address the hardware transmission times associated with specified enabling technology links and add them to the headquarters processing times, the mean and

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standard deviation associated with specified units, and a queuing model to vary the mean and standard deviation during times of increasing message traffic for a unit.

7. Loss Of Sensor Information

The seventh component of the general control model is the capability to describe the probability of receiving a message to simulate the loss of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $PR(\rho_{ij})$. A successful transmission will be reflected as either a complete message received, (1), or not received, (0). The probability of receiving a transmission is represented using a Bernoulli distribution with parameter ρ, the mean. The Bernoulli distribution is often used to simulate the random occurrence with two possible outcomes and will ensure either a complete message is received or lost. (Law, 1991) A Monte Carlo process is used to stochastically vary the occurrence of receiving a message at the receiving unit defined by the sensor-to-unit or unit-to-unit directed link. Future development of the control model can address specific mean parameter values associated with equipment reliability and human the staff process of processing information.

8. Staffing Ability Multiplier

The eighth component of the general control model is the capability to describe a staffing ability multiplier that is a characteristic of an individual unit and indicative of the unit's ability to perform the staff function of processing information, denoted as $SAM(\alpha_i)$. Given that a unit has a unique identity and is capable of processing information in either a reliable and timely fashion or in a not reliable and not timely fashion, new sensor information can be fused with previous perceptions to either better define the situation or increase the "fog of war." The staff's performance when processing information is a function of explicitly defined qualities such a training, personnel fill level, and experience. Future developments of the control model can create a function to map these qualities into a Staffing Ability Multiplier.

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C.   FUTURE THEATER LEVEL MODEL IMPLEMENTATION

The eight components of the general control model defined in the previous section have all been integrated into the most current version of FTLM. This section discusses the implementation of those eight components in FTLM as additions to both the executable code and the defining scenario network file. The scenario network file is used to establish the operational context of the simulation and is also used to define the parameters required for the executable code to function. The eight components will be discussed in two parts. The first part will pertain to the components which change the characteristics of individual units. The second part will pertain to the components which define the characteristics of directed sensor-to-unit and unit-to-unit links.

1.   Individual Units Components

a)   Individual Perceptions

The first component of the general control model implemented into FTLM is the capability for units to maintain their own, individual perceptions of the battlefield environment and the enemy course of action (COA). FTLM uses sensor observations to build a perception of the enemy force's type and size and then to estimate the enemy's prosecuted course of action based upon the accumulated sensor observations. The following two subsections are a summary from the study by Karl Schmidt describing FTLM. (Schmidt, 1993)

(1)   Enemy Force's Type and Size

The first step in building a perception of the enemy force's type and size is to compute the mean $m_j(u_i, N, t)$, and variance, $V_j(u_i, N, t)$, of the total number of j-assets of u_i units of type i, at node N, at time t. This computation is a two part process. First, the ground truth mean and standard deviation of the enemy unit assets are estimated. Second, the observed mean and standard deviation of the enemy unit assets are estimated.

The ground truth mean is calculated using the mean number of assets of type j that are with a unit of type i, denoted $\alpha_{i,j}$, and the standard deviation of the

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number of assets of type j that are with a unit of type i, denoted $\sigma_{i,j}$. The parameters $\alpha_{i,j}$ and $\sigma_{i,j}$ are tabled counts of all j-assets associated with units of type i prior to combat and are similar to a standard military Table of Organization and Equipment (TOE). These parameters are referred to by FTLM as TOE values.

Ground truth is estimated by a random draw for each unit for each j-asset from a normal distribution with a mean and standard deviation from the TOE values. The normal distribution is used in FTLM predominantly because of its ability to provide an approximation to a counting distribution, such as the binomial, and for mathematical convenience. The draw represents the actual number of assets of type j that will be in the respective unit. It is rounded to the nearest integer, or to zero for negative draws. The TOE standard deviation value is used to represent the number of j-assets for each unit.

This process is used to compute the mean and variance of the total number of j-assets of $\bar{u}$-unit combinations at node N, at time t based upon the unit TOE values. The computed means and variances are:

$$m_j(\bar{u};N;t) = \sum_{i=1}^{totun} u_i \alpha_{i,j} \tag{1}$$

$$v_j(\bar{u};N;t) = \sum_{i=1}^{totun} u_i \sigma^2_{i,j} \tag{2}$$

u_i is the number of units of type i and they are summed from one to the total number of unit types, denoted totun. $\bar{u}$ represents the sets of unit type combinations and is written as a vector equal to the number of units by unit type. For example, let $\bar{u}$ = (0 light infantry units, 4 armor units, 2 mechanized units).

Next, the observation of the j-assets of a unit of type i on a node N must be computed. A sensor which makes the observation has a list of attributes which describe its capabilities. The description consists of a sensor standard deviation which provides the error associated with the observation of a type j-asset. The standard

deviation, $\tau_j(s;N;t)$, is a function of the sensor type s in addition to the asset of type j, the node N, and the time of day t. Time of day reflects whether the sensor is observing during the day or the night.

An estimate is made of the numbers and types of units at node N. The sensor of type s from the set of all sensors S must determine the total number of j-assets at node N. A normal distribution is specified using the mean equal to the ground truth mean of the number of j-assets of all the units at node N along with the standard deviation of the sensor, $\tau_j(s;N;t)$. Again, a random number is drawn from the specified normal distribution to become the number of j-assets at node N, at time t; denoted $x_j(t)$. These observations are assumed to be independent in FTLM. The sensor observations are combined in vector form and written as:

$$\bar{x}(t) = (x_1(t), x_2(t), \ldots, x_J(t)) \tag{3}$$

where J represents the total number of j-asset-types. These sensor observations are used to compute the posterior distribution of the number and type of units at a node and is subsequently passed on to determine the perception of the enemy COA discussed in subsection (2).

Before the posterior distribution of the perception of the number and type of units at node N can be calculated, the initial prior distribution of each possible grouping of units at node N must be specified. The initial prior distribution uses the uniform distribution over the set of all possible groupings of units at a node thereby defining each grouping as equally likely.

Equation 4 gives the Bayesian posterior density for a mixture of normal distributions. This posterior distribution represents the updated probability of the number and type of units at a node N. Note that the new sensor observation is referred to as $\bar{x}(t+1)$ and $\bar{x}(t)$ refers to the past sensor observations. The product over j refers to those asset types detected by the sensor where c is the normalizing constant.

$$\Pi_{\text{unit}_i}\left(\overline{u}, \overline{x}(t+1); t+1; N\right) =$$

$$c * \Pi_{\text{unit}_i}\left(\overline{u}, \overline{x}(t); t; N\right) * \prod_j \left\{ \frac{\exp\left\{ -\frac{1}{2}\frac{\left(x_j(t+1) - m_j(\overline{u}; N; t)\right)^2}{\left(v_j^2(\overline{u}; N; t) + \left(\tau_j^2(s; N; t)\right)\right)} \right\}}{\sqrt{2\Pi\left(v_j^2(\overline{u}; N; t) + \tau_j^2(s; N; t)\right)}} \right\} \quad (4)$$

In addition to computing the posterior distribution, the groups of conditional moments of each asset type j which the sensor can detect, given the configuration of unit types at a node N, must be computed. If a sensor cannot observe an asset type, that conditional moment remains the same. The conditional moments are:

$$m_j(\overline{u}; \overline{x}; N; t+1) = \frac{v_j^2(\overline{u}; N; t) * x_j(t)}{v_j^2(\overline{u}; N; t) + \tau_j^2(s; N; t)} + \frac{\tau_j^2(s; N; t) * m_j(\overline{u}; \overline{x}; N; t)}{v_j^2(\overline{u}; N; t) + \tau_j^2(s; N; t)} \quad (5)$$

$$v_j^2(\overline{u}; \overline{x}; N; t+1) = \frac{v_j^2(\overline{u}; \overline{x}; N; t) * \tau_j^2(s; N; t)}{v_j^2(\overline{u}; \overline{x}; N; t) + \tau_j^2(s; N; t)} \quad (6)$$

These conditional moments, along with the posterior distribution in (4), are used to update the perception of the number and type of enemy assets unit types with each subsequent sensor observation.

    (2) Enemy Course of Action

    The development of the computations used to provide a perception of the enemy course of action is similar to the preceding discussion. Essential to determining the enemy COA is the definition of a COA. A COA consists of one or more avenues of approach which consists of more than one route. Each route consists of transit nodes and physical nodes. There may be multiple COAs and each may be very different or very similar, depending upon the schemes of maneuver, the objectives, the unit combinations associated with each route, or a combination of each mentioned attribute. COAs are represented by c and belong to the set of all COAs called C.

Three items are required for the initial calculation and the following perception updates, referred to as $\prod_{COA}(c; k+1)$. These items include the prior probability distribution of the enemy COA, $\prod_{COA}(c; k)$, of COA c, for the interval $[k\Delta, (k+1)\Delta]$; the variance of the error of the lth sensor observation, $\tau_{n,j}^{2}(l)$, as l goes from 1 to $b_k(N)$; and the sensor observation on node N, or asset j, $s_l(N, j, k)$, for all the $b_k(N)$ sensor observations in the interval $[k\Delta, (k+1)\Delta]$.

The initial prior probability distribution of the enemy COA is distributed uniform over the number in the set C of COAs. This provides an initial equally likely probability with each potential COA. The variance of the error of the lth sensor comes from the FTLM Scenario Data File Record which describes sensor attributes. $\tau_{n,j}^{2}(l)$ for the lth sensor observation is assigned the sensor standard deviation for the sensor type used for the lth observation. The sensor type standard deviation, $\tau_j(s; N; t)$, was discussed in the previous subsection.

Perceptions are updated in FTLM at a fixed time interval designated by the user-analyst. The perceptions of the enemy COAs are updated regardless of detection. At the kth perception update cycle, $b_k(N)$ sensor observations are taken at node N. The sensor observations, $x_j(t)$, have been defined in the previous section. The accumulation of the sensor observations between perception updates, $[k\Delta, (k+1)\Delta]$ where Δ is the user-analyst defined update time interval, is defined as $s_1(N, j, k)$. l is the lth ordered sensor observation from 1 to $b_k(N)$.

The computation of the perception update in FTLM is composed of the perceived mean and variance of the numbers of j-assets at node N, for perception cycle k, over the total of $b_k(N)$ sensor observations, which follow:

$$m_{N,j}(k) = \frac{\displaystyle\sum_{l=1}^{b_k(N)} \frac{S_l(N;j;k)}{\tau_{n,j}{}^2(l)}}{\displaystyle\sum_{l=1}^{b_k(N)} \frac{1}{\tau_{n,j}{}^2(l)}} \tag{7}$$

$$v_{N,j}{}^2(k) = \frac{1}{\displaystyle\sum_{l=1}^{b_k(N)} \frac{1}{\tau_{n,j}{}^2(l)}} \tag{8}$$

It is important to note that l resets itself at the start of each new perception update cycle. FTLM surveys all nodes that can be occupied during the time interval [kΔ, (k+1)Δ] for each avenue of approach (AA). Potentially occupied nodes are referred to as $N(AA;k)$. Subsequently, the model computes the perceived means and variances of the total number of observed j-assets over the entire avenue of approach during the interval [kΔ, (k+1)Δ] using the potentially occupied nodes and the mean and variance associated with the avenues of approach shown below:

$$m_j'(AA,k) = \sum_{n \in N(AA,k)} m_{n,j}(k) \tag{9}$$

$$v_j'(AA,k) = \sum_{n \in N(AA,k)} v^2{}_{n,j}(k) \tag{10}$$

Next, the moments of the total number of all units using avenue of approach AA, under course of action c, during the interval [kΔ, (k+1)Δ], is defined as a mean value using the TOE values previously discussed and is referred to as $\mu_j(AA,k,c)$. The standard deviation is calculated as 10 percent of the mean and is referred to as $\sigma_j(AA,k,c)$.

A unit normal density function is used to compute a normal distribution using the previously mentioned mean and standard deviation.

$$\xi_j(AA, k, c) = \frac{\exp\left\{\dfrac{-\dfrac{1}{2}\left(m'_j(AA, k) - \mu_j(AA, k, c)\right)^2}{\left(v'^2_j(AA, k) + \sigma^2_j(AA, k, c)\right)}\right\}}{\sqrt{2\pi\left(v'^2_j(AA, k) + \sigma^2_j(AA, k, c)\right)}} \tag{11}$$

It is important to note that the value of this normal distribution is 1.0 if no observations are made during the interval $[k\Delta, (k+1)\Delta]$.

Finally, the posterior distribution representing the probability that the enemy is using COA c during the interval $[k\Delta, (k+1)\Delta]$ is defined as:

$$\prod_{UNITi}^{FINALCOA}(c; k+1) = \frac{\prod_{COA}(c; k) * \prod_{AA}\prod_{j}\xi_j(AA, k, c)}{\sum_{C}\prod_{COA}(c; k) * \prod_{AA}\prod_{j}\xi_j(AA, k, c)} \tag{12}$$

Note that the sum of all COA probabilities is one. The Bayesian posterior distribution represents the updated probability of the perceived enemy course of action. The Bayesian posterior distribution applied in association with the general control model reflects the posterior distribution is for a specified unit i. The set from which unit i draws includes the theater and each divisional unit as defined in the operational scenario. Each combat, naval, or airbase unit has the capability to maintain its own perception. (Schmidt, 1993)

b)   *Unit Ownership Of Sensor Assets*

The second component of the general control model implemented into FTLM is the capability to describe unit ownership of sensor assets and specify the sensor characteristics commensurate with the hierarchical level of the unit. Table 8 represents a sensor-to-unit data structure from a FTLM Scenario Data File Record.

Sending Sensor	Receiving and Owning Unit	Control Architecture	Control Doctrine	Time Delay Mean	Time Delay Standard Deviation	Probability of Receipt
Red.Sens.1	Red	1	1	20	2	1.

Table 8. Sensor-To-Unit Data Structure

The sensor-to-unit data portion of the scenario network file describes unit ownership of sensors by type (Yamauchi, 1994, Section 35). Appendix A contains an extract from a FTLM Scenario Data File Record.

In Table 8, a theater unit called Red, column two, owns and receives sensor reports from a sensor of type Red.Sens.1, column one. Red.Sens.1 is defined elsewhere in the scenario network file (Yamauchi, 1994, Section 13). The remainder of the columns are explained later in this chapter. Refer to the thesis by Carl Schmidt for a complete explanation of sensors (Schmidt, 1993).

c) *Sensor Observations*

The third component of the general control model implemented into FTLM is the capability to restrict a unit to acquire sensor observations from geographic locations within the unit's area of influence. The following is an abbreviated excerpt from a FTLM scenario network file that describes this component:

```
    *End of sensor group data - start who receives sensor reports
    1
            PYONGYANG
    1
            Red.Div.1
    * end of who receives sensor reports - start sensor-to-unit data
```

The "start who receives sensor reports" portion of the scenario network file lists the units capable of receiving sensor observations of a specified geographic location. FTLM is based upon a physical node and transit node representation of the geographic

area of interest. (Schmidt, 1993) The first entry in this portion of the scenario network file is the number of nodes capable of being observed by other than the controlling theater unit. In this example only one node may be observed by the divisional units. The second entry is the name of the node, or geographic location. In this example the city of Pyongyang is described. The third entry is the number of divisional units capable of observing Pyongyang. In this example only one unit will be listed which can observe Pyongyang. The fourth entry is the name of the division capable of observing Pyongyang. In this example Red.Div.1 is capable of observing Pyongyang. (Yamauchi, 1994, Section 34)

d) *Staffing Ability Multiplier*

The eighth component of the general control model implemented into FTLM is the capability to describe a Staffing Ability Multiplier that is a characteristic of an individual unit and indicative of the unit's ability to perform the staff function of processing information, denoted as SAM(α_i). This paper will use three categories for the Staffing Ability Multiplier: one less than 1.0 to tighten the associated standard deviation of the new sensor observation about the ground truth number of units by type which the Bayesian posterior distribution is using as the mean, one at 1.0 which effects no change to the normal update computation, and one greater than 1.0 to spread the associated standard deviation of the new sensor observation about the ground truth number of units by type which the Bayesian posterior distribution is using as the mean. This thesis will determine if the Staffing Ability Multiplier behaves in a consistent manner and is worth additional future research.

Mathematically increasing or decreasing the sensor variance by a multiplier will either tighten or spread the new observation estimate from the sensor. This is convenient since the Bayesian update cycle centers about the ground truth number of units by type. This tightening or spreading of the new observation estimate by the unit simulates the unit processing of the sensor information more or less effectively as it is combined with the prior of the Bayesian perception update cycle.

The following equation represents the Staffing Ability Multiplier change made to the posterior distribution for Unit i, previously discussed in subsection (*a*).

$$\tau_{u,j}^{2}(l) \Leftarrow \alpha_i * \tau_j^{2}(s; N; t) \tag{13}$$

When Unit i updates its perception of the enemy COA, it applies the Staffing Ability Multiplier, α_i, to the sensor variance of the sensor type which is assigned to the lth sensor observation. This occurs for every sensor observation Unit i receives, either directly from a sensor or from another unit. The remainder of the perception update cycle is unchanged from the previous discussion. The Staffing Ability Multiplier is associated with units and is described in the unit description portion of the scenario network file. The Staffing Ability Multiplier must be a real number greater than zero. (Yamauchi, 1994, Sections 24, 25, 26, & 27)

2. Directed Link Components

The fourth, fifth, sixth, and seventh components of the general control model implemented in FTLM define the characteristics of the directed links. Table 9 represents these four components as a data structure from a FTLM Scenario Data File Record.

Sending Unit	Receiving Unit	Control Architecture	Control Doctrine	Time Delay Mean	Time Delay Standard Deviation	Probability of Receipt
Red	Red.Div.1	1	1	10	1	1.0

Table 9. Unit-To-Unit Data Structure

a) *Control Architecture*

The fourth component of the general control model implemented into FTLM is the capability to describe sensor-to-unit and unit-to-unit relationships due to the enabling technologies infrastructure, called the control architecture. The third column

entry of Table 9, Control Architecture, describes the control architecture. If the entry is one, the sensor or unit in the first column can communicate with the unit in the second column, and zero otherwise. In this example, Red has a directed, enabling technology communications capability with Red.Div.1. (Yamauchi, 1994, Section 35)

To prevent a cycle from occurring and the same sensor observation information being posted to the Bayesian posterior distribution, a flag is used within FTLM to ensure that a message is not received and processed more than once if the specified control architecture matrix describes a cycle.

b) *Control Doctrine*

The fifth component of the general control model implemented into FTLM is the capability to describe sensor-to-unit and unit-to-unit relationships as prescribed by doctrine, called the control doctrine. The fourth column entry of Table 9, Control Doctrine, describes the control doctrine. If the entry is one, the sensor or unit in the first column chooses to communicate with the unit in the second column, and zero otherwise. In this example, doctrine specifies that Red share information with Red.Div.1. (Yamauchi, 1994, Section 35)

c) *Time Delay Of Sensor Information*

The sixth component of the general control model implemented into FTLM is the capability to describe a stochastic time delay of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $TD(\mu_{ij}, \sigma_{ij})$. The fifth and sixth column entries of Table 9, Time Delay Mean and Standard Deviation, describe the parameters of the Lognormal distribution associated with the specified sensor-to-unit and unit-to-unit directed link described by the first and second column. The fifth column entry specifies μ, the mean. The mean time delay must be greater than zero and is in minutes. The sixth column entry specifies σ, the standard deviation. The time delay standard deviation must be greater than zero and is in minutes. In this example, the mean of the time delay between Red and Red.Div.1 is 10 minutes with a standard deviation of 1 minute. (Yamauchi, 1994, Section 35)

d) *Loss Of Sensor Information*

The seventh component of the general control model implemented into FTLM is the capability to describe the probability of receiving a message to simulate the loss of sensor information associated with each directed sensor-to-unit and unit-to-unit link, denoted as $PR(\rho_{ij})$. The seventh column entry of Table 9, Probability of Receipt, describes the parameter of the Bernoulli distribution associated with the specified sensor-to-unit and unit-to-unit directed link described by the first and second columns, respectively. The seventh column entry specifies ρ, the probability mean. The probability of receipt mean must be a real number in the range of zero to one. In this example, the probability of receipt mean is 1.0 between Red and Red.Div.1. This simulates that Red.Div.1 receives all messages from Red. (Yamauchi, 1994 Section 35 & 36)

IV.   RESULTS AND ANALYSIS

This chapter presents the results from the test design discussed in Chapter II and determines whether or not the general control model, as implemented in FTLM and discussed in Chapter III, is consistent with representing a realistic simulation capability of battlefield control.

The results will be presented and discussed in three parts. The first part will address the test run of two sets of replications for the base case and each of the alternative cases. The first set of replications will consist of a simple test run using just two units with individual perceptions; the theater and a combat unit. The second set of replications will consist of a more rigorous test run using eleven units with individual perceptions: the theater, six combat units, three naval units, and an airbase.

The second part will address the variations in parameters for the characterization of time delays, probabilities of receipt, and unit staffing abilities with information. The applicable parameters will be varied to determine the effect they cause during the course of a replication and their propensity to reflect realism of the characteristics they intend to model.

The third part will be an excursion to determine the limitations associated with increasing the number of units with individual perceptions and the amount of time required to run the replication. A composite case representing a few of the defined cases in Chapter II will also be discussed to show the robust capability to model various control representations.

The results for each test run replication will be presented in the form of a chart. Each chart will display the trends associated with the unit perceptions of the Red ground truth course of action over time in days. Because the purpose of this analysis is to demonstrate the similarity or dissimilarity between trends in unit perceptions, the magnitude of the COA probabilities are not included. Furthermore, the computer algorithms used to compute the COA updates have not yet been subjected to rigorous

verification. Since the analysis is only concerned with determining similarities in the correct perception of the battlefield, this chart representation is an adequate means to display the results. An audit can be made between a unit's changing perception, and the sensor-to-unit or unit-to-unit sensor observations, using the sensor observation history file which is available for each replication. Appendix B contains an extract from a sensor observation history file. FTLM is designed to provide the analyst all information on the replication which is produced within the simulation. Selecting the optional history file record to be generated and selecting sensor observations, each replication will provide the analyst the audit capability. Sensor observation history files can be anywhere from a few hundred pages to a few thousand pages depending upon the number of units with individual perceptions and the control representation. The sensor observation history reflects each sensor observation that is made, from the initial detection to the passing of that sensor observation between units as defined by the control representation in the scenario network file.

A.   TEST RUN

1.   Two-Unit Test Run of Korean Scenario

a)   Case 1

Case 1 is shown in Figure 13. For Case 1, both units have sensors and information which is shared higher-to-lower and lower-to higher.

The chart shows that both units share the same perception for the duration of the test run. Both units begin at time zero with an equal probability of the three possible courses of action. When presented more than one course of action, FTLM currently uses the notion of equally probable amongst all courses of action for the initial start of the simulation. In this case, since there are three COAs, a Blue unit initially perceives each of them initially to be equally possible. Each chart presented in this research has units initially perceiving each COA to be equally probable.

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The following is an explanation of the curves represented on a Figure 13. Recall that each curve represents a Blue unit's perception that it correctly perceives the Red ground truth COA. Time increments and the associated perception probability value coincide with COA updates which are set to occur every 6 hours or 0.25 days.

Case 1 - Parameter Set 1 - 2 Units
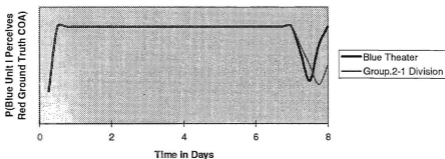
Figure 13. Case 1, Two Units

At time zero, each unit perceives the ground truth COA with an equally likely prior. At time 0.25 days, Blue Theater makes its first detection on transit node 112. It immediately schedules a sensor to go to the physical node where the detection occurred. Blue Sensor observes a Red unit on transit node 112 and counts 48 tankers and 76 flatbeds from a logistics units. Transit node 112 is occupied in ground truth by a Red logistics unit with 45 tankers and 76 flatbeds. The observed count of the assets by type for a logistics unit is very close to the ground truth. The following is an explanation of the application of this sensor information to the Bayesian posterior distribution for a mixture of Normal distributions associated with Blue Theater.

Once the observation, in the form of a count of assets by asset type of a unit by unit type, has been made for a specified node; a comparison of the expected asset count by asset type of a unit by unit type for that node is made for each COA. This comparison uses the Bayesian distribution to record and maintain the information in the

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form of a posterior. If the comparison of the observed count to the expected count yields a small deviation, meaning the two counts are similar, and after normalization by the variance of the expected count of assets of a unit type and the variance of the sensor, a relatively large number occurs within the range of zero to one. This process is performed for each asset count by asset type of a unit-by-unit type for a specified node. Each comparison is combined as a product. If all the observed counts of assets are similar to the expected asset counts, a product consisting of relatively large numbers close to one results. The resulting product, called the posterior, is the probability that the observing unit perceives that COA as ground truth. This occurs for each of the COAs.

Described in the FTLM Scenario Data File is a listing by COA of the avenues of approach and the corridors to be used by unit for that COA. Each avenue of approach and corridor consists of nodes and expected units by unit type to be found on those nodes. When the observed information is compared to the first COA, in this case COA One, a query is made to determine if the node where the observation was taken is contained in the description of the COA as part of an avenue of approach or corridor. Once it is determined that transit 112 is contained in COA One, a comparison is made by asset type and by unit type.

If a node is contained in multiple COAs, overlap occurs which may cause confusion when comparing a unit's perception to ground truth. If the expected asset count by asset type of a unit-by-unit type is similar between two or more COAs, there is a chance that the observation may be closer, providing smaller deviation when compared to the expected count, to a COA which is not the ground truth. The sensor observation is stochastic and is influenced by the standard deviation of the sensor. Generally, good sensors with smaller standard deviations will provide observations closer to the ground truth than poor sensors with large standard deviations. This realistic modeling of sensor information is the reason why charts later in this chapter will depict a unit perceiving the ground truth COA with near certainty, and suddenly perceiving the ground truth COA with a smaller probability.

In Case 1, the node and the associated expected asset count is clearly defined as part of COA One. This process occurs for observations by Blue Theater on transit nodes 109, 110, 113, 111, and physical node Pyongyang. Group.2-1 makes one observation of physical node Haeju. Each observation results in comparisons with small deviations from the expected asset count. A few of the observations are on nodes with expected asset counts which are clearly defined for COA One. The result of these observations and the comparisons using the Bayesian posterior distribution by COA update at time 0.5 days is that Blue Theater perceives the ground truth COA with a posterior probability near certainty. After each sensor observation and subsequent perception update, the posterior becomes the prior for the next perception update. This allows the previous perception to be remembered along with the current information. Once a strong opinion is formed by the posterior, a value close to one, it requires substantial sensor observations to decrease the posterior value.

This audit process can be performed for the remainder of chart using the 836 page history file of sensor observation information for this one simulation run. The initial five days of the scenario represents a logistics build-up by North Korea. The majority of sensor activity, and therefore observations concerns logistic units. Battle does not begin until the start of the sixth day. As combat units, in this case Group.2-1, begin to maneuver according to the scripted counter COA, detections occur which cause observations on physical nodes that decrease the posterior value associated with the ground truth COA. This occurs because of the overlap of physical nodes and the expected count of assets by asset type and by unit type for more than one COA. In this scenario, COA One and Two are very similar. Many of the nodes and the expected units are very similar. This makes it difficult to determine which is the correct COA to perceive and the model represents this confusion realistically.

At COA update time day 7.0, the Blue units still perceive the ground truth COA with near certainty. Observations occur on nodes defined for both COA One and COA Two and by COA update time day 7.25, Blue perceives Red's ground truth COA as

shown in Figure 13. By COA update time 7.5, Blue's perceptions have changed, as indicated in the figure. Observations after this time occur on nodes more clearly defined for COA One, and the chart depicts the Blue units perception of the ground truth COA to increase towards certainty.

Auditing the history file and observing the chart, the units are sharing the information according to the Case 1 control representation. Once a sensor observation is received by the owning unit, that unit sends the information to the other unit as described by the control representation. Each transmittal can be checked using the audit process. The slight lag by the division is appropriate considering the parameters for the time delay when receiving a sensor observation from the theater. The units in Case 1 behave in accordance with the intent of the control representation.

                b)   *Case 2*

Case 2 is shown in Figure 14. For Case 2, both units have sensors and information which is shared higher-to-lower. The theater perceives only according to its own sensor observations while the division has both its own sensor observations and, eventually, the theater sensor observations. Note that if there were more than one divisional unit, divisional sensor observations would not be shared and each division would perceive only according to its own sensor observations and the theater observations.

Case 2 - Parameter Set 1 - 2 Units

Figure 14. Case 2, Two Units

The chart shows that both units share the same perception for the duration of the test run. Again, both units begin at time zero with an equal likelihood of the three enemy COAs. As in Case 1, Blue Theater detects a Red unit on a physical node at time 0.25 days. The same description of events as discussed in Case 1 applies to Case 2 and will not be repeated. Auditing the history files show that the majority of observations are being made by Blue Theater which is not restricted to a limited set of physical and transit nodes which it can sense. Blue Theater can send sensors to any defined location in the simulation. The similarity suggests that Blue Theater observations are predominantly influencing the posterior for all units who receive the observations, in this case Group.2-1, and this is indeed the case when reviewing the history file. The units in Case 2 appear to behave in accordance with the intent of the control representation given only one divisional unit.

    c)   Case 3

Case 3 is shown in Figure 15. For Case 3, both units have sensors and information is shared lower-to higher. The division perceives only according to its own

sensor observations while the theater has both its own sensor observations and, eventually, the division sensor observations. Note that if there were more than one divisional unit, divisional sensor observations would not be shared and each division would still only perceive according to its own sensor observations. The theater is a composite perception of all available sensor information.
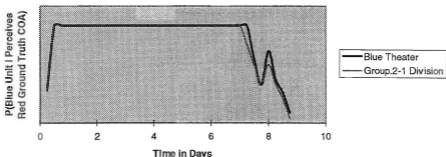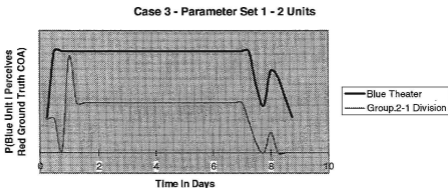

Figure 15. Case 3, Two Units

The chart shows that both units do not share the same perception for the duration of the test run. Again, at time 0.25 days, Blue Theater receives the sensor observations as previously discussed throughout the run of the simulation. However, at time 0.5 days, Group.2-1 detects a Red unit which is occupying a physical node within its area of influence. This observation and the associated count of assets by asset type and by unit type contributes to the COA update cycle in such a way to indicate that Group.2-1 perceives a course of action other than the ground truth COA. The physical node is defined similarly for two COAs. This is represented by the posterior associated with the ground truth COA which decreases at time 0.75 days. This sensor observation information is sent to Blue Theater, but Blue Theater continues to receive numerous sensor observations which support the COA One posterior. The single Group.2-1 sensor observation was insufficient to alter Blue Theater's perception.

Prior to time 1.0 days, Group.2-1 observes another node uniquely defined in COA One. The count of assets on that node is sufficient to increase the posterior of the ground truth COA. After time 1.0 days, Group.2-1 receives another sensor observation on a physical node similarly defined for two COAs. This results in a subsequent decrease in the perception of the ground truth COA. No additional sensor observations are made by Group.2-1 until time 7.0 days. Recall that at time 6.0 days, the logistics build-up is over and combat has begun. Group.2-1 receives a sensor observation which is sufficient to cause a shift in perception for both Blue Theater and for Group.2-1. Blue Theater being influenced by this observation is in part due to luck in choosing Group.2-1 to own a sensor and have the ability to share information with Blue Theater. If another sub-unit had been chosen, the results could be very different, either due to no contact, or contact very similar to previous Blue Theater contact with Red.

Audit of the history file shows that the sensor observations by Group.2-1 after time 7.0 days greatly influence Blue Theater's perception. Note that the shifts in perception do occur at approximately the same time and in the same direction once combat has begun due to Group.2-1's relative level of contact with Red units. Blue Theater is updating its perception with Group.2-1 provided sensor reports. The posteriors held by the two units are different because the priors at time 7.0 days were different.

Considering Case 2 of the same scenario where the direction of information flow between the theater and the division is higher-to-lower, it becomes apparent that the theater observations were indeed influencing the division more strongly than the division observations influencing the theater. This was due to the larger proportion of Blue Theater observations to Group.2-1 observations.

The audit process indicates that the units in Case 3 behave in accordance with the intent of the control representation.

d) Case 4

Case 4 is shown in Figure 16. For Case 4, only the division has a sensor and information is shared lower-to higher. The division perceives only according to its

own sensor observations and the theater perceives only according to the same divisional sensor observations. Note that if there were more than one divisional unit, divisional sensor observations would not be shared and each division would perceive only according to its own sensor observations. The theater is a composite perception of all available sensor information.

Case 4 - Parameter Set 1 - 2 Units
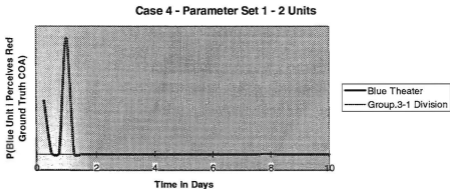
Figure 16. Case 4, Two Units

The chart shows that both units share the same perception for the duration of the test run. This simulation run is similar to Group.2-1's behavior in Case 3. The difference in Group.2-1's perception in Case 4 occurs at time 1.25 days, Group.2-1 receives a sensor observation on a physical node located in two COAs. Due to the stochastic process of the sensor observation, the observation count of assets is sufficient to result in a small posterior for the ground truth COA. Auditing the history file shows that the posterior associated with the ground truth COA is maintained for the remainder of the simulation since the few subsequent observations occur on nodes defined similarly for COA One and COA Two.

Blue Theater only receives the information from Group.2-1. Auditing the history file shows that each time Group.2-1 receives a sensor observation, the information is passed to Blue Theater. Both units maintain the same posterior for the run of the

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simulation. This results in Blue Theater perceiving exactly as Group.2-1 as indicated by the overlapping curves in the chart.

The units in Case 4 behave in accordance with the intent of the control representation given only one divisional unit. It is necessary to look at the multi-divisional test run for Case 4 to see if the composite perception held by the theater better reflects the ground truth COA given a multi-sensor control representation.

e) Case 5

Case 5 is shown in Figure 17. For Case 5, only the theater has a sensor and information is shared higher-to-lower. The theater perceives only according to its own sensor observations and the division perceives only according to the same theater sensor observations. Note that if there were more than one divisional unit, each division would receive all the available sensor observation information since there is only one sensor in this control representation. Both the theater and the division maintain a composite perception for all available sensor information. The chart shows that both units share the same perception for the duration of the test run.

Case 5 - Parameter Set 1 - 2 Units
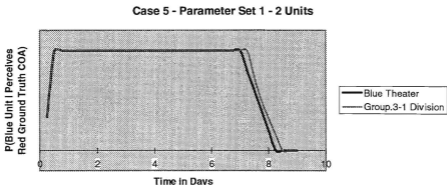
Figure 17. Case 5, Two Units

Case 5 is similar to Case 1 which has been discussed in detail. The differences occur in two places. The observation discussed in Case 1 prior to time 0.5

days made by Group.2-1 does not occur in Case 5 since Group.2-1 does not own a sensor in this case. The omission of this single sensor observation results in no changes between the two cases. Blue Theater makes the same observations on nodes similarly defined in two COAs which result in a decreasing posterior for the ground truth COA by time 7.5 days. However, the observation made in Case 1 by Group.2-1 at time 7.5 days does not have the opportunity to occur since Group.2-1 does not own a sensor in Case 5. As a result, the subsequent increase in the posterior of the ground truth COA does not occur. By time 8.0 days, Blue Theater's posterior for the ground truth COA has further decreased.

Auditing the history file shows that the units in Case 5 behave in accordance with the intent of the control representation.

f) Case 6

Case 6 is shown in Figure 18. For Case 6, both units have sensors but they do not share information. The theater perceives only according to its own sensor observations while the division perceives only according to its own sensor observations. Note that if there were more than one divisional unit, divisional sensor observations would not be shared and each division would perceive only according to its own sensor observations. There is no composite perception of all available sensor information. The chart shows that both units do not share the same perception for the duration of the test run.

Case 6 - Parameter Set 1 - 2 Units
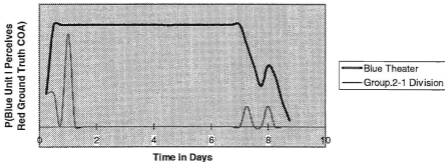
Figure 18. Case 6, Two Units

Case 6 is a combination of Case 5 for Blue Theater and Case 4 for Group.2-1. Looking at Blue Theater's curve in Case 5 where Blue Theater only has information from its own sensor and comparing it to Blue Theater's curve in Case 6, there is a remarkable similarity. Auditing the history file shows that the sensor observations are the same as in Case 5, with slight differences due to the stochastic process of the sensor model. The difference occurs at time 7.75 where Blue Theater makes an observation on a node contained in two COAs and in this simulation run, the deviations from the expected counts for that node in COA One are smaller than the deviations for the expected counts for COA Two. The two different curves show the randomness caused by the stochastic process of the sensor count on similarly defined nodes. In one case, COA Two is more probable; in the other case, COA One is more probable.

Looking at Group.2-1's curve in Case 4 where Group.2-1 only has information from its own sensor and comparing it to Group.2-1's curve in Case 6, there is a also remarkable similarity. Auditing the history file shows that the behavior is the same as discussed for Blue Theater. The differences occur at time 7.0 days where subsequent observations occur on nodes similarly defined for more than one COA. This results in the increase and decrease of the posterior associated with the ground truth COA.

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Auditing the history file shows that each unit is receiving sensor reports exclusively from the sensor the unit owns. No information is being shared. This results in the two distinct perceptions of the enemy ground truth COA. If Group.2-1 had been associated with nodes that the Blue Theater observed, the resulting posteriors may have been more similar to Blue Theater. Case 2 behaves in accordance with the intent of the control representation.

2. Eleven-Unit Test Run of Korean Scenario

The detailed level of discussion for the two-unit test runs of the Korean Scenario will not be used to evaluate the eleven-unit test runs. Each history file for the two unit test runs range from 300 pages to 900 pages. The history files associated with the eleven unit test run are over 2000 pages. The intent of this portion of the analysis of the results is to determine whether the control representations are behaving as one would expect them to behave given more than two units. In each of the two unit cases, the units behaved as intended by the control representation.

a) Case 1

Case 1 is shown in Figure 19. For Case 1, all units have sensors and information is shared higher-to-lower and lower-to higher. The chart shows that all units share the same perception for the duration of the test run. A check using the audit process discussed in the previous section shows that the units are updating their posteriors of the ground truth COA in the same manner. There are no substantial differences in this test run of Case 1 over the two unit test run of Case 1.
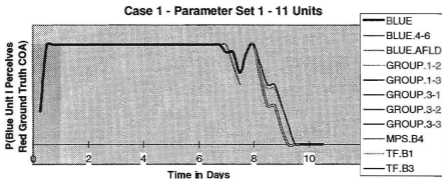
Figure 19. Case 1, Eleven Units

Note that the unit whose perception abruptly stops, as indicated by the line that ends at approximately 7.75 days, has become combat ineffective according to the rules of FTLM and is no longer capable of maintaining a perception. All slight differences reflect the randomness of the asset counts by the sensor model.

    b)   *Case 2*

Case 2 is shown in Figure 20. For Case 2, all units have sensors and information is shared higher-to-lower. The theater perceives only according to its own sensor observations while the divisions have their own sensor observations and, eventually, the theater sensor observations. Note that divisional sensor observations are not shared and each division perceives only according to its own sensor observations and the theater observations. There is no composite perception of all available sensor information. The chart shows that the units do not share the same perception for the duration of the test run.

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Case 2 - Parameter Set 1 - 11 Units

Figure caption legend: BLUE, BLUE.4-6, BLUE.AFLD, GROUP.1-2, GROUP.1-3, GROUP.3-1, GROUP.3-2, GROUP.3-3, MPS.B4, TF.B1, TF.B3

Y-axis: P(Blue Unit I Perceives Red Ground Truth COA)

X-axis: Time in Days

Figure 20. Case 2, Eleven Units

All units initially perceive similar to the discussion of Case 1 of the two unit test run. An audit of the sensor observation history file indicates that the theater provides proportionally more sensor observation information to the divisional units than the sensor observations by the division sensors. This provides an overall influence on the posterior values for each COA held by the divisions. However, just prior to time 2.0 days, Blue Theater receives a sensor observation sufficient to decrease the ground truth posterior value and increase the COA Two posterior value. This information is sent down to each of the divisional units by the COA update time 2.0 days with the exception of TF.B3. All unit posterior values respond according to Blue Theater except for TF.B3, who maintains its current posterior for the ground truth COA. By the time the next COA update occurs, Blue Theater has received another sensor observation on a node clearly defined by COA One which results in an increased posterior value for the ground truth COA. TF.B3, along with all other divisional units, receive the same information prior to the COA update. As a result, TF.B3 never deviates from its posterior for the ground truth COA. The divisional units increase their posterior values with a slight time lag which is appropriate considering the mean time delay of information specified between the theater and divisional units. A similar series of events occur at time 2.75 where one unit receives a sensor observation too late for inclusion in the COA update. Group.1-3 does not receive a sensor report

from Blue Theater in time for inclusion in the COA update and subsequently does not alter its posterior. No subsequent observations occur during the next period between COA updates and by the following COA update, a new sensor observation increases all unit posterior values for the ground truth COA with high probability. Group.1-3 never deviates from perceiving the ground truth COA. Subsequent fluctuations in the posteriors reflected by the curves in the chart are due to the stochastic nature of the sensor model as previously discussed.

c)   Case 3

Case 3 is shown in Figure 21. For Case 3, all units have sensors and information is shared lower-to higher. The divisions perceive only according to their own sensor observations while the theater has both its own sensor observations and, eventually, each division's sensor observations. Note that divisional sensor observations are not shared between the divisions. The theater is a composite perception of all available sensor information. The chart shows that the units do not share the same perception for the duration of the test run.

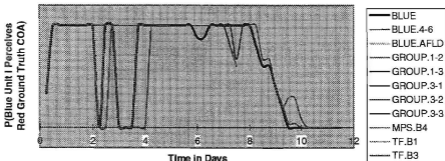**Case 3 - Parameter Set 1 - 11 Units**
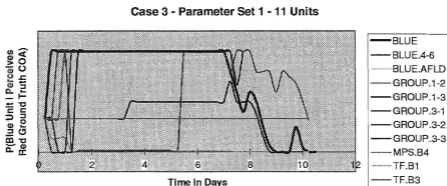
Figure 21. Case 3, Eleven Units

The units in this simulation run behave as discussed in the two unit simulation run of Case 3. There are more units receiving their own reports and perceiving

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only according to those reports. Blue Theater's curve represents a composite of all divisional sensor information to include its own sensor information and is similar to the two unit simulation run of Case 3. Note that a few of the units (Navy task forces) never receive any sensor information and remain at the equally likely perception. Many of the units eventually receive sensor observations on clearly defined nodes indicating COA One, while a few units receive information on nodes similarly defined on two COAs and as a result perceive the incorrect COA.

A check using the audit process indicates that each divisional unit is perceiving exclusively according to the sensor reports generated by the sensor it owns, while Blue Theater is receiving all sensor observation information as intended by the Case 3 control representation.

        d)   *Case 4*

Case 4 is shown in Figure 22. For Case 4, only the divisions have sensors and information is shared lower-to higher.

Case 4 - Parameter Set 1 - 11 Units
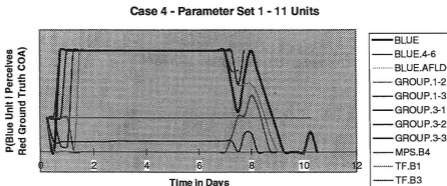
Figure 22. Case 4, Eleven Units

The divisions perceive only according to their own sensor observations and the theater perceives according to all the divisional sensor observations. The chart shows that the units do not share the same perception for the duration of the test run. The striking difference between this simulation run and the two unit simulation run is the Blue Theater perception over the course of the run. In the two unit case, the theater perceived exactly as did the unit sending the theater its only source of information. The posterior for the ground truth COA was small over the course of the run. The eleven unit run results in a Blue Theater posterior of the ground truth COA similar to a case where the theater owns a sensor. In essence, Blue Theater, given enough information from various units on the battlefield, arrives at the same perception as it would if it owned a sensor and was looking at the theater itself. All the divisional perceptions are occurring as previously discussed in the two unit simulation run.

     e)   *Case 5*

Case 5 is shown in Figure 23. For Case 5, only the theater has a sensor and information is shared higher-to-lower. The results of this simulation run are exactly as discussed in the two unit case and will not be repeated.

Case 5 - Parameter Set 1 - 11 Units

Legend:
- BLUE
- BLUE.4-6
- BLUE.AFLD
- GROUP.1-2
- GROUP.1-3
- GROUP.3-1
- GROUP.3-2
- GROUP.3-3
- MPS.B4
- TF.B1
- TF.B3

Y-axis: P(Blue Unit I Perceives Red Ground Truth COA)

X-axis: Time in Days
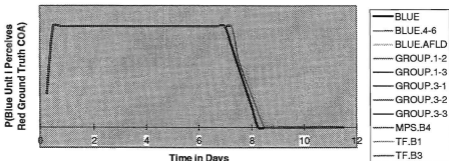
Figure 23. Case 5, Eleven Units

The theater perceives only according to its own sensor observations and each division perceives only according to the same theater sensor observations. Note that each division receives all the available sensor observation information since there is only one sensor in this control representation. Both the theater and the divisions maintain a composite perception of all available sensor information. The chart shows that all units share the same perception for the duration of the test run.

     f)   *Case 6*

Case 6 is shown in Figure 24. For Case 6, all units have sensors but they do not share information. The divisional sensor observations are not shared and each division perceives only according to its own sensor observations. There is no composite perception of all available sensor information. The chart shows that the units do not share the same perception for the duration of the test run. The analyses of the results of this run are similar to those discussed for the two unit Case 6 simulation run.

Case 6 - Parameter Set 1 - 11 Units
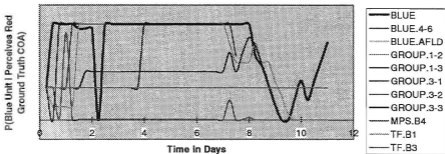
Figure 24. Case 6, Eleven Units

B. VARIATIONS IN PARAMETERS

1. Parameter Set 1

Parameter Set 1 as applied to control representation Case 1 is shown in Figure 19 and is referenced to for all comparisons of the variations in parameter sets.

2. Parameter Set 2

Parameter Set 2 as applied to control representation Case 1 is shown in Figure 25. Parameter Set 2 changes the receipt of transmission parameter as defined by a Bernoulli distribution. Parameter Set 1 has a Bernoulli parameter of 1.0 which insures all transmissions are received. This provides a "perfect" information flow condition since no interruptions are possible. Parameter Set 2 reduces the Bernoulli parameter to 0.90 and provides a less than "perfect" condition in which transmission may be lost between two units. The loss may be due to unit error, interface failure, or interface jamming.

Case 1 - Parameter Set 2 - 11 Units
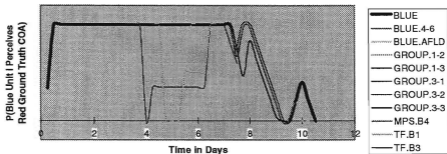
Figure 25. Parameter Set 2, Eleven Units

Figure 25 shows that three units had sensor information interrupted which caused a subsequent shift in their perceptions of the battlefield. An audit of the sensor observation history file shows that the divisional units; Blue.4-6, Group.1-2, and the Blue Airfield; each "lost" receipt of a sensor observation from the theater at times 3.75 days, 4.25 days, and 4.25 days, respectively. At approximately the same time, each unit received its own sensor observation on nodes which are similarly defined for more than two COAs. This resulted in a decrease in the posterior of the ground truth COA and shifted their individual perceptions away from the group perception held by the majority of the units. Eventually, with the receipt of subsequent sensor information, each unit which suffered from a lost message increased the posterior associated with the ground truth COA and rejoined the common group perception. All other COA updates occurred as previously discussed.

3. Parameter Set 3

Parameter Set 3 as applied to control representation Case 1 is shown in Figure 26. Parameter Set 3 changes the time delay parameter as defined by a Lognormal distribution. Parameter Set 1 has Lognormal parameters as specified in Table 1. This provides a basis for the time delay of information condition from which to compare changes in the

parameter values of the mean and standard deviation in minutes that describes the time for information between two specified units. Parameter Set 3 increases the mean and standard deviation parameters as specified in Table 3 significantly as compared to Parameter Set 1.

Case 1 - Parameter Set 3 - 11 Units
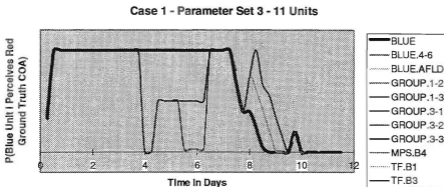
Figure 26. Parameter Set 3, Eleven Units

Figure 26 shows that all units suffered from the consequences of increased time delays when compared to the base case, Parameter Set 1 of Case 1. Three units had sensor information delays serious enough to cause a subsequent shift in their perceptions of the battlefield away from the perception held by the group. This result was similar to a previous discussion on receiving information after the COA update has occurred. In this case, Blue Theater, in the time interval prior to COA update time 3.75, is continuing to receive sensor observations indicating the ground truth COA. However, observations on nodes clearly defined for COA One occur which do not reach Group.3-2, Group.3-3, and Blue.AFLD. Each of these units receive their own sensor observation which indicate a COA other than the ground truth. Because of the increased time delay and the stochastic process associated with the time at which a unit receives a message, the COA update occurs and these three units update their perceptions according to their own observations and not the observations sent by Blue Theater. The posteriors associated with these three

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units' perception of the ground truth decreases. Over time and according to the stochastic processes involved, each unit eventually recovers to the shared perception of the group.

Again, auditing the sensor observation history file, Group.3-3 received an observation prior to update time eight days. This caused an upward shift in Group.3-3 perception. The delay of that sensor observation caused the theater not to benefit from that information until approximately day nine. At this time, the theater's perception responded with a similar upward shift. In the mean time, Group.3-3 received sensor observations which resulted in a decrease in the ground truth posterior and quickly reached the same perception held by the theater.

4. Parameter Set 4

Parameter Set 4 as applied to control representation Case 1 is shown in Figure 27. Parameter Set 4 changes the Staffing Ability Multiplier which is applied to the variance of the sensor observation and is associated with individual units. Parameter Set 1 has the Staffing Ability Multiplier set to 1.0 for all units, whereas Parameter Set 4 increases the Staffing Ability Multiplier to 5.0 for each unit. Figure 27 shows very similar perceptions when compared to the base case.

Initially, the Staffing Ability Multiplier did not appear to behave as intended; in this case to increase the variance of sensor information and therefore "fog" the perception of the battlefield. This result potentially confirms a suspicion that the variance component in the COA update may not be applied properly in the coding of FTLM. A similar result has been discovered during other research endeavors using FTLM. (Nelson, 1994) Conducting a sensitivity analysis of the variance by increasing the Staffing Ability Multiplier for successive runs of the same scenario will confirm this suspicion.

Case 1 - Parameter Set 4 - 11 Units
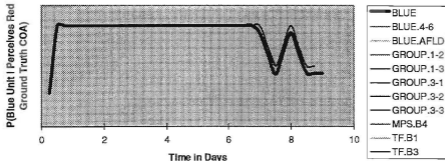
Figure 27. Parameter Set 4, Eleven Units

Subsequent changes to the Staffing Ability Multiplier were made to determine if a positive direction of change would produce the intended behavior and what magnitude of change was required when applied to the set variance of the sensor. The simulation run results were not sensitive to change until the following parameter set was reached. Table 10 shows Parameter Set 4a.

	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ²)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	1.0	100.0	1.0	100.0

Table 10. Parameter Set 4a

Parameter Set 4a increases the Staffing Ability Multiplier to a factor of 100 for the divisional units and keeps the Staffing Ability Multiplier at 1.0 for the theater for

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comparison internal to the run. This should produce a sharp increase in the variability associated with the sensor observations when received by the divisions. Essentially, the Staffing Ability Multiplier is controlling the variance associated with the sensor. To further define the effect of the increased Staffing Ability Multiplier, only two units were allowed to have individual perceptions, the theater and a division. The effects due to the Staffing Ability Multiplier should occur to the division alone. Parameter Set 4a as applied to control representation Case 1 is shown in Figure 28.

Case 1 - Parameter Set 4a - 2 Units
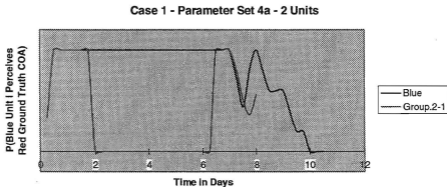
Figure 28. Parameter Set 4a, Two Units

Given a very large Staffing Ability Multiplier, the divisional unit does have its perception drawn away from the theater perception in a control representation where it has been shown that the two perceptions would be similar if not for the confounding introduced by the Staffing Ability Multiplier. However, it requires a relatively large magnitude of change to the variance to achieve this "intended" result. Clearly, the suspicion that the variance may be applied improperly in the coding of FTLM is justified and warrants investigation.

5.   Parameter Set 5

Parameter Set 5 as applied to control representation Case 1 is shown in Figure 29. Parameter Set 5 changes the Staffing Ability Multiplier which is applied to the variance of the sensor observation and is associated with individual units. Parameter Set 5 decreases the Staffing Ability Multiplier to 0.8 for each unit.   Figure 27 shows very similar perceptions when compared to the base case. It appears that all the units begin to decrease in their perception of the Red ground truth COA earlier than the base case. Again, the Staffing Ability Multiplier does not appear to behave as intended; in this case to decrease the variance of sensor information and therefore "clarify" the perception of the battlefield.   This leads to the same confirmation that the variance may not be applied properly as discussed previously.

Case 1 - Parameter Set 5 - 11 Units
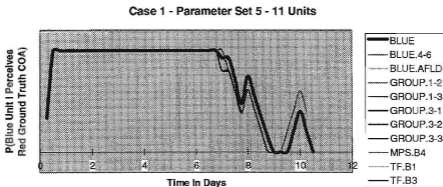
Figure 29. Parameter Set 5, Eleven Units

Again, a sensitivity analysis was performed to determine the magnitude of change required to effect the results of the simulation run. Table 11 shows Parameter Set 5a and represent the first Staffing Ability Multiplier values less than one where a noticeable sensitivity in the simulation run resulted.

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	Sensor to Theater	Sensor to Division	Theater to Division	Division to Theater
Delay Time Lognormal mean (μ)	15	10	20	10
Delay Time Lognormal variance (σ^2)	1	1	5	2
Successful Receipt Bernoulli mean (ρ)	1.0	1.0	1.0	1.0
Staffing Ability Multiplier (α)	1.0	0.01	1.0	0.01

Table 11. Parameter Set 5a

Parameter 5a decreases the Staffing Ability Multiplier to a factor of 0.01 for the divisional units and keeps the Staffing Ability Multiplier at 1.0 for the theater. This should produce a sharp decrease in the variability associated with the sensor observations when received by the divisions. Again, to further define the effect of the decreased Staffing Ability Multiplier, only two units were allowed to have individual perceptions, the theater and a division. The effects due to the Staffing Ability Multiplier should occur to the division alone. Parameter Set 5a as applied to control representation Case 1 is shown in Figure 30.

Case 1 - Parameter Set 5a - 2 Units

Figure caption legend: Blue, Group.2-1

X-axis: Time in Days
Y-axis: P[Blue Unit I Perceives Red Ground Truth COA]
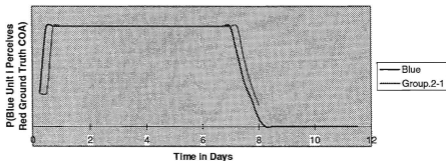
Figure 30. Parameter Set 5a, Two Units

The divisional unit reaches the same perception as the theater, but with a delay. Given the control representation, both units should share the same perception. It also holds the ground truth perception longer than the theater. Again, this confirms the suspicion the variance may be applied improperly in the coding of FTLM is justified and warrants investigation.

C. EXCURSIONS

1. Unit Test Run of Case 1 of the Korean Scenario

Case 1 is shown in Figure 31. For Case 1, all units have sensors and they share all information. The chart shows that all units share the same perception for the duration of the test run. The rationale for the results is the same as explained for the two unit and the eleven unit case and will not be repeated. The purpose of the excursion is to determine the cost in computer time resources by increasing the number of units with perceptions, and therefore the number of Bayesian posterior distributions, to be maintained.

This excursion took a 486/66 Megahertz personal computer over 48 hours to run one replication and produced 3,661 pages of sensor observation history output. The eleven unit test run for Case 1 took the same personal computer one and a half hours and produced 2,872 pages of sensor observation history output. Increasing the number of units with individual perceptions clearly consumes a large amount of computing resources. This resource problem will be reduced or eliminated once FTLM is converted to operate on Sun Workstations.

Figure 31. Case 1, 26 Units
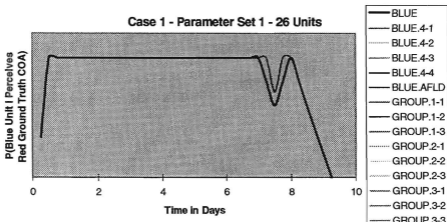
2. **Six Unit Test Run of a Composite Case of the Korean Scenario**

    The composite case is shown in Figure 32. The composite case control representation is shown in Figure 11. The purpose for this excursion is to show that a control representation may include a mixture of relationships between units and sensors. Any desired control relationship is capable of being represented. The rationale for the behavior of the units follows what has been discussed in the previous sections and may be analyzed using the audit process of the history file.

    Overall, the units generally tend to share a similar perception of the battlefield with a few units experiencing deviations. The theater and the divisional units; Group.3-1, Blue.4-6, and TF.B1; suffer from the effects of the time delays associated with the control representation and the multiple levels that sensor information must pass. Eventually, all units receive all information in this representation.

Composite Case - Parameter Set 1 - 6 Units
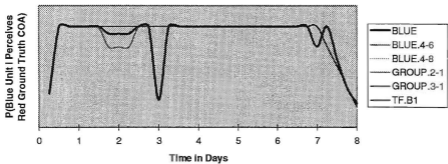
Figure 32. Composite Case, Six Units

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. General

The intent of this research effort was to provide the capability to model battlefield control of sensors and units in a perception based computer simulation and thereby provide an analysis tool to determine the effects of varying control structures given an operational context. Eight components represent the general control model. All eight components were computer coded and integrated into the latest version of the Future Theater Level Model. All eight components are easily managed by the analyst using FTLM to study the effects of control in battlefield simulations.

Seven of the eight components clearly provide the intended control characterization. An operational side can now have individual units with their own, potentially unique, perceptions of the battlefield. An operational side can describe the ownership of sensor assets and restrict those assets to observe only within the owning unit's area of influence. An operational side can describe, within a simulation, their control architecture and control doctrine. Finally, useful and nominally realistic representations of time delays of information and the probability of receipt of information can be managed by the analyst to specify sensor-to-unit and unit-to-unit enabling technology links.

One component, the Staffing Ability Multiplier, requires the proper application of the variance in the COA update prior to a complete test of the Staffing Ability Multiplier.

B.   RECOMMENDATIONS

1.   Modifications to FTLM, Application of Sensor Variance

The application of Sensor Variance within the COA update requires further investigation to determine its correctness. This will either confirm or improve FTLM and provide a clear foundation to test the Staffing Ability Multiplier.

2.   Modifications To The General Control Model

The following recommendations for future work will enhance the general control model as currently implemented in FTLM.

a)   *Staffing Ability Multiplier Verification*

Test the Staffing Ability Multiplier once the application of the sensor variance is applied properly in the coding of FTLM. Determine the relative magnitude of the multiplier to ensure realistic changes in the results of the simulation run.

b)   *Time Delay Parameter Research*

Future development of the control model can address the hardware transmission times associated with specified enabling technology links and add them onto the headquarters processing times if substantial. Parameter values associated with links between units of specified types need to be determined. This research will provide a more realistic representation of delay times based upon the types of units involved in the link. As an alternative to enumerating a fixed set of parameter values for all unit type relationships, a First-In-First-Out (FIFO) (Ross, 1989), single server queuing model may be developed to vary the delay time between units based upon the quantity of information the units are receiving at any given time.

c)   *Receipt of Transmission Parameter Research*

Future development of the control model can address specific mean parameter values associated with units when receiving information. The parameter value should account for the effects of human error, equipment failures, and jamming. This

research will provide a more realistic representation of the probability associated with receiving transmissions based upon the types of units involved.

3.   Additions to the General Control Model, Dynamic Courses of Action

The following recommendation for future work will build upon the general control model as currently implemented in FTLM. Now that sub-units have the capability to maintain their own perception of the battlefield, sub-units should be allowed to choose their own course of action at critical decision points. The use of enumerated decision sets for a unit at critical decision points will permit the unit to pursue what it believes is the correct counter course of action. Courses of action will become dynamic and flexible. Control representations ensuring hierarchical guidance will become even more important to ensure sub-units do not act as renegade units; however the potential will exist for such.

APPENDIX A. AN EXTRACT FROM A FTLM SCENARIO DATA FILE RECORD

The following is an extract of the general control model components which have been incorporated into the FTLM Scenario Data File Record. This record is used to define the operational context of the simulation.

```
757816775 1 0  12  5  6  .1 40-18N  121-30E  34-29N  131-15E  150
0.1  1  1  .35  1  1¹
```

* end of parameter data - start side data

```
  BLUE 1  1    1    1
          1.   1.   1.   5.   1.   1.   1.²
          1.   2.   .05 2.   .01  .01 .05 2.  .8
          0    2    2    .8   24 5
    24  60  5  2   3  1  0  10
  ...
```
* end of side data - start side relationship data
  ...
* end of atom data - start combat unit data

```
  SOUTH Group.1-1 ARMOR    DIVISION NONE    .60 .005 6³ 1⁴ 0.5 0.
    4
        ARMOR
        ARMOR
        ARMOR
        MECHANIZED
  4400 3990 3990 3990 3990 4400 4400 4400 3990
  ...
```
* end of combat unit data - start logistic unit data
  ...
* end of logistic unit data - start naval unit data

```
  South TF.B1      Battle.Group NONE  6³ 1⁴
        6
        NIMITZ    NIMITZ_CVN
        C'VILLE   BHILL._CG
        O'BRIEN   SPRUANC_DD
        SPRUANCE  SPRUANC_DD
        THACH     PERRY_FFG
        RENTZ     PERRY_FFG
```
* end of naval unit data - start air base data
  ...

---

[1] Flag used to indicate the option to add perceptions for individual combat units, naval units, and/or air bases.
[2] Staffing Ability Multiplier for the operational side Blue.
[3] Time between COA updates. Used only if the individual unit maintains a perception.
[4] Staffing Ability Multiplier for the sub-unit.

* end of sensor group data - start who receives sensor reports
```
 33
    PYONGYANG
8
Group.1-1
Group.2-1
Blue.4-1
Blue.4-2
Blue.4-6
Blue.4-7
Blue.4-8
Group.1-2
...
```
* end of who receives sensor reports - start sensor to unit data
```
 Red.Sens.1 Red   1 1 10 1  1.
 Red.Sens.2 Red   1 1 12 .5 1.
 Blue.Sen.1 Blue  1 1 15 1  1.
 Blue.Sen.1 Group.1-2 1 1 10 1  1.
 Blue.Sen.1 Group.1-3 1 1 1 10 1  1.
 Blue.Sen.1 Group.3-1 1 1 10 1  1.
 Blue.Sen.1 Group.3-2 1 1 10 1  1.
 Blue.Sen.1 Group.3-3 1 1 10 1  1.
 Blue.Sen.1 Blue.4-6 1 1 10 1  1.
 Blue.Sen.1 TF.B1 1 1 10 1  1.
 Blue.Sen.1 TF.B3 1 1 10 1  1.
 Blue.Sen.1 MPS.B4 1 1 10 1  1.
 Blue.Sen.1 BLUE.AFLD 1 1 10 1  1.
```
* end of sensor to unit - start unit to unit data
```
 Blue Group.1-2 1 1 20 5  1.
 Blue Group.1-3 1 1 20 5  1.
 Blue Group.3-1 1 1 20 5  1.
 Blue Group.3-2 1 1 20 5  1.
 Blue Group.3-3 1 1 20 5  1.
 Blue Blue.4-6 1 1 20 5  1.
 Blue TF.B1 1 1 20 5  1.
 Blue TF.B3 1 1 20 5  1.
 Blue MPS.B4 1 1 20 5  1.
 Blue BLUE.AFLD 1 1 20 5  1.
 Group.1-2 Blue 1 1 10 2  1.
 Group.1-3 Blue 1 1 10 2  1.
 Group.3-1 Blue 1 1 10 2  1.
 Group.3-2 Blue 1 1 10 2  1.
 Group.3-3 Blue 1 1 10 2  1.
 Blue.4-6 Blue 1 1 10 2  1.
 TF.B1 Blue 1 1 10 2  1.
 TF.B3 Blue 1 1 10 2  1.
 MPS.B4 Blue 1 1 10 2  1.
 BLUE.AFLD Blue 1 1 10 2  1.
```
* end of unit to unit data

APPENDIX B. AN EXTRACT FROM A FTLM SENSOR OBSERVATION HISTORY FILE

The following is an extract of the composite case sensor observation history file. This type of file is used as the audit record for each sensor observation. A sensor observation can be traced from the initial detection and as it is passed from unit-to-unit until its final receipt as defined by the control representation in the FTLM Scenario Data File Record.

```
Time   3.34254 BLUE.4-8's sensor BLUE.SEN.1 searching node WONSAN
Time   3.34949 BLUE.4-8 receives transmission from sensor BLUE.SEN.1 about node WONSAN
RED combat unit assets
     TANK count - 6
     IFV count - 24
     APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )
```

```
    Unit
Combination Posterior    TANK       IFV        APC      ARTILLERY
------------ ---------  -----------  ----------  ----------  ------------
(0,0,0,0) 1.000000    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.34949 BLUE.4-8 will pass information to GROUP.2-1
Time   3.34949 BLUE.4-8 receives transmission from sensor BLUE.SEN.1 about node WONSAN
RED logistic package assets
  TANKERS count - 347
  FLAT_BEDS count - 513
Logistic type combinations are as follows:
( LOGUNIT, )
```

```
    Unit
Combination Posterior    TANKERS     FLAT_BEDS
------------ ---------  ---------------  ---------------
    (0) 0.000000     0 ( 0.00)    0 ( 0.00)
    (1) 0.000000   198 ( 3.54)   390 ( 4.24)
    (2) 0.000000   265 ( 4.08)   454 ( 4.57)
    (3) 0.000000   298 ( 4.33)   480 ( 4.70)
    (4) 0.000000   318 ( 4.47)   494 ( 4.77)
    (5) 0.000000   331 ( 4.56)   503 ( 4.82)
    (6) 0.000019   340 ( 4.63)   509 ( 4.84)
    (7) 0.999981   347 ( 4.68)   514 ( 4.87)
Time   3.34949 BLUE.4-8 will pass information to GROUP.2-1
Time   3.35807 GROUP.2-1 receives information from BLUE.4-8 about node WONSAN
RED logistic package assets
  TANKERS count - 347
  FLAT_BEDS count - 513
Logistic type combinations are as follows:
( LOGUNIT, )
```

```
    Unit
Combination Posterior     TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000      0 ( 0.00)    0 ( 0.00)
    (1) 0.000000    198 ( 3.54)  390 ( 4.24)
    (2) 0.000000    265 ( 4.08)  454 ( 4.57)
    (3) 0.000000    298 ( 4.33)  480 ( 4.70)
    (4) 0.000000    318 ( 4.47)  494 ( 4.77)
    (5) 0.000000    331 ( 4.56)  503 ( 4.82)
    (6) 0.000019    340 ( 4.63)  509 ( 4.84)
    (7) 0.999981    347 ( 4.68)  514 ( 4.87)
Time   3.35807 GROUP.2-1 will pass information to GROUP.3-1
Time   3.35863 GROUP.2-1 receives information from BLUE.4-8 about node WONSAN
 RED combat unit assets
     TANK count - 6
     IFV count - 24
     APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )


    Unit
Combination Posterior     TANK      IFV       APC     ARTILLERY
------------ --------- -------------- -------------- -------------- --------------
  (0,0,0,0) 1.000000     0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.35863 GROUP.3-1 will pass information to GROUP.2-1
Time   3.36550 GROUP.3-1 receives information from GROUP.2-1 about node WONSAN
 RED logistic package assets
   TANKERS count - 347
   FLAT_BEDS count - 513
Logistic type combinations are as follows:
( LOGUNIT, )


    Unit
Combination Posterior     TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000      0 ( 0.00)    0 ( 0.00)
    (1) 0.000000    198 ( 3.54)  390 ( 4.24)
    (2) 0.000000    265 ( 4.08)  454 ( 4.57)
    (3) 0.000000    298 ( 4.33)  480 ( 4.70)
    (4) 0.000000    318 ( 4.47)  494 ( 4.77)
    (5) 0.000000    331 ( 4.56)  503 ( 4.82)
    (6) 0.000019    340 ( 4.63)  509 ( 4.84)
    (7) 0.999981    347 ( 4.68)  514 ( 4.87)
Time   3.36809 GROUP.3-1 receives information from GROUP.2-1 about node WONSAN
 RED combat unit assets
     TANK count - 6
     IFV count - 24
     APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )


    Unit
```

```
Combination Posterior      TANK      IFV      APC      ARTILLERY
------------ --------- -------------- -------------- --------------
  (0,0,0,0) 1.000000    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.44046 BLUE sensor BLUE.SEN.1 searching node P'YONGGANG
Time   3.44713 BLUE sensor BLUE.SEN.1 searching node KOSONG
Time   3.45124 BLUE commander receives transmission from sensor BLUE.SEN.1 about node
P'YONGGANG
 RED logistic package assets
    TANKERS count - 359
    FLAT_BEDS count - 485
Logistic type combinations are as follows:
( LOGUNIT, )

   Unit
Combination Posterior      TANKERS      FLAT_BEDS
------------ --------- -------------- --------------
      (0) 0.000000    0 ( 0.00)    0 ( 0.00)
      (1) 0.000000    204 ( 3.54)    370 ( 4.24)
      (2) 0.000000    273 ( 4.08)    430 ( 4.57)
      (3) 0.000000    307 ( 4.33)    455 ( 4.70)
      (4) 0.000000    327 ( 4.47)    469 ( 4.77)
      (5) 0.000000    341 ( 4.56)    477 ( 4.82)
      (6) 0.000082    351 ( 4.63)    483 ( 4.84)
      (7) 0.999918    358 ( 4.68)    487 ( 4.87)
Time   3.45124 BLUE commander will pass information to GROUP.2-1
Time   3.45124 BLUE commander will pass information to BLUE.4-6
Time   3.45124 BLUE commander will pass information to TF.B1
Time   3.45124 BLUE commander receives transmission from sensor BLUE.SEN.1 about node
P'YONGGANG
 RED combat unit assets
      TANK count - 8
      IFV count - 4
      APC count - 0
   ARTILLERY count - 3
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )

   Unit
Combination Posterior      TANK      IFV      APC      ARTILLERY
------------ --------- -------------- -------------- --------------
Time   3.45124 BLUE commander will pass information to GROUP.2-1
Time   3.45124 BLUE commander will pass information to BLUE.4-6
Time   3.45124 BLUE commander will pass information to TF.B1
Time   3.45776 BLUE commander receives transmission from sensor BLUE.SEN.1 about node KOSONG
 RED logistic package assets
   TANKERS count - 349
   FLAT_BEDS count - 522
Logistic type combinations are as follows:
( LOGUNIT, )

   Unit
Combination Posterior      TANKERS      FLAT_BEDS
------------ --------- -------------- --------------
      (0) 0.000000    0 ( 0.00)    0 ( 0.00)
```

```
          (1) 0.000000    200 ( 3.54)    396 ( 4.24)
          (2) 0.000000    266 ( 4.08)    461 ( 4.57)
          (3) 0.000000    299 ( 4.33)    488 ( 4.70)
          (4) 0.000000    319 ( 4.47)    502 ( 4.77)
          (5) 0.000000    332 ( 4.56)    511 ( 4.82)
          (6) 0.000002    342 ( 4.63)    518 ( 4.84)
          (7) 0.999998    349 ( 4.68)    522 ( 4.87)
Time   3.45776 BLUE commander will pass information to GROUP.2-1
Time   3.45776 BLUE commander will pass information to BLUE.4-6
Time   3.45776 BLUE commander will pass information to TF.B1
Time   3.45776 BLUE commander receives transmission from sensor BLUE.SEN.1 about node KOSONG
RED combat unit assets
     TANK count - 3
     IFV count - 7
     APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )

  Unit
Combination Posterior      TANK        IFV        APC      ARTILLERY
------------ ---------  --------------  --------------  --------------  ---------------
  (0,0,0,0) 1.000000     0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.45776 BLUE commander will pass information to GROUP.2-1
Time   3.45776 BLUE commander will pass information to BLUE.4-6
Time   3.45776 BLUE commander will pass information to TF.B1
Time   3.46178 BLUE.4-6 receives information from BLUE commander about node P'YONGGANG
RED combat unit assets
     TANK count - 8
     IFV count - 4
     APC count - 0
  ARTILLERY count - 3
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )

  Unit
Combination Posterior      TANK        IFV        APC      ARTILLERY
------------ ---------  --------------  --------------  --------------  ---------------
  (0,0,0,0) 1.000000     0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.46424 GROUP.2-1 receives information from BLUE commander about node P'YONGGANG
RED combat unit assets
     TANK count - 8
     IFV count - 4
     APC count - 0
  ARTILLERY count - 3
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )

  Unit
Combination Posterior      TANK        IFV        APC      ARTILLERY
------------ ---------  --------------  --------------  --------------  ---------------
  (0,0,0,0) 1.000000     0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.46424 GROUP.2-1 will pass information to GROUP.3-1
Time   3.46533 TF.B1 receives information from BLUE commander about node KOSONG
```

RED logistic package assets
  TANKERS count - 349
  FLAT_BEDS count - 522
Logistic type combinations are as follows:
(LOGUNIT,)

  Unit

Combination	Posterior	TANKERS	FLAT_BEDS
(0)	0.000000	0 (0.00)	0 (0.00)
(1)	0.000000	200 (3.54)	396 (4.24)
(2)	0.000000	266 (4.08)	461 (4.57)
(3)	0.000000	299 (4.33)	488 (4.70)
(4)	0.000000	319 (4.47)	502 (4.77)
(5)	0.000000	332 (4.56)	511 (4.82)
(6)	0.000002	342 (4.63)	518 (4.84)
(7)	0.999999	349 (4.68)	522 (4.87)

Time 3.46540 TF.B1 receives information from BLUE commander about node P'YONGGANG
RED logistic package assets
  TANKERS count - 359
  FLAT_BEDS count - 485
Logistic type combinations are as follows:
(LOGUNIT,)

  Unit

Combination	Posterior	TANKERS	FLAT_BEDS
(0)	0.000000	0 (0.00)	0 (0.00)
(1)	0.000000	204 (3.54)	370 (4.24)
(2)	0.000000	273 (4.08)	430 (4.57)
(3)	0.000000	307 (4.33)	455 (4.70)
(4)	0.000000	327 (4.47)	469 (4.77)
(5)	0.000000	341 (4.56)	477 (4.82)
(6)	0.000082	351 (4.63)	483 (4.84)
(7)	0.999918	358 (4.68)	487 (4.87)

Time 3.46613 BLUE.4-6 receives information from BLUE commander about node P'YONGGANG
RED logistic package assets
  TANKERS count - 359
  FLAT_BEDS count - 485
Logistic type combinations are as follows:
(LOGUNIT,)

  Unit

Combination	Posterior	TANKERS	FLAT_BEDS
(0)	0.000000	0 (0.00)	0 (0.00)
(1)	0.000000	204 (3.54)	370 (4.24)
(2)	0.000000	273 (4.08)	430 (4.57)
(3)	0.000000	307 (4.33)	455 (4.70)
(4)	0.000000	327 (4.47)	469 (4.77)
(5)	0.000000	341 (4.56)	477 (4.82)
(6)	0.000082	351 (4.63)	483 (4.84)
(7)	0.999918	358 (4.68)	487 (4.87)

Time 3.46862 GROUP.2-1 receives information from BLUE commander about node KOSONG

RED logistic package assets
    TANKERS count - 349
    FLAT_BEDS count - 522
Logistic type combinations are as follows:
(LOGUNIT,)

    Unit
Combination Posterior   TANKERS   FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000   0 (0.00)   0 (0.00)
    (1) 0.000000   200 (3.54)   396 (4.24)
    (2) 0.000000   266 (4.08)   461 (4.57)
    (3) 0.000000   299 (4.33)   488 (4.70)
    (4) 0.000000   319 (4.47)   502 (4.77)
    (5) 0.000000   332 (4.56)   511 (4.82)
    (6) 0.000000   342 (4.63)   518 (4.84)
    (7) 0.999998   349 (4.68)   522 (4.87)
Time   3.46862 GROUP.2-1 will pass information to GROUP.3-1
Time   3.46945 GROUP.2-1 receives information from BLUE commander about node KOSONG
 RED combat unit assets
    TANK count - 3
    IFV count - 7
    APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

    Unit
Combination Posterior   TANK   IFV   APC   ARTILLERY
------------ --------- -------------- -------------- -------------- --------------
   (0,0,0,0) 1.000000   0 (0.00)   0 (0.00)   0 (0.00)   0 (0.00)
Time   3.46945 GROUP.2-1 will pass information to GROUP.3-1
Time   3.46975 GROUP.3-1 receives information from GROUP.2-1 about node PYONGGANG
 RED combat unit assets
    TANK count - 8
    IFV count - 4
    APC count - 0
  ARTILLERY count - 3
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

    Unit
Combination Posterior   TANK   IFV   APC   ARTILLERY
------------ --------- -------------- -------------- -------------- --------------
   (0,0,0,0) 1.000000   0 (0.00)   0 (0.00)   0 (0.00)   0 (0.00)
Time   3.46975 GROUP.3-1 will pass information to BLUE.4-8
Time   3.47134 GROUP.2-1 receives information from BLUE commander about node PYONGGANG
 RED logistic package assets
    TANKERS count - 359
    FLAT_BEDS count - 485
Logistic type combinations are as follows:
(LOGUNIT,)

    Unit

100

```
Combination Posterior     TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000    0 ( 0.00)    0 ( 0.00)
    (1) 0.000000  204 ( 3.54)  370 ( 4.24)
    (2) 0.000000  273 ( 4.08)  430 ( 4.57)
    (3) 0.000000  307 ( 4.33)  455 ( 4.70)
    (4) 0.000000  327 ( 4.47)  469 ( 4.77)
    (5) 0.000000  341 ( 4.56)  477 ( 4.82)
    (6) 0.000082  351 ( 4.63)  483 ( 4.84)
    (7) 0.999918  358 ( 4.68)  487 ( 4.87)
Time   3.47134 GROUP.2-1 will pass information to GROUP.3-1
Time   3.47206 BLUE.4-6 receives information from BLUE commander about node KOSONG
RED logistic package assets
  TANKERS count - 349
  FLAT_BEDS count - 522
Logistic type combinations are as follows:
( LOGUNIT, )

  Unit
Combination Posterior     TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000    0 ( 0.00)    0 ( 0.00)
    (1) 0.000000  200 ( 3.54)  396 ( 4.24)
    (2) 0.000000  266 ( 4.08)  461 ( 4.57)
    (3) 0.000000  299 ( 4.33)  488 ( 4.70)
    (4) 0.000000  319 ( 4.47)  502 ( 4.77)
    (5) 0.000000  332 ( 4.56)  511 ( 4.82)
    (6) 0.000002  342 ( 4.63)  518 ( 4.84)
    (7) 0.999998  349 ( 4.68)  522 ( 4.87)
Time   3.47456 TF.B1 receives information from BLUE commander about node P'YONGGANG
RED combat unit assets
  TANK count - 8
  IFV count - 4
  APC count - 0
  ARTILLERY count - 3
BRIGADE combinations are as follows:
( INFANTRY, SINFANTRY, ARMOR, MECHANIZED, )

  Unit
Combination Posterior   TANK      IFV      APC    ARTILLERY
------------ --------- ---------- ---------- ---------- -----------
  (0,0,0,0) 1.000000    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
Time   3.47511 GROUP.3-1 receives information from GROUP.2-1 about node KOSONG
RED logistic package assets
  TANKERS count - 349
  FLAT_BEDS count - 522
Logistic type combinations are as follows:
( LOGUNIT, )

  Unit
Combination Posterior     TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
    (0) 0.000000    0 ( 0.00)    0 ( 0.00)
    (1) 0.000000  200 ( 3.54)  396 ( 4.24)
```

101

```
       (2) 0.000000   266 ( 4.08)   461 ( 4.57)
       (3) 0.000000   299 ( 4.33)   488 ( 4.70)
       (4) 0.000000   319 ( 4.47)   502 ( 4.77)
       (5) 0.000000   332 ( 4.56)   511 ( 4.82)
       (6) 0.000002   342 ( 4.63)   518 ( 4.84)
       (7) 0.999998   349 ( 4.68)   522 ( 4.87)
```
Time 3.47511 GROUP.3-1 will pass information to BLUE.4-8
Time 3.47658 BLUE.4-6 receives information from BLUE commander about node KOSONG
RED combat unit assets
    TANK count - 3
    IFV count - 7
    APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

Unit Combination	Posterior	TANK	IFV	APC	ARTILLERY
(0,0,0,0)	1.000000	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)

Time 3.47689 BLUE.4-8 receives information from GROUP.3-1 about node PYONGGANG
RED combat unit assets
    TANK count - 8
    IFV count - 4
    APC count - 0
  ARTILLERY count - 3
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

Unit Combination	Posterior	TANK	IFV	APC	ARTILLERY
(0,0,0,0)	1.000000	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)

Time 3.47705 TF.B1 receives information from BLUE commander about node KOSONG
RED combat unit assets
    TANK count - 3
    IFV count - 7
    APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

Unit Combination	Posterior	TANK	IFV	APC	ARTILLERY
(0,0,0,0)	1.000000	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)

Time 3.47772 GROUP.3-1 receives information from GROUP.2-1 about node KOSONG
RED combat unit assets
    TANK count - 3
    IFV count - 7
    APC count - 1
  ARTILLERY count - 0
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

```
      Unit
Combination Posterior    TANK      IFV      APC    ARTILLERY
------------ --------- -------------- -------------- --------------
  (0,0,0,0) 1.000000    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)    0 ( 0.00)
```
Time 3.47772 GROUP.3-1 will pass information to BLUE.4-8
Time 3.47867 GROUP.3-1 receives information from GROUP.2-1 about node P'YONGGANG
RED logistic package assets
   TANKERS count - 359
   FLAT_BEDS count - 485
Logistic type combinations are as follows:
(LOGUNIT,)

```
      Unit
Combination Posterior    TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
      (0) 0.000000    0 ( 0.00)    0 ( 0.00)
      (1) 0.000000  204 ( 3.54)  370 ( 4.24)
      (2) 0.000000  273 ( 4.08)  430 ( 4.57)
      (3) 0.000000  307 ( 4.33)  455 ( 4.70)
      (4) 0.000000  327 ( 4.47)  469 ( 4.77)
      (5) 0.000000  341 ( 4.56)  477 ( 4.82)
      (6) 0.000082  351 ( 4.63)  483 ( 4.84)
      (7) 0.999918  358 ( 4.68)  487 ( 4.87)
```
Time 3.47867 GROUP.3-1 will pass information to BLUE.4-8
Time 3.48130 BLUE.4-8 receives information from GROUP.3-1 about node KOSONG
RED logistic package assets
   TANKERS count - 349
   FLAT_BEDS count - 522
Logistic type combinations are as follows:
(LOGUNIT,)

```
      Unit
Combination Posterior    TANKERS     FLAT_BEDS
------------ --------- -------------- --------------
      (0) 0.000000    0 ( 0.00)    0 ( 0.00)
      (1) 0.000000  200 ( 3.54)  396 ( 4.24)
      (2) 0.000000  266 ( 4.08)  461 ( 4.57)
      (3) 0.000000  299 ( 4.33)  488 ( 4.70)
      (4) 0.000000  319 ( 4.47)  502 ( 4.77)
      (5) 0.000000  332 ( 4.56)  511 ( 4.82)
      (6) 0.000002  342 ( 4.63)  518 ( 4.84)
      (7) 0.999998  349 ( 4.68)  522 ( 4.87)
```
Time 3.48310 BLUE.4-8 receives information from GROUP.3-1 about node KOSONG
RED combat unit assets
   TANK count - 3
   IFV count - 7
   APC count - 1
   ARTILLERY count - 0
BRIGADE combinations are as follows:
(INFANTRY, SINFANTRY, ARMOR, MECHANIZED,)

```
      Unit
Combination Posterior    TANK      IFV      APC    ARTILLERY
```

```
------------  ---------  --------------  --------------  --------------  --------------
  (0,0,0,0) 1.000000    0 (  0.00)    0 (  0.00)    0 (  0.00)    0 (  0.00)
Time   3.48412 BLUE.4-8 receives information from GROUP.3-1 about node P'YONGGANG
RED logistic package assets
   TANKERS count - 359
  FLAT_BEDS count - 485
Logistic type combinations are as follows:
( LOGUNIT, )

    Unit
Combination Posterior    TANKERS      FLAT_BEDS
------------  ---------  --------------  --------------
     (0) 0.000000    0 (  0.00)    0 (  0.00)
     (1) 0.000000  204 (  3.54)  370 (  4.24)
     (2) 0.000000  273 (  4.08)  430 (  4.57)
     (3) 0.000000  307 (  4.33)  455 (  4.70)
     (4) 0.000000  327 (  4.47)  469 (  4.77)
     (5) 0.000000  341 (  4.56)  477 (  4.82)
     (6) 0.000082  351 (  4.63)  483 (  4.84)
     (7) 0.999918  358 (  4.68)  487 (  4.87)
```
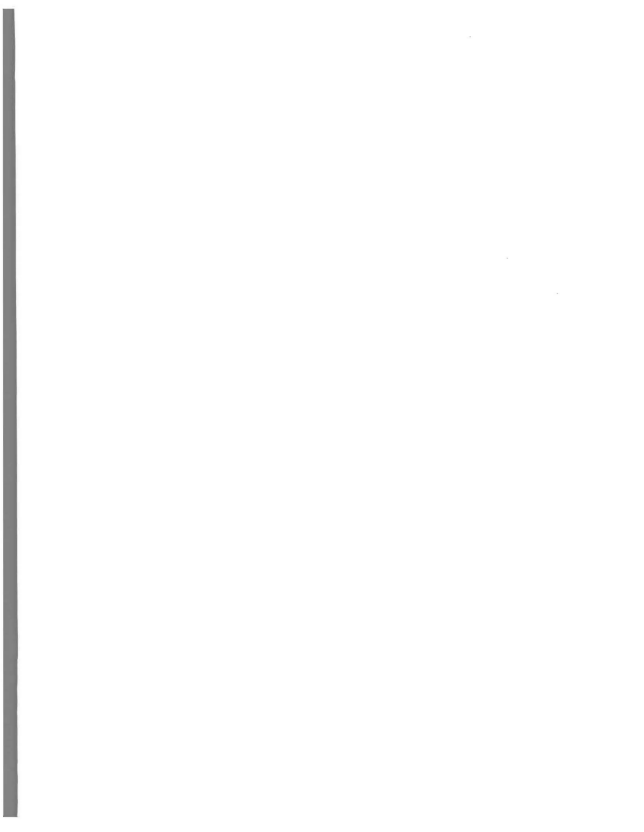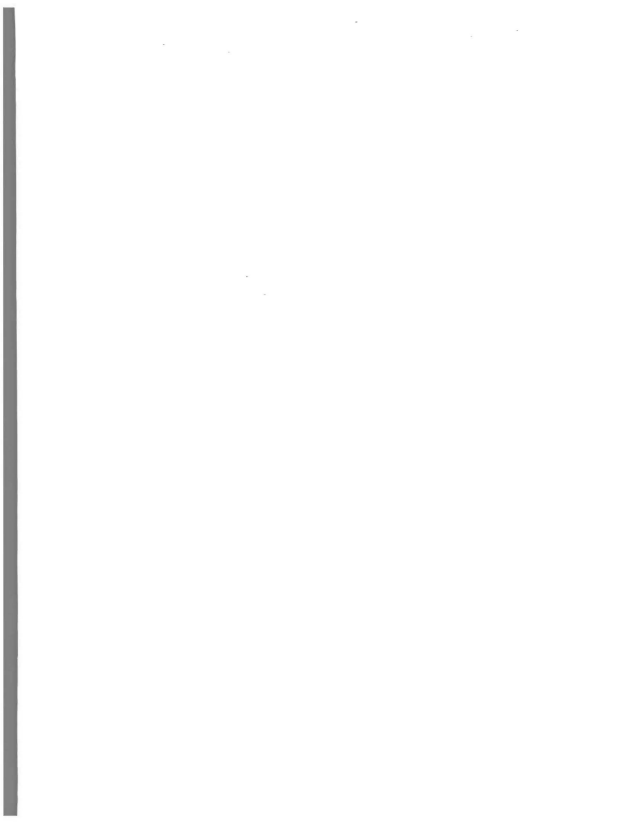
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