ARMY RESEARCH LABORATORY

Research in Modeling and Simulation for Command and Control

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ARL-SR-97

September 2000

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5067

ARL-SR-97 **September 2000**

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Abstract

This report is intended to stimulate discussion on both the general nature of and specific projects for the evolving command and control analysis mission of the Simulation Concepts Branch, with emphasis on course of action analysis/evaluation. This is a "living document" that will be expanded and modified as our research gels. We focus on project possibilities most directly associated with course of action analysis tools.

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1. Introduction

1.1 This Report. This report is intended to stimulate discussion on both the general nature of and specific projects for the evolving command and control (C2) analysis mission of the Simulation Concepts Branch (SCB), with emphasis on course of action (COA) analysis/evaluation. This is a "living document" that will be expanded and modified as our research gels.

We focus on project possibilities most directly associated with course of action analysis (COAA) tools. These can be categorized as (1) an analysis of existing tools and methods and (2) the development of concepts for new tools and methods.

1.2 The Big Picture. "Army 2010 and Beyond" is a basis for the evolution of operational procedures and Army doctrine for planning joint war fighting on future battlefields. The future Army must be prepared to deploy on short notice and operate in many environments. It must tailor its forces to the contingency, whether war fighting or operations short of war. Versatile forces, easily tailorable to a wide range of operations under all environmental conditions, are required.

It appears that Army 2010 and Beyond can use analytical tools.. SCB is considering ideas on what it takes to bring the operational and simulation worlds together to benefit the commander and his staff. Motivation for this work includes much from other battlefield digitization areas, including handling information overload, reacting quickly to contingencies, and incorporating new sensors.

The Army must be prepared to project overwhelming combat power from the United States. Timely mobilization and training of reserves are essential. Forces, both inside and outside the continental United States, must be deployable on short notice, arriving ready to control crises. They must be lethal to win quickly with minimal casualties. A smaller Army must be expansible to meet threats of global war.

Disparate operations, power projection, decisive advantage, and joint and combined operations are inherent. Army forces will be employed with other forces, often with other nations and agencies, under joint headquarters. Joint forces depend on a common knowledge base and must employ each service's strengths to avoid incompatibility. Commanders must become familiar with planning joint task forces.

The United States must be able to counter a wide array of somewhat unpredictable threats with a relatively small force, utilizing high-quality people and equipment, adequately sustained. Operations may range from small evacuation actions to much larger engagements, possibly with weapons of mass destruction. They require a mix of armored, light, and special operations forces.

The future Army will focus on the enemy, but some terrain and cultural features are important for operational objectives. Operational maneuverability is best developed by separating and destroying selected enemy forces and capabilities prior to maneuver. Attrition is avoided in favor of precision destruction of necessary targets.

There is a need to conduct detailed intelligence preparation of the battlefield (IPB). The pace and accuracy of information flow must be greatly improved. C2 must be increasingly mobile and capable of continuous operations. Signature reduction is obtained by increased distances between systems. Army 2010 and Beyond must provide significant enhancements to crew and system survivability. Protective counters to ballistic, nuclear-biological-chemical (NBC), and directed-energy threats must be incorporated. Army 2010 and Beyond must improve maintenance on the battlefield, enhance mobility, and achieve stockage accuracy.

Battlefield areas can be exclusive or overlapping. Nonlinear battles will stress leaders greatly. The pace and dispersion will require decision aids. Preparation by obtaining information and planning movements is the first stage of battle. Predictive software for logistics and automated supply and distribution is key. Embedded technologies for failure prediction, identification, and resolution will reduce maintenance costs. Integrated combined arms simulations and embedded training are needed.

Technologies for sensors, weapons, and C2 allow us to capitalize on nonlinear conditions. The Joint Surveillance Target Attack Radar System (JSTARS) gives the commander a real-time picture of the battlefield. Today's technology enables him to see more clearly and, with long-range precision systems, to dictate the terms of battle. The commander's assets can be synchronized to provide overwhelming power at critical points. It is possible with near-term electronic technology to plan and adjust precision fires. Air, land, and naval operations depend on space systems for warning, targeting, intelligence, and even platoon-level location and communications. The application of technical advances in automation and communication will provide real-time visibility and improved logistics.

Budget deficits, social and ecological needs, and perceived lessening of threat produce pressures to reduce defense spending. Finite choices of technology must contribute to decisive battlefield advantage. The United States must acquire and use increasing knowledge of third-world technologies, capabilities, and tactics. The Army must improve range, accuracy, and lethality without escalating costs.

1.3 Command and Control.

1.3.1 Definition. Command and control (C2) can be defined as the exercise of a commander's direction over his forces to accomplish a mission. C2 can be considered a hierarchical process. The commander gathers information about his and the enemy's forces, understands the implications of terrain and weather, receives missions from (and otherwise communicates with) superiors, assigns missions to (and otherwise communicates with) subordinates, tracks the progress of battle, comparing it with his plans, and develops and executes changes to his plans. One way of thinking of the process is that "command" is telling units to perform some mission, while "control" monitors and limits its actions.

For our purposes, the future commander's decision process can be broken initially into three areas: (1) information gathering, subsumed by what is called "situational awareness" or "battlefield visualization," (2) human cognition, which involves all the perceptual and mental manipulations (including experience and intuition) that the commander goes through in arriving at a decision, and (3) artificial intelligence (AI), which includes computer-assisted database access and both numerical and symbolic calculations.

1.3.2 Aspects of C2. C2 involves intangible aspects such as battlefield missions, soldier training, and military doctrine, as well as physical aspects such as sensors, information processors, and telecommunication equipment. There have been advances in modeling (even fairly complex networks of) the physical elements; the intangibles are much more difficult to study, even subjectively.

C2 can be analyzed with regard to organization. For instance, entities can be organized in terms of major operational capabilities, specialized branches, and geographic location. In some senses, such a "meta-C2" problem is beyond the scope of our research, since it might be argued that Army 2010 and Beyond, operations other than war, and joint/coalition operations require extreme flexibility in future C2 organizations. However, we believe that strategic and logistical considerations can be handled (at least eventually) with analytical/predictive methodologies similar to those we propose developing for the effort at hand.

There seem to be several phases of C2. Information is gathered about terrain, weather, friendly forces, and enemy forces. This external information is fused or consolidated for the commander into positions, relative strengths, and other information. The commander can then relate his intent or desiderata to a snapshot of the battlefield and consider the best COA, possibly using automated decision aids. The decision is executed and monitored as the cycle begins again.

C2 can, in a sense, be considered all that is used in making a decision and seeing that it is executed. It involves planning and coordinating via a system of equipment, people, information, authority, communications, and methods. In addition, the commander's mind may be the most important component, bringing elements of cognitive science to bear on the problem. Along these lines, studies of soldiers have shown that extended combat can produce severe exhaustion and loss of effectiveness; certainly, such problems affect C2 throughout the hierarchy.

1.3.3 Some Philosophy. We should not make the mistake of considering C2 only as a process involving abstractions. Although such models facilitate analysis of C2 activities, they should not be confused with the commander's reality. Similarly, we should not make the mistake of considering C2 only as a system involving technology. It includes procedures, facilities, and people as well as equipment and communications. In particular, without cognizant personnel, at least for the foreseeable future, even technologically advanced equipment is useless.

We are interested in developing techniques or systems to help the commander and his staff more easily and quickly make better decisions. However, we need to define the salient words in terms of scientific metrics, even if such metrics are subjective. Another fundamental dichotomy (one that is often glossed over as obvious) is whether the user should adapt his doctrine to C2 materiel or whether the materiel should be developed to adapt to the user's decision-making "personality."

Any combat analysis must involve, in some sense, attrition (fairly well in hand), target acquisition (more problematic), movement (being modeled by the U.S. Army Research Laboratory [ARL] and others), combat support and combat service support (somewhat handled by other government agencies), and command, control, communications, computers, and intelligence (C4I) (our emerging bailiwick). In improving earlier approaches to combat modeling, we will utilize (analogs to) basic logical structures and iteratively consider more variables, fewer assumptions, more complex (e.g., stochastic) relations, and enhanced solution/approximation methods.

One basic problem is how to use modeling and simulation (M&S) to develop new techniques for improving the ability of the commander and his staff to process combat information on present-day and future battlefields. Again, this is a rather difficult undertaking without initial appreciation for what C2 comprises in a given scenario and what problems exist for the user there. For instance, if the future battlefield is (at least in part) cyberspace, the nature of C2 becomes much different from most current concepts.

1.4 Our Branch. An area of interest to the Computer and Communications Science Division (CCSD) is situational awareness. Improving the commander's ability to visualize the battlefield in real-time or near real-time would result in a powerful combat force multiplier. One aspect of situational awareness being addressed, by various parts of the Army, is tracking unit actions at all echelons to develop a common picture of the rapidly changing battlefield. A challenge matching the future vision of SCB is developing methods to integrate battlefield computer visualization with situational awareness, planning systems, and mission rehearsal.

A more immediate CCSD interest is COA evaluation, specifically techniques to enable a commander to compare actual force accomplishments with mission objectives as combat occurs and to facilitate modification of force arrays or tactics for bringing about desired results.

Major thrusts for SCB are linking battlefield data to simulation and wargaming, developing software architecture(s) for execution monitoring, and COA analysis/evaluation. Our desired products include tested and validated COAA tools, a multimodal simulation test bed, and Web-based simulation control, monitoring, and collaboration.

Our work comprises both military science and computer science. Decision support tools involve COAA and tactical monitoring. Wargaming involves work with the Modular Semi-Automated Forces (ModSAF) and scenario development. Simulation techniques include visual simulation, Web-based systems, and multimodal displays. These are linked via simulation interfaces such as the high-level architecture (HLA), distributed interactive simulation (DIS), and the C2 simulation interface language. The major COAA project of the branch is called course of action technology integration (COATI). This research project is designed to increase tactical agility by providing the capability to evaluate the "goodness" of COAs. COATI links a prototype COA generator, the FOX-GA [1], with the Army's object-oriented warfighter simulation of choice, Modular Semi-Automated Forces (ModSAF). COATI then uses this link to feed FOX-GA-generated COAs to ModSAF, play out the scenarios in ModSAF, and capture and analyze the battle outcomes.

The main work package for these purposes is simulation research for battle planning and execution. Its objective is to conceptualize, evaluate, and develop methods for software simulation of the digital battlefield with integrated M&S support. Research focus is on integrating M&S with C2 systems, improving COAA, exploiting distributed simulation architectures, integrating simulation with real-time battlefield data for outcome prediction, and exploiting advanced controls and displays for improved situational awareness. The goal of this research effort is to build logically into a robust, modular COA evaluation testbed, closely coupling a combat simulation to a COA generation tool by integrating both with an automated scenario translation program and a solid statistical analysis package. Testbed component interactions will be specified by both internal process design and external user/information interfaces.

This work is relevant to the ARL mission, as it supports the Army by developing a flexible open architecture system for integrating realistic models and simulations into C2 operations. Our collaborators include the Displays Federated Laboratory (FedLab) and the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM); our contractors include the Texas Center for Advanced Technology (TCAT) and the Advanced Distributed Simulation Research Consortium. We continue to develop linkages with the U.S. Army Communications and Electronics Command (CECOM) and the Battle Command Battle Lab at Fort Leavenworth.

The SCB project team, whose mission includes COAA and other C2 simulation issues, is known as the Battlespace Decision Support Team (BDST). It is led by Rich Kaste; the other members are Dr. Barry Bodt, Joan Forester, Charlie Hansen, and Eric Heilman. Each is pursuing aspects of the main project. Dr. Bodt is the resident mathematical statistician in charge of the experimental design for C2 projects and developing and applying probabilistic techniques for COAA. Ms. Forester is in charge of a seminal TCAT study, installing general simulation software, and developing (along with Janet O'May) branch capabilities for further use of ModSAF and the dismounted infantry simulation (DISim). Mr. Hansen is investigating the use and improvement of COAA techniques (specifically, Fox-GA) based on genetic algorithms (GAs) and historical cases, and of intelligent collaborative systems for military intelligence analysis. Mr. Heilman brings to the team a wealth of real-world Army field knowledge and military science in various forms of wargaming.

Our objectives include development of methodologies to analyze, evaluate, and improve COAs through simulation and feedback (the main objective), techniques for incorporating real-time battlefield data into simulations and war games, software architectures using the same data for planning/gaming and execution/monitoring, and HLA-compliant tools for simulation efforts (an ancillary objective). The desired capability resulting from this work is automating the C2 process to ease battle management burdens on commanders and staffs. Scientific barriers associated with the project include decision-making techniques for evaluating COAs, the consideration of granularity mismatches, (e.g., with respect to terrain or echelon resolution) and methods to account for incomplete or missing data. Technology barriers include interface/integration with C2 systems (e.g., the Combat Information Processor [CIP] Application Programmer Interface [API]) having real-time data feeds, methods to integrate predicted outcomes with ground truth, display configurations for situational awareness in tactical operations centers (TOCs), and incorporation of intelligent agent technology. Technical approaches involve the use of Bayesian methods, multimodal displays, and HLA.

2. COAA

2.1 Introduction. Before we discuss analysis of COAs, we should define what is meant by a COA. In the military sense, it is a plan possible for the commander that is related to mission accomplishment. In particular, it is a feasible way to perform a task that meets the given guidance, does not cause unwarranted risk, and significantly differs from other ways under consideration. This last criterion is fundamental to our COAA research, in that it comprises many aspects of the overall problem of characterizing a good (or even optimal) COA.

We consider for this report that the COAs to be evaluated are given to the analyst (or decision-making process). That is, at this point we do not go into depth about the COA development process. However, we are investigating the mathematics of a combined development-analysis paradigm in lieu of the separated scheme implemented in the current manual process. As a summary, we note that the development process comprises several steps, some of which are intimately related to the COAA process. The staff considers friendly and enemy combat power relative to each other. Options are generated, and initial forces arrayed. The scheme of maneuver is developed. Finally, headquarters are assigned and the COA documentation is prepared.

The collaborative planning process is based on items set forth in established field manuals (FMs). It is typically data, labor, and time intensive, involving aspects of intelligence, operations, logistics, and specific branches of the Army (e.g., artillery, air defense). Moreover, there is a rule of thumb in military planning: for any echelon, two-thirds of the time available should be given to subordinates. It would be useful in automating the process to improve the analysis of COAs, both with regard to speed and degree of evaluation (e.g., assessing the ramifications and risks). There are various possible technical approaches that we are interested in investigating.

The staff officers have a variety of roles and tasks in performing COA development and analysis. For instance, the S1 (personnel officer) thinks in terms of projecting casualties—he determines if certain COAs would have unacceptable personnel losses and does a formal risk analysis. The S2 (intelligence officer) plays the part of the enemy commander by developing probable reactions to friendly actions and estimating enemy losses. The S3 (operations officer) has large roles in preparing the COAs; he develops the decision matrix, performs time analyses (along with the S2), etc. Of course, the entire group has collaborative tasks, and the Executive Officer (XO) is in charge of the entire effort.

There are several doctrinal criteria for a good COA. At the very least, the COAA must examine the alternatives in terms of these. First, it must meet the commander's guidance in accomplishing the mission (suitability). Each friendly unit must have the wherewithal (assets, time, space) to follow the plan (feasibility). The cost (especially human cost) must be overbalanced by the advantage (acceptability). Each COA must be obviously distinct, be it in terms of main effort, task organization, scheme of maneuver or use of assets; this is the distinguishability criterion. A good COA should be flexible to accommodate contingencies, position the friendly force for new operations, and provide freedom for further initiative.

A complex criterion (actually a set of criteria) is completeness. What forces will execute the plan? Why will each conduct its part of the operation? What will the action comprise: defense, offense, or another action? When will the planned action start? Where will it happen: objectives, sectors, zones, etc.? How will assets, two echelons below, be employed by the commander?

There are many benefits of the process for the tactical situation. The staff can develop a good intelligence preparation of the battlefield, focused on enemy weaknesses, strengths, and centers of gravity. Analyzing the anticipated battlefield events, desired end state, and decisive points helps the staff to decide when and where to apply force and to determine the required resources, conditions, and synchronizations.

In short, then, COAA identifies which COA (1) accomplishes the mission (2) with minimum casualties (3) while best positioning the force (4) to retain the initiative for future operations. These four items can form the basis for automated decision aiding.

2.2 Phases of COAA. There are several phases in developing COAs that are summarized here to set the stage for discussions of COA evaluation and other C2 problems. Army doctrine for battle planning is basically set forth in FM 101-5, "Staff Organization and Operations" [2]. It involves a decision-making process of developing and analyzing alternative solutions, then comparing them and selecting one. An initializing mission analysis phase comprises the commander's staff gathering and understanding the information about the upcoming conflict, such as mission, enemy, troops, terrain, and time available. In a development phase, the staff, utilizing the commander's guidance, produces three, four, or five distinct, apparently feasible COAs.

Continuing with the process, in the analysis phase, each COA is wargamed for additional understanding and improvement. Wargaming generally consists of at least the S2, S3, and S4 (logistics officer) collaborating as they work through the COA. It is a difficult activity to develop the moves and countermoves, so the planners may be assisted by other staff experts. In the comparison phase, COAs are evaluated according to the commander's criteria; he selects one, and the staff performs deeper analysis and development. The staff finally produces the operations order (OPORD), which sets forth specific instructions for subordinate commanders. In actual practice, it appears that that Army planners basically follow this approach, even though development and analysis of COAs may be somewhat combined, and refinement of a COA "sketch" may be performed as part of gaming.

After a set of COAs is developed, the next phase is to either manually or automatically evaluate, flesh out, correct, and enable the commander to choose the best among them. An important aspect of the development and evaluation is all the uncertainty in the COAs, particularly with regard to enemy location, strength, and mission. A major area of research is assessing how a given COA can be shown to be reasonable or not in the "fog of war."

After all the COAs are gamed, the staff must recommend one to the commander. Using actual detailed analysis during the comparison process must be done to ensure that the COA chosen will probably be the most successful. Simply voting the most popular COA does not necessarily do this, but using a decision matrix has been found to be fairly rapid and effective.

Using the commander's guidance and critical events, the staff develops criteria for comparing the advantages and disadvantages of each COA.

Of course, this can be computerized for cross referencing and report generation. Conventionally, empty matrices on large acetate-covered boards can be used in both the comparison process and for briefing the commander subsequently. The S3 fills in selected criteria and sketches the COA, and the process begins. For each criterion, the COAs are ranked with regard to satisfaction (e.g., the best COA is given rank one). When all criteria and all COAs have been considered, the ranks are totaled to determine the best COA (in this example, the one with the lowest score).

In order to evaluate COAs, we must be able to compare them against the commander's concept of the operation. This is a broad statement of his intent and assumptions. It must be detailed enough for the commander's staff and subordinates to understand it without further instruction in what they are to do. Given as a written, verbal, or graphical statement, it includes at least one picture of the scheme of maneuver and fire-support plan. There can also be discussions of the allocation of forces, the disposition of command elements, such as the location of each headquarters and the deployment of its subordinate forces, and logistical resources. Another aspect often considered is combat multipliers, those auxiliary means that significantly increase the relative combat strength of a force despite actual force ratios. Multipliers include psychological operations, camouflage, deception, surprise, smoke, close air support (CAS), electronic warfare, reinforcing terrain, and economizing in one area to mass in another.

Traditional doctrine prescribes a format for briefing the results of the wargaming process to the commander. This format may prove useful as a vehicle for developing tools for COAA. The methods used for gaming and recording are spelled out. In setting the context of the battle, the mission of the higher headquarters is given, along with the commander's intent. The general situation is described and includes friendly assets, enemy situation and capabilities, and assumptions.

Terrain analyses, critical events, and deception plans are factored into the briefing. The most recent IPB systematically relates the enemy doctrine, the geography and weather, and the friendly mission. (The IPB analysis yields an evaluation of enemy weaknesses, capabilities, and possible actions. This process lends itself to automated decision-aiding as a separate, or derivative, research project.) The most dangerous and most probable enemy COAs are described, and the friendly COAs are gamed.

The staff must, as one of the first steps, set forth for the affected units the "what, where, when, why, and how" of the mission. Conventionally, the staff develops the COAs together, with the S3 specifying a scheme of maneuver for the others to functionally integrate their appropriate assets. The following five steps are performed in a loop to develop the number of COAs the commander requires. (We believe that a strict looping of independent COAs is not necessary and may even be counterproductive.)

(1) The staff first considers friendly and enemy combat power by adding and comparing similar subordinate units without other combat multipliers. The analysis of relative combat power provides insights into possible types of operation from both friendly and enemy perspectives, enemy vulnerabilities, maneuver/firepower/leadership/protection plusses/minuses, applications of friendly capabilities, allocations of resources and requirements for more, etc. Estimating mission success is then possible by comparing the relative-force ratio with planning ratios derived historically.

(2) Next, in order to estimate the amount needed for mission accomplishment, the staff identifies the forward edge of the battle area (FEBA) (or line of departure [LD]/line of contact [LC]), and arrays ground forces to two echelons below (considering force ratios in the process) at expected points of contact. The staff estimates the amount of force needed for various broad tasks such as objective assault or fire support; but they do not identify units, perform task organization, or assign missions. If it turns out the available force is excessive, the staff can place the excess in reserve or strengthen the main effort; if it is too small, then the staff considers combat multipliers.

(3) Now, a narrative is produced describing how all (including "excess") maneuver forces will accomplish the commander's intent. The staff must ensure that this scheme of maneuver addresses the complete battle space, including deep and close operations, covering/security force, rear operations, and reserve considerations. The staff identifies the type of unit (infantry, armor, mechanized) for each task, but not the specific unit (except in special cases). That is the commander's job.

(4) Next, the staff considers maneuver control measures and C2 means. In particular, the S3 groups the lowest arrayed units into higher echelons, organizing subordinate commands. Then (for purposes such as synchronization and fratricide minimization), the S3 sets forth control measures and, with the rest of the staff, specifies axes of advance, boundaries, and fire control measures.

(5) Finally, a statement and sketch are prepared to explain the "what, where, when, why, and how" of the complete duration of the operation.

2.3 Wargaming. Gaming is traditionally the most useful (and hence, most time consuming) portion of COAA. It helps the staff develop tasks and organizations, combat power requirements, critical events and decision points, prioritize efforts, and command and support relationships. However, it is difficult for many staffs to produce a detailed plan by effectively gaming a COA. As a practical matter, when the entire staff participates, the plan is better synchronized. In particular, information recorded during the game is used for developing the execution paragraph of the operations order, synchronization matrices, and the decision-support template.

The gaming method is selected based on the type of operation and available time. Doctrinally, there are three from which to choose, each with certain advantages. The belt technique is preferred as the most effective method for the entire force, enhancing synchronization by analyzing everything that affects specific events. The S3 divides the AOO into belts the width of the zone or sector and along phase lines or adjacent, covering specific phases. The belts are overlapped, and the intersections especially analyzed in detail. The staff games all events within a belt simultaneously. The disadvantage is that, since it analyzes more critical events, it is a lengthy process.

The box technique is best if there is little time. It analyzes selected critical events considered most important by the staff. The S3 draws boxes around these events, and each is then analyzed by the staff.

The avenue-in-depth technique is better suited for the offense. It focuses the staff on one avenue of approach (AOA), starting with the main effort. It allows gaming the battle in sequence from the assembly area to the objective (offense) or throughout the main battle area (defense). It takes more time than the box technique since all critical events along the AOA are analyzed. Of course, the staff can utilize a combination or its own custom method. Indeed, the intent of this report is to discuss concepts and implementations of novel gaming and analysis techniques.

The S3 selects the gaming technique. If the avenue-in-depth or belt method is used, the starting point is the unit assembly area or defensive position; if the box method is used, the starting point is the most important critical event. The gaming sequence of "friendly action, enemy reaction, friendly counteraction" continues for each critical event until all are completed. However, we contend that without further analysis of this technique, it is not clear that each iteration should be precipitated by a friendly action, critical events should be gamed independently, or a single gaming technique should be used for all COAs being developed.

Doctrinal guidance for the gaming process is comparatively straightforward. First, the staff lists friendly forces, assumptions about the postulated conflict, and critical events and decision points known at the time. Then they determine criteria for the upcoming evaluation, and for the methods for gaming, recording, and displaying results. Finally, the battle is actually gamed and the results evaluated in accordance with the preceding information.

There are several doctrinal gaming rules that should apply, whatever the method. The game must be entirely objective, with no preconceptions or influences of personality. In particular, the staff should not be swayed to gather facts to support a premature conclusion. Advantages and disadvantages should be accurately recorded as they are observed.

First, the staff gathers the gaming tools, of which conventionally the most important is a map (printed or sketched and preferably large for visibility) of the area of operations, covered with acetate overlays of the disposition of the friendly units and of the situation template for the chosen enemy COA. The S3 sketches the proposed COA on this area of operations overlay (AOO) for revision during gaming.

The inputs to the gaming process are provided in large part by the S2. These items include the situation template, event template, modified combined obstacle overlay, high-value target list, and draft reconnaissance and surveillance plan.

As part of the gaming process, the S4 notes ammunition and fuel requirements, probable maintenance and supply needs, transportation needs, including supply routes and logistical resupply points, losses of critical weapons, etc.

There are a few traditional methods of recording the game results. For instance, the sketch-note technique seems to be a fairly casual graphical way of enabling the recorder to reconstruct the basic game for briefing and analysis. For our purposes of automating the COAA process, the synchronization matrix would appear to be a more structured method, lending itself better to computerization. In this scheme, the recorder lists the mission, time, enemy action, and decision. There is an entry for each arm, including fire support, intelligence and electronic warfare (IEW), and air defense. Of particular importance are the maneuver elements, with separate entries for close, reserve, and rear, as well as reconnaissance and deception plans. Other aspects, such as engineers, logistics, and C2, are also given slots in the matrix.

In the wargaming process, the entire staff participates in a simulated battle in order to develop what actions will be needed for mission success. Each critical event is examined with respect to tasks and employment of assets for each area of responsibility and with regard to probable enemy responses. There are various methods for recording and portraying the results of gaming. We hope to improve on the essentially manual techniques by using modern computer hardware and developmental algorithms. Currently, the sketch-note technique, often used as a critical event, is gamed. On a synchronization matrix, terrain sketch, and/or gaming worksheet, a scribe records notes about the staff's considerations of actions and locations.

Gamers should continually assess feasibility and acceptability, rejecting a COA immediately if it is found unsuitable. (This tenet is open to debate in the light of automation and rapid gaming. It is possible that an apparently unacceptable COA may be modified to yield a workable solution, or, at least, a secondary analysis of the reasons that the COA is deemed infeasible may lead to insights for producing a good COA.)

The staff should avoid comparisons of COA during the game. Again, new systems of gaming may call this into question. Although humans may be distracted from the main task of gaming by not waiting until a separate comparison phase of analysis, there is no particular reason that an automated system must necessarily wait. Indeed, it can be argued that waiting is actually counterproductive, especially with little time available, since comparison in process may result in dropping, or at least postponing, the analysis of an "obviously" lesser COA.

2.4 Products of COA Development. It will be necessary to consider, in some detail, the products of COA development, since these are in a real sense the inputs to the COAA process that we are trying to improve. Here, by way of introduction, we just mention them briefly: statements, sketches, operational graphics, generic task organizations, and purposes and tasks for every subordinate.

Named areas of interest connote points along a mobility corridor at which enemy activity is expected. (Evidence for or against a particular enemy COA can result from activity or lack thereof in a named area of interest [NAI].) Similarly, targeted areas of interest connote points that, interdicted, will result in the enemy's inability to follow a particular COA.

The targeting process is based on the friendly plan, scheme of maneuver, and IPB. It identifies and prioritizes enemy formations, facilities, equipment, functions, and terrain that should be attacked to further friendly success. It also considers why and when the attacks should occur, as well as success/failure criteria. Beginning with the commander's guidance, it ends with his decisions on attack options (maneuver, fire support, etc.). The high-value target list sets forth targets that, if successfully attacked, contribute to significantly diminishing an important enemy capability and to significantly improving the success of friendly plans.

Another product of the gaming process that is recommended by some doctrine is the wargame worksheet. This write-up is a record summarizing the gaming of each COA. It comprises a numbered sequential list of critical events, with associated action/reaction/counteraction, assets, time, decision point, commander's critical information requirement (CCIR), and control measures. Remarks by the staff may also be indicated.

An important step in COA development, and one that greatly impacts our improvement of the COAA process, is listing the assumptions the staff sets forth in the development of estimates. In particular, the situation template is the S2's belief (until confirmed or modified by intelligence) as to the most probable enemy COA.

2.5 Elements of COAA. Inputs to the COA evaluation process include unit tables of organization and equipment (TOE) and combat power (the latter in itself is somewhat problematic), a map of the areas of interest and operations, the situation, objectives and required times, etc. Use of an analysis tool might involve staff actions like assigning units tasks and control measures based on the commander's mission. Then the system could perform automatic checking against doctrinal and physical constraints. Examining aspects of interactions with the enemy and of logistical support are areas of research; perhaps here is one area where fuzzy logic (FL) might be applied.

There are various principles of war that factor into COA development and evaluation, whatever the actual technique(s) might be. Observations by the likes of Sun Tzu [3] and von Clausewitz [4] are derived from experience and common sense and have proven useful throughout history. Several of these are set forth in the remainder of this paragraph, again to give a flavor for the kinds of items that would be considered in evaluating the feasibility of COAs. (Notice that a technical challenge in utilizing some of these lies in "quantifying the unquantifiable.") The assigned objective of a unit is the basis for interpreting orders, making decisions, and employing forces. Only through offense can an engagement be decided. There are many factors that constitute combat power, including tactics, ability, weapons, numbers and ability of troops, morale, discipline, and leadership. Concentrate force at the proper place and time to accomplish a definite purpose. The commander should move forces to the most critical point in the battle. Exercise surprise with regard to time, place, direction, tactics, etc. Take measures to secure against being observed or taken by surprise. Use simple operations, clear orders, and unchanging plans when possible. Coordinate and synchronize operations properly. No plan survives the first enemy contact.

COAA has several purposes. In determining the most flexible COA, the staff and commander must essentially have the same mental picture of the upcoming conflict. The best COA, then, protects friendly forces, minimizes collateral damage, and maximizes destructive power against the enemy. (Of course, for other types of operation the goals may be different; one objective of our research is to abstract the COAA process sufficiently that the commander and staff have tools applicable to operations other than war [OOTW].)

Many criteria may be used for evaluating COAs. Developing the best set of these attributes, along with techniques for the reasonable assignment of values, is of course among the goals of this research. It is the intent of our team to consider the application of computer science to the (semi-) automation of decision aiding. The following areas must be considered in detail—separately at first and then in relation to each other. Certain aspects are definitely required in any COAA. For instance, if the commander's intent (his vision of what he expects to accomplish and how he expects to fight) is violated by a COA, then that COA is by definition infeasible.

(However, it is valuable to consider what about the COA is causing the violation.) Fundamental elements underlie any good COA, and these should be checked throughout the development and analysis process; these elements include principles of war, tenets of Army operations, and characteristics of the defense or offense. In the particular battle being planned are more specific components, such as the commander's guidance, levels of risk, and the battlefield operating systems. Each of these items is spelled out explicitly and related to the others in a semantic net for automated checking of the postulated plan.

In analyzing the COA, it is essential to consider critical events. In defensive mode, these include events such as destruction of the enemy's first echelon force, committing friendly reserves, and counterattacking; in the offense, critical events include seizing the initiative, crossing a river, and reacting to an enemy counterattack. Sound military judgment must be used to set forth critical events (and decision points) and their probable effect on the conflict.

Control measures are verbal or graphical directives to subordinates from the commander. They control operations, coordinate maneuver and fires, and assign responsibilities. Measures are exemplified by objectives, boundaries, direction of attack, assembly areas, coordinating points, axes of advance, lines of departure, phase lines, and contact points. The fewest number and least-restrictive measures should be utilized in order to allow subordinates the highest degree of freedom in carrying out the operational concept. Generally, measures should be identifiable on the ground and easily graphed on a map.

Several essential items must be set forth for each COA gamed. The results of the war game are presented in the context of critical events and friendly/enemy actions/reactions. Then, the positive and negative points of the COA are spelled out for the commander. It may be possible at this point to suggest modifications to a COA that would either improve it outright or enable tailoring it for a contingency. Such excursion analyses are facilitated by computerized gaming. Highly abstracting the COAs would also provide a vehicle for mathematical analyses; this unconventional approach is of interest to our group, especially since there can be an interchange of results with a "higher grained" simulation such as ModSAF.

There are other elements of the battlefield planning and execution process that should be considered in the evaluation of COAs. Priority intelligence requirements (PIRs), for example, are quite important. They are items of information regarding the enemy and his environment, which must be collected and processed and for which the commander states priority in his decision-making tasks. Important related elements are the commander's decision points and decisive points, essential to triggering planned phases of the operation. The reconnaissance and surveillance plan assists in ensuring proper collection of the needed information. Battlefield timing must be explicitly analyzed in order to have a properly synchronized operation. Target selection standards, in conjunction with an attack guidance matrix, help particularly with offensive aspects.

Each COA to be analyzed must have a complete description in terms of the five W's: who, what, where, when, and why. The purpose of the operation is given, the friendly units are arrayed by force, the type of action and time it begins are specified, and the zones, sectors, and objectives are set forth. The staff inherently considers the "how" in determining employment of the commander's assets.

There is some doctrine for performing COAA under severe time limitations. The staff is to develop only one COA, which is to be done by gaming only a small number of possible COAs against a small number of enemy COAs. At the least, however, the most dangerous and most probable enemy COAs should be considered. (Tools for determining these two enemy COAs is a project for our COAA research.) As we have seen, the box gaming method can be applied, especially by first considering the most critical events. A restricted set of evaluation criteria may be applied. Tools for identifying and ranking critical events and evaluation criteria are essential aspects of our research. Another way to speed up the process is to involve the commander, who can monitor the gaming and indicate his preferred COA.

An important aspect of our research is associated with the step in which the staff identifies (for each COA) the critical events and decision-making information needed by the commander. These events, as discussed elsewhere, must be addressed via detailed analysis. Some critical events can be identified due to their nature even before gaming. In the offense, they include assaulting an objective, breaching an obstacle, and the passage of lines; in the defense, these critical events include initiating a counterattack, displacing forces, and committing the reserve. A related consideration by the staff are decision points, which are the use of time and distance factors to estimate the location of the forward line of own troops (FLOT) when the commander (in order to synchronize battle execution) must make an important decision (e.g., call for fire or move a unit).

2.6 Problems of COAA. It is difficult to develop COAs that follow the commander's guidance, comply with doctrine, and are feasible. Ensuring completeness and uniqueness is harder still. Although many techniques can be used to develop COAs, we seek a viable method that lends itself to rapid evaluation of COAs with respect to these (and other) criteria.

In developing or modifying a COA, the staff wants to include factors (e.g., information requests, asset allocations) that either reduce uncertainty (e.g., of enemy location and intent, friendly weapon performance, terrain features) and/or maximize success even in the face of such uncertainty. However, any COA (as will be seen later in discussing the chaos of war) can have an infinity of outcomes. The COAA must deal with this uncertainty by somehow characterizing the plausible and most dangerous outcomes. In analyzing a set of COAs, the staff attempts to flesh out and improve them, as well as develop measures of effectiveness (MOEs) to facilitate the commander's choice. C2 systems often provide tools for planning, but not for plan analysis or evaluation. There are a variety of technologies (including M&S) with such potential, however, and it is part of the work of our team to examine them and to develop improved methodologies and implementations. We seek tools that extract the plusses and minuses of a plan, identify interrelationships among factors, and develop measures of risk.

There has been some confusion over the difference between COA development and COAA. At the risk of minor oversimplification, we can say that COAA is basically the same process as COA development but more detailed and labor intensive. It also includes "players," such as the fire support and logistics officers, beyond the G2 and G3 who developed the COAs being analyzed. All of the players examine friendly actions, enemy reactions, and friendly counteractions as they wargame each COA. As the players refine the COA, a "synchronization matrix" could be semi-automatically updated with tasks, named areas of interest, critical decision points, and comments.

Other aspects of COA (beyond considerations of creation and execution per se) that lend themselves to analyses of varying degrees of difficulty include ease of modification in the face of changing/unexpected circumstances, coordination among internal participants, ability to merge with "external" plans, and computer science issues of storage, retrieval, and transmission.

Simulated or actual C2 systems can incorporate many tools to aid the decision-maker. For example, as actual combat occurs, real-time action data could be portrayed to assist in the fragmentary order process. However, development/analysis of COAs is problematic. A variety of techniques could be brought to bear on this aspect of aiding the commander. As part of our division's mission to investigate techniques for integrating operational and simulated combat, it is proposed that, at a minimum, SCB pursue a research program of exploring, assessing, and developing COA evaluation methods. One natural method for us is computerized modeling, simulation, and wargaming. There are related technical and doctrinal issues dealing with integrating M&S with C2 systems.

Another long-term goal is to utilize M&S in development of predictive and analytical algorithms for recommendation with regard to COAs. It is hoped that human decision-making can be improved by the computerized system's ability to handle large numbers of battlefield factors and alternatives. We intend to perform research in adapting GA techniques (and others discussed elsewhere) to understand C2 processes, make predictions, offer advice to commanders during battle planning and execution, provide alternate COAs, and possibly address "what if" situations as the plan is updated during different phases.

One problem with this scheme is that not all criteria should be weighted equally. The modification is simply to have a weight assigned to each criterion to multiply the rank of each

COA before summing. Another similar concern is that, for some criteria, the staff could do better than just rank the COAs. That is, one COA might legitimately be said to be n times better than another, particularly if quantitative measures (such as casualties) can be applied. In this case, the "rankings" should be normalized; so, in our continuing example, the worst COA for the criterion under consideration would be given a score of 1 and the other 1/n.

Another difficulty, one that may be remedied somewhat by automation, is the inability to develop very widely ranging COAs. That is, the staff tends to come up with options in accordance with their (especially recent) experience and what the commander has (especially recently) expected. The staff should be proactive in generating alternatives beyond those that are obvious or have been traditionally presented.

3. Further Discussion

3.1 Doctrinal Issues.

3.1.1 High-Level Issues. We can also investigate what might be considered metaproblems of C2. For instance: Are large numbers of cheap C2 devices better than small numbers of very sophisticated ones? Another question is: Should devices be connected into small redundant link-ups facilitating continuation of operations, vice entirely interoperably networked? We are pursuing more detailed research dealing with such issues.

Users of C2 systems should provide input toward their design. Moreover, due to modern military operations involving multiple services (and even multiple nations), interoperability of procedures and systems is a prime concern. Perhaps the central military should specify the C2 systems per se, and the operational should command the procedural and technical interfaces. This would enable the services to consider their individual requirements.

An indirect problem arises in that sophisticated C2 equipment serves not only as a force multiplier, but also as a logistics multiplier; that is, such equipment requires additional maintenance and training.

3.1.2 The Commander's Situation. Suppose the commander could absolutely secure communications so he could monitor his status and ensure that his commands are heard by his troops but not by the enemy. Suppose he could move instantly to any position on the battlefield and his line of sight was totally unobstructed. Several observations and questions arise from such a perfect scenario. For instance, no matter how the commander chooses to communicate with sets of his colleagues or tries to scan the battlefield, he will, out of necessity, be missing certain things; complete, current, perfect information does not exist. It is not clear what is really to be done with such information even if it were attainable. This would be an interesting research project, and the nonabstract situation involving levels of uncertainty (ranging even from total ignorance of the battlefield situation) is a possible application for what might be called fuzzy game theory.

There are other projects dealing with the impact of the friendly and enemy commander's intents on these scenarios and with the notions of prediction under various levels of uncertainty. Moreover, in general, one side has sufficient information to win the battle. Any commander will miss opportunities by waiting for perfection in information and doctrine and will be defeated by a commander whose information and doctrine are sufficient. Perhaps we can develop a combination of military and computer science mechanisms that will enable spotting of such "good enough" items and opportunities. Indeed, there may be a set of related projects for automation, probably through techniques of AI—tools for recognizing, taking advantage of, extracting from the fog of war, and even creating opportunities. Developing such algorithms and tools is part of the mission of the Computational and Information Sciences Directorate (CISD).

The commander must deal with a universe of possibilities that may overlap those of other decision-makers and that contains both "known" unknowns and "unknown" unknowns. He generally needs a particular fact at the proper time, rather than large amounts of data. For instance, it is probably better to realize that an enemy tank is just over the next hill than to have a database of its technical capabilities.

It is probable that the commander would never want to place all of his tasks involving information gathering, situation evaluation, and decision making entirely under the auspices of computerized C2 systems. Although the military user seems increasingly comfortable with allowing machines to manage "low level" tasks of this sort, he wants the ultimate responsibility for his troops to be personal and human.

C2 technology is risky business in the sense that, while it does give "access" to the battlefield (e.g., via improved communication, sensors, and databasing), it has flaws and vulnerabilities that can increase the commander's level of uncertainty, and its structure can limit his options. Its sophistication can apparently provide precision and timeliness that may be not be real. Information overload per se is still an issue as well; that is, "too much" information (at least if improperly presented) can also cause problems. A comprehensive program of research should examine such concerns and develop means to alleviate them.

3.1.3 Procedural Possibilities. Even in planning and evaluation with operationally realistic data, there is the possibility, if doctrinally acceptable, of using generic (vice named) units. Templating C2 for such units could be facilitated by using any number of models. Reasoning could be done about abstracted basic force units, where the plan feasibility is roughed out in phases before actual allocations are done, such as named units or C2 measures. Evaluation and fine tuning of COAs may then be warranted after allocations. An option could be to use named units and their specific capabilities in both planning and evaluation. Perhaps there could be a mixture of generic and named units applied to various phases or locations of the battle. Another possible area of investigation is computerized assistance to current methods for allocating C2 measures after developing the overall plan; once a COA is chosen, then measures might be semi-automatically scribed in, relying heavily on geographical considerations.

A methodology could be developed for the commander or staffer to review COA evaluation results and use them for accepting or rejecting phases or portions of a COA. This work could capitalize on the generate-and-test technique. This should be usable for interactive planning. For instance, if a user accepts a portion, he can incorporate it into further planning or use the projected results for other decisions. Further, the user might even modify results but not the plan fragment itself (e.g., changing the battle duration but accepting the force array). Probably only one OPORD should be considered at a time, with future plans being determined by the actual results of combat. We would like to implement these ideas in what might be called an iterative planning/replanning tool, which would develop fragmentary improvements to a plan as the actual battle was monitored or as better information was entered by the user.

We propose to extend current planning techniques for use with proposed Army 2010 and Beyond doctrine. Here, "extend" is used loosely, since the methods of fighting and, hence, planning will probably be quite different. For instance, as alluded to earlier, notions of attack and support, of close and deep battles, etc., may blur.

In military decision-making, it is often difficult to use regular methods and heuristics because of the rapid pace and dynamic uncertainty of the information involved. However, decision-making in such an arena is a skill that can be developed. One way to do this is hierarchically, that is, by considering the components or subproblems in a well-ordered way. We can first think of a problem as comprising its goals, its risks, and any options or alternatives that can be generated. The options have ramifications or consequences—the advantages and disadvantages of which can be examined with respect to the goals and risks. Now the problem is simply to choose the COA that maximizes (in a reasonable sense) the goals vis-a-vis the risks.

It is crucial to understand the desired goals in depth to avoid disaster later. One technique that may help, one that we argue is explicitly dismissed by current doctrine, is to consider an inherently poor option; in examining why it is poor, the staff can better grasp which goals are being missed.

It is essential to examine conflicting goals and make value judgments. However, in the complex COAA process, there are generally many such conflicts requiring tradeoff. One way of dealing with this is to explicitly spell out all the foreseeable repercussions of a COA. Then, peruse the positive and negative aspects, "dropping" the reasons that seem to balance each other (and they may be cases, of course, where a positive, say, is balanced by several negatives). After passing through the list, there may be a strictly positive or negative determination or (probably) a distilled problem. We intend to develop software to assist the staff in this process for COAA. For instance, there may be several ways that positives and negatives can be grouped for balancing, and research may be able to capitalize on automation to come up with the best determination. Assigning hierarchical and numerical relations to the aspects should also be valuable, and we are considering how best to develop the mathematics.

Another difficulty for the military decision-maker is the incompleteness of apparently necessary information. The staff cannot afford to wait without considering whether this is in itself a wise decision. If there is a problem in focusing, the staff can discuss the reasons why a decision cannot be made. Here again, software (at least "groupware") may expedite this search for information. In particular, if the staff has available templates that indicate the relationships between information, then computers can instantly point out areas requiring fleshing out for a good COAA, as well as tactical items such as PIRs. Again, we are considering how to couch this in mathematical structures.

3.2 Toward Applications.

3.2.1 Programmatic Intents. Even prior to ascertaining the doctrinal and practiced methods of the Army for COAA (and there may be quite a few), it would appear that information science and computerization can assist in at least two areas. One is to improve the commander's understanding of the advantages, disadvantages, and tradeoffs involved in each of the COAs presented to him by the staff. Another is to improve the speed of COA development and analysis and, by implication, the number of COAs the system is able to consider.

With regard to real-world application, there are several areas that can be dealt with at the basic research level before transitioning methods/prototypes to the Communications-Electronics Research, Development, and Engineering Center (CERDEC). In particular, validation is a major problem. Perhaps novel approaches to generating test data sets would be a start. The greensuiters know and use Warrior/Warlord notebooks. We should find out about these and investigate application to our projects.

We intend that the approach be quite flexible. That is, it should be applicable to military operations in urbanized terrain (MOUT), to Air Force force protection, and even to civilian analogs such as fire fighting or disaster relief. An integrated scheme being developed with the division is to have distributed battlefield visualization, intelligent agents providing warnings and advice, integrated C2 of sensors to shooters, and mission rehearsal software.

While the tools and techniques that are developed and explored as part of our research program come from widely varying fields of science and mathematics, the work is bound by a common goal: improving the ability of C3 systems to deliver important information on the battlefield when and where it is needed and to adapt their operation to changing environments.

3.2.2 System Requirements. Any technique will (at least according to foreseeable doctrine) utilize fairly conventional elements of battlefield units (such as position, strength, time to reach objectives, and fuel consumption), so-called named areas of interest (places on the battlefield that are observed for battle synchronization), and critical decision points (e.g., phase line passages enabling the commander to decide on whether to commit reserves). It is also probable that the same or similar processes can be utilized for COA development, as well as for evaluation.

In evaluating COAs, there are several factors that are apparently less quantifiable and, hence, generally more problematic than traditional wargaming measures of effectiveness. For instance, each commander typically has his own criteria for comparing battle plans (if only whether his intent is met or not); as part of our research we will investigate and characterize such criteria, probably in conjunction with other Fort Leavenworth work. Another, more explicit, factor is "riskiness" of a COA. We propose to explore what constraints are overridden in developing particular COAs.

One aspect of the analysis must involve a "side by side" comparison of several COAs. There should be a breakout of various criteria, both objective and subjective, that the commander can use in evaluating the COAs, both stand-alone and in relation to each other. Moreover, there should be at least one algorithm for performing automatic computations of the utility, value, risk, or whatever measure the commander deems necessary for an evaluation or ranking. We believe that a good COA should be robust. Therefore, we intend to perform "perturbation" analyses and evaluations against a variety of enemy actions and environmental conditions. The process should involve the capability for doing sensitivity analysis or "what-iffing" via adding/modifying/deleting constraints. Ideally, this last item would be quickly available, at least in the form of trend indications, without full-up regaming; if it turns out that additional runs of the combat simulation are necessary, perhaps the system can indicate the amount of time required to perform such analyses.

COAA tasks, such as analysis of critical events, requires each staff officer to have good understanding of friendly and enemy capabilities of his kind of unit. Complete detailed factors must be considered to develop and synchronize a good plan. Perhaps we could develop a kind of "online help" that would serve as a memory refresher for the properties of particular equipment, the organization of enemy units, etc. Such knowledge repositories, or at least data warehouses, would take some of the burden off the staff as far as recalling "low-level" facts. This would also lend itself to expert system inferencing as part of the planning/evaluation/execution processes.

In any event, since effective creation of a COA involves certain well-known factors, then certainly COAA must consider them as well: doctrine, mission, tactics, techniques, and procedures. The rub, of course, is exactly how to consider them, particularly in an automated environment. That is what our research is about.

3.2.3 ***Human Issues.*** SCB believes there are important human issues that need addressing first or in parallel as we investigate methods for helping commanders make decisions faster and better. An initial assessment of how the staff and commander go about the "manual" tasks of C2 decision-making would be quite useful. But do we merely want to automate these processes? How can we provide (say in a COA evaluation) the commander with all of the information (even if properly analyzed/summarized) needed but not inundate him with too much?

As part of the general research into C2 decision-aiding, we intend to investigate (probably in conjunction with other scientists at the ARL Human Research and Engineering Directorate [HRED] and/or the Army Research Institute for the Behavioral and Social Sciences [ARI]) cognitive architectures. The idea is, in part, that good COAs should make sense to the soldiers following it and that mental maps, in a broad sense, are necessary to the construction and execution of good COAs. Similarly, it seems that modeling the long- and short-term knowledge repositories and reasoning processes of the commander and his staff will prove useful in developing new methods for transforming information so that the TOC of the future can be made more efficient. It is appropriate to examine the state-of-the-art of C2 M&S, in particular with regard to linkages with force-on-force simulations. (Other elements of the FedLab are examining the impacts of advanced sensors and telecommunications.) We note that there has been much work done over the years along such lines. We may consider techniques utilized for factory-control systems, personal digital assistants, and vehicle pilot associates.

3.2.4 ***Methodological Implications.*** Real-world optimization problems generally involve complex interactions that do not yield closed form mathematical solutions. We need clever methods for exploiting high fidelity simulations to yield quick (reasonable time) and accurate predicting and planning results.

The problem space is essentially infinite and, moreover, involves "unknown" unknowns. Therefore, we propose trying to enable the evaluation by quantitatively or qualitatively assessing advantages, disadvantages, and risks in the face of uncertainties of (at least certain types of)

COAs. These assessments must also be readily convertible from the automated system for explanation to the commander.

There are many techniques for projecting the effects of a given type of combat force or battle element in a given role or scenario. For instance, conventional wargaming could be used for mortar units in MOUT, or symbolic decision-making for rangers in a deep attack. Almost any of these could be a reasonable approach to beginning a study of military planning. However, for a comprehensive investigation of operation planning/replanning, or even for a less-definitive look at COA evaluation, we should probably consider them all, at least in some sense. That is, we must clearly define the problem (if such a thing is possible, or at least a representative set of problems) and nature of the solution space. When must then consider the metaproblem of how to go about mapping the latter to the former in a way that really means something and can be practically used by the commander and his staff. Moreover, in "thinking outside the box," we intend to investigate more generic planning and monitoring methodologies in addition to obviously applicable technologies like computerized wargaming.

From our experience, combat simulations are generally useful only for assessing trends based on changes to input parameters. For example, by running a series of excursions, the probable value on the outcome of a postulated scenario of changing the range of a howitzer can be evaluated; however, to claim that any one of these excursions would correspond to an actual battle is not wise. The state of the art of combat modeling, even using actual operational data, is not that good. Models are, after all, simplifications of reality, and the complex stochastic nature of combat compounds are the difficulty. Combat simulations are appropriate for examining the nature of warfare and for analyzing trends; they are not appropriate for making predictions about the outcome of any scenario, due to the inherent mathematical chaos of the battlefield (and, to some extent, the modeling and computational thereof). COAA must rapidly produce insights for the commander so that he can make important decisions, but combat simulations typically require significant initialization, run, and postprocessing times. So, we take the position that wargaming might help the commander's staff look at possible outcomes of a COA in a given situation, but understanding bigger pictures (discussed elsewhere) is problematic. SCB has decided that traditional combat simulation is insufficient for COAA. It is not even clear whether is it necessary. In any event, we must consider other approaches.

4. Areas of Investigation

4.1 Introduction. This section, by way of introduction to the scope of our effort, deals with challenges for C4I analysis vis-a-vis M&S. Associated issues and a variety of possible approaches are also mentioned. Many of these items are discussed in more detail in subsequent sections.

There are a variety of research topics (both basic and applied) in the science and technology of M&S that our group can pursue. Some of these lend themselves to creation of engineering prototypes in specific applications that could eventually be transitioned to CECOM or STRICOM for advanced development and fielding.

Various technologies (including GA, FL, generate and test, and other AI techniques) are probably necessary for addressing our C2 problems, particularly the COA aspects. This is due, in part, to the fact that there will never be mathematically certain analytical solutions. Indeed, in the face of a relatively intractable problem, humans use imperfect models (consciously or unconsciously) to develop "good enough" solutions, even if they are subject to criticism. Our approaches could model these human thought processes, and computerization can improve them in various arenas: visualization of relationships, vastly greater speed, improved recall of structure, and highlighting of assumptions. Even though the models are still imperfect, they could produce faster and better analyses.

There is interest in some circles in incorporating a facility for monitoring the unfolding of the battle. This could help development of a real-time unified plan-monitor-replan system. Again, this is quite technically and doctrinally challenging. For instance, the machine must somehow incorporate knowledge for recognizing important events. Mathematical techniques for determining deviations of the actual battle from projected results are being considered by our team. Indeed, there could be development of software for finding critical events and for focusing the execution monitor on these events. However, such techniques, even if not incorporated directly into replanning, will be useful in identifying problems in the plan. Indeed, the "mere" development of a tool that shows the battle will assist experts in identifying problems.

A specific area involves validation of COAs developed by a GA program such as Fox-GA. Research is to be done into assessing the feasibility of COAs developed using a fairly abstract wargaming mechanism. One approach would be running the COAs in a more realistic combat simulation (e.g., ModSAF) for evaluations that would include more detailed situations and commanders preferences. An auxiliary aspect of this approach is automation of the typically time- and labor-intensive scenario setups of such simulations. An even more difficult extension of this work would be a determination of the level of optimality for a given COA.

Although SCB is involved with combat M&S, there are other techniques that can be investigated for application to C2 problems such as the COA analyses we have been discussing. There are various statistical methods that can be used for COA comparison, in particular, nonparametric hypothesis testing. FL is similarly applicable due the somewhat subjective nature of many evaluation factors. The assessment could be couched in terms of a constraint satisfaction or multiattribute utility analysis problem.

Another technique is to check the COA against certain standards (e.g., the principles of war) or criteria (e.g., the commander's intent). Such checks may be objective (utilize numerical scores), subjective (be supported by an argumentative narration), or a combination. A related possibility is to examine the value of a COA developed according to a certain set of criteria by considering a complementary or "orthogonal" set of MOEs. For instance: Does the plan measure up with regard to logistical supportability or historical "sanity?"

Another technique is to "rederive" the COA through some other method, based on the same inputs, and compare it with the original COA. For instance, if the first COA was developed by the staff of Commander X, then see what the staff of Commander Y comes up with. A related approach is to perform a sensitivity analysis by slightly perturbing the inputs and rederiving with the same method. This may be useful at least for assessing the robustness of a plan. Moreover, all these techniques lend themselves to different sorts of algorithmic or mechanical implementation. That is, systems for performing COAA using such approaches may be built around printed decision trees, belief network software, expert system shells, etc. There could be techniques based on hierarchical search through decision spaces, classification and regression tree analyses, comparisons of vectorized or state-space representations of the battle, etc. This is truly an area where researchers can think outside the box.

4.2 Challenges. In this research are many scientific barriers—decision-making techniques accounting for incomplete/missing data and methods for rectifying mismatches in granularity of simulated/actual information are two in the forefront. There are technology barriers as well; the division is dealing with interfaces to C2 systems having real-time data feeds and with integrated displays of predicted outcomes and ground truth. Incorporating intelligent agent technology is both a scientific and technical challenge.

Real-world optimization involves complex interactions that do not yield closed form mathematical solutions. It is essential that the community develop clever methods for exploiting high fidelity simulations yielding reasonable time (i.e., sufficient for the required task) prediction and planning. In particular, we must enable COA evaluation by quantitatively/qualitatively assessing advantages, disadvantages, and risks under uncertainties. Moreover, these assessments must be readily convertible from the (semi-) automated system for explanation to the commander, a task made more difficult due to new factors that are less quantifiable and more problematic than traditional MOEs (e.g., commander's criteria, "riskiness"). We are considering the mathematical tractability and potential applicability of Bayesian belief nets (BBNs), case-based reasoning (CBR), genetic algorithms (GAs), rule-based systems (RBSs), etc. Assessment of robustness (a.k.a., sensitivity analysis or "what-iffing") may be performed through "perturbation" analyses against a variety of enemy actions and environmental conditions. A long-term hope is to develop algorithms that will perform automatic computations of utility, value, risk, and whatever measure the commander requires.

Improving the state of the art of computerized wargaming is a traditional challenge. Among the current issues are transitioning our work to the emerging follow-on to ModSAF, known as OneSAF, and the fact that traditional feasibility in examining changes to battle space parameters (e.g., combat ratios) may be more difficult in future conflicts that seem to be becoming increasingly "unconventional." We may be able to handle such problems with novel approaches such as characterization of battlefield states and use of control theory to determine optimal responses. New differential equation (DE) models and chaos theory may permit other kinds of investigations. A more straightforward approach is breaking the conflict into segments for basing parametric changes for a period on analyses of the preceding period(s). In any event, we will probably need methodologies for incorporating numerical values based on historical data or field experiments.

A related challenge is that COAA based on items set forth in established FMs may not meet future needs. Moreover, since conventional COAA is typically data, labor, and time intensive, we do not want to expend effort needlessly pursuing obsolescent techniques. We are working to understand developmental COA processes via interactions with Forts Benning, Irwin, Leavenworth, and Knox.

A long-term challenge is development of a real-time unified plan-monitor-replan system. Such work entails many software issues: monitoring unfolding of the battle, determining deviations from projections, finding critical events, focusing an execution monitor on these events, identifying problems in the plan, etc. This will require military research into factors (e.g., info requests, asset allocations) that reduce uncertainty (e.g., of enemy location, friendly weapons) and scientific research into algorithms for maximizing success even under such uncertainty. In particular, we intend to adapt/develop techniques to make predictions, offer advice during battle planning/execution, provide alternate COAs, address "what if" situations, update plans, and spot "good enough" items/opportunities.

One challenge being imposed on the group as a result of FedLab research is that of validation of COAs developed semi-abstractly. There is some concern that such plans may not lend themselves to real-world application, due to granularity mismatches and the inability to integrate predicted outcomes with ground truth. We are considering a variety of approaches, including: (1) run the COAs in a more realistic combat simulation (e.g., ModSAF) for evaluations that include more detailed situations; (2) check the COA against standards (e.g., principles of war), criteria (e.g., commander's intent), and doctrinal/physical constraints; (3) examine the value of a COA developed according to a certain set of criteria by considering "orthogonal" MOEs; (4) rederive the COA through some other method, based on the same inputs; (5) perform a sensitivity analysis by perturbing inputs and rederiving with the same method. As a practical matter, the implementation will probably be a hybrid.

A qualitatively different "challenge" is that of handling a variety of related tasks. These comprise such issues as software infrastructure to build tools, architectures for networked distributed computing, database access and manipulation, multimodal human-computer interfaces, intelligent software/physical agents, and "soft computing" methodologies. Our approaches are to collaborate with appropriate research and development (R&D) groups performing these kinds of work, leverage FedLab work, and apply lessons learned during system integration.

Dealing with the uncertainty and magnitude of the complex interactions and results of COAA presents both scientific and military challenges. The problem space is essentially infinite and involves incomplete/missing data and unknown unknowns. Approaches under consideration include characterization of plausible and dangerous outcomes, extraction of the pluses and minuses of each plan, and identification of interrelationships among factors. Development of measures of risk is an auxiliary approach that will have benefits in other arenas as well.

4.3 Abstract Formulation. COAA is a classic problem for an operation research/systems analysis (ORSA) solution; it is characterized by uncertainty and complexity. The general methodology involves an interdisciplinary approach that includes specification of constraints, goals, and options, consideration of the probable risks, benefits, and costs for each option, and a comparative portrayal of the results to the decision-maker. Decision analysis compares and ranks alternatives by considering their known attributes. (We extend this by also considering unknown attributes.) Cost-effectiveness analysis ranks alternatives by cost (effectiveness) given fixed effectiveness (cost). Cost-benefit analysis considers time histories of costs and benefits for each alternative, ranking either by benefit/cost or benefit minus cost. Risk-benefit analysis assigns a cost to each risk (usually having small probability but large adverse consequences) in order to compare the sum of costs with the sum of benefits. Feasibility analysis looks at whether a COA violates a constraint. In any type of analysis, it is essential to specify the criteria that the decision-maker considers in evaluating the alternatives.

As a precursor to mathematical formulation, we can also abstract the notion of COA to basically any means possible for a decision-maker through which the desired goals may be accomplished. In this sense, COAA involves several alternatives, among which the decision-maker chooses the final COA to be implemented. It is important (at least initially) for us to consider the alternatives as differing not only quantitatively but qualitatively. Indeed, mutual exclusivity will generally simplify the analysis. We consider that a new alternative results from combining aspects of two given COAs. (In a sense this is what Fox-GA does.)

Abstraction can help prepare us for applications of decision theory. A COA chosen by a decision-maker can be considered to result in consequences that are predicted via M&S. Consequences contributing to goal achievement are benefits, those that the decision-maker wants to minimize are costs, and those that impact the goals only slightly (and so are not usually analyzed) are externalities. The further consequences of a direct consequence may be graphed in a "consequence tree." Features of a consequence considered in the evaluation are attributes. A COA is generally said to have a multiattribute consequence.

We are interested in analytical models for describing mappings from the action space of COAs to the consequence space. In battle, these mappings are one too many, due to the inherent uncertainty and nondeterminism—a COA may conceivably result in any of a number of consequences. An item is feasible if not prevented by constraints; constraints determine a feasible set in each space. The decision-maker's selection of variables defines the possible variety, which is reduced to that actually seen by constraints. These rules for interaction among the variables are natural or artificial limitations; by prohibiting certain actions, certain objectives may be forbidden. Constraints may be unquestionable or removable, long term or short term. We may be able to bring information theory to bear on COAA, since it can be argued that constraints can be measured by the information in battlefield messages (or states).

Objectives may or may not be quantified. Often, objectives are not measurable, and, in this case, proxy objectives may be utilized. Part of our work is constructing reasonable proxies for the commander's qualitative objectives. Due to constraints such as limited resources, multiple objectives are generally competitive or conflicting, in that improving one results in lessening another. Mathematically, we may consider multiple objectives as a point in n-dimensional objective space; similarly, we may consider target values as a point (or, more probably, a region) in objective space.

4.4 Technical Approaches. It is important to consider, in detail, the inputs that are used to develop a COA, since these will factor directly or indirectly into the analysis and evaluation processes. A major portion comprises the products of the mission analysis phase of planning. We intend, as part of our research, to develop software for linking these items (and others) as a cross-referenced or "audit trail" multidimensional template that the staff can consult, add to, or modify as appropriate. We will analyze the structure of these elements in detail in order to more fully automate the COAA environment. Items to be examined initially include restated mission, modified obstacle/AOA overlay, commander's intent and guidance, enemy situation templates, specified/implied/mission-essential task lists, initial PIRs and reconnaissance and surveillance plan, detailed time line, initial event template, constraints and restrictions, and risk analysis. In particular, study of methodologies associated with the last item should provide insight into improving the COAA process as a whole.

A set of tools tailored to the particular operation is a vital item for COA development and analysis. The tool set could include various Army models (e.g., simulation data, historical data, information from FMs) and be based, in part, on existing charts used in current planning cells.

The set could handle various mechanical aspects of the battle such as time-distance calculations, duration estimation, attrition, and fuel consumption over a given path. It could also do some tasks more quickly and completely than planning cell experts.

Perhaps we could develop a commander's associate (or set of associates) analogous to the Rotorcraft Pilot's Associate. An artificially intelligent assistant could monitor the commander's battlefield operating systems, assess enemy activities, propose tactics, and help modify the COA as the situation changes. Another notion is that of a companion with enhanced memory and symbolic/numeric computational powers that would assist the commander and his staff with culling, noting, and recalling significant facts and implementing desired actions. For most proposed responses, such an associate would probably be designed to wait for the commander's approval or to start developing the action, with the commander having override authority. However, although this notion is technically ambitious and doctrinally controversial, it is conceivable that, under some circumstances, it could act autonomously.

SCB believes that incorporation of explanations should be emphasized in development of COAA. However, such interaction must be short and to the point to avoid wasting the staff's time. There should be user inspection of logic, algorithms, and code. The user should be able to view the inputs that result in a machine decision. The explanation facility should be able to provide information about input/output and step through the analytical process. Moreover, ideally, the user should be able to query the system as if discussing the analysis with a human colleague.

Planning and evaluation parameters should be under the control of sophisticated users. For example, the soldier-machine interface might set forth constraints based on the user's underlying knowledge or on how much change is possible without requiring a total revision of the analysis. This sort of inverse problem offers a significant technical challenge.

An interesting and useful C2 project would be a planning tool that would take as input, or help develop, a commander's COA and compare it with a doctrinally acceptable knowledge base. Any inconsistencies, actions founded on improper principles, etc., could be brought to the user's attention. Moreover, this would lend itself to modification based on experience, what-iffing based on possible changes to the mission, etc. It appears that CBR using the Army Historical Archive System or other historical data may be a reasonable approach.

Along these lines, we are interested in utilizing battlefield data (obtained from a variety of sensors or other sources) in conjunction with historical information (e.g., "libraries" of conflicts, National Training Center exercise records, lessons from the Center for Army Lessons Learned) for development of tools to gather, generate, filter, fuse, or otherwise manipulate information to assist the commander and his staff to better create, evaluate, monitor, and modify COAs.

One area in which automation (e.g., the "opportunity spotter" or "sufficient information decider" alluded to elsewhere in this report) may help is to alleviate the commander's (somewhat emotional/dogmatic) requirement to decide now, even if that is inappropriate due to "noise" in the process. For instance, if pattern recognition algorithms were able to tell the commander that, by waiting just a little longer, a much more reasonable decision could be made, that would, we believe, be a valuable tool toward which to direct research.

We may be able to generate "synthetic data" for use in simulations/wargames and even near-real-time battlefield information processing. For example, there could be artificial test cases (including terrain and scenarios) produced for testing new simulations or for stimulating near-real-time battlefield information processing systems. By accessing archived historical data and utilizing actual ongoing-battle information obtained from various sources, we may be able to filter, fuse, or extrapolate data to test tools/systems and fill in gaps in situation awareness via a form of sophisticated educated guessing.

To rapidly develop and assess multiple COAs, a combat estimator is needed with execution speeds much faster than real time. Detailed simulation is not likely to meet this constraint in the near future. However, other techniques (e.g., heuristics, event-based simulation, CBR) may be developed to meet the challenge, particularly if realistic operational data can be brought to bear in an appropriate manner. Moreover, multiple models in parallel on separate processors could assist a staff by developing competing analyses. Although a new "architecture" may have to be developed to facilitate this, one advantage here is that agreement of analyses tends to increase confidence, while disagreements may help identify critical events.

4.5 Applicable Technologies. There are many technologies that can be applied generally to areas of C2 and specifically to COAA. Some work has been done toward assessing the feasibility of several technologies for application to command decision modeling. Here, we summarize descriptions of techniques (along with a few words about potential applicability) including the analytical hierarchy process (AHP), AI planning systems, BBNs, CBR, constraint satisfaction, FL, GAs, lattice automata, neural networks (NNs), Petri nets, and RBS.

One basis for a COAA tool might be the AHP. When both quantitative and qualitative elements are important to the solution of complicated multicriteria decisions, AHP offers flexibility and power. The analyst couches the problem as a tree structure and reduces it to a sequence of relatively simple rankings, which are synthesized into an optimal decision having a straightforward rationale. This technique is decades old and has the advantage of being similar to the way people typically make their (simpler) decisions in practice. It is widely used and well regarded. There are various AHP-based commercial products. For instance, the analytic network process can synthesize and justify decisions via nonhierarchical, nonlinear modeling of relations. This may be a good system to consider for complex battlefield situations involving feedback among the elements and other interdependencies.

AI planning systems utilize any of a number of computational processes to put together a sequence of actions accomplishing a goal. Probably most germane to COA work is "generative" planning, which attempts to be independent of any particular application through the use of action templates known as "operators." The planning comprises searching through the space of plans for a sequence of operators that would bring about the desired goal. Generally, planning is computationally intractable, and practical planners formally restrict the problems they can address. For modeling command decision-making, there are a few approaches that seem most suitable: case-based planning (which has difficulties in case indexing and retrieval), nonlinear (which uses means-ends analysis and delay commitment to action ordering and tends to have somewhat weak representations), and hierarchical (which decomposes problems into more concrete tasks with ordering constraints that help the search algorithm). However, military planning generally has special considerations, such as reasoning under uncertainty, multiagent coordination, adversarial reasoning, execution monitoring, and dynamic replanning.

BBNs, causal probabilistic networks, probabilistic cause and effect models, and influence diagrams are graphical networks representing probabilistic relationships among variables. Some of these variables are chance variables reflecting the states of nature of battlefield conditions. Others are expressions of decisions made in response to actual or potential battlefield states. Generally, BBNs provide a basis for reasoning in uncertain environments (even when experimental data are sparse or nonexistent), with the decision methodology supported by the calculus of probability and with probability being subjectively defined in a less-restrictive Bayesian context. In application, the BBN and its associated influence diagram may be utilized to interrogate the impacts of alternative COAs with respect to both the previously defined benefit (utility) of each action and the probabilities governing the stochastic interdependencies among states. Moreover, the influence diagram is dynamic in its ability to reevaluate a postulated COA in the presence of new evidence (hard or conjectured). A BBN has great potential as a commander's decision tool due to (1) the ability to graphically model a complex network of decision and state-of-nature nodes (2) the ability to incorporate subjective estimates of probability to complement those supported by data, and (3) the ability to dynamically assess the effect of COAs in a game of "what if."

CBR is a problem solving and machine learning technique that uses a knowledge base of previous experiences. Similar cases are retrieved and modified as appropriate for the current situation. The new case is added, and each retrieved case is updated as to its support in solving the new case. Refinement and weighting of case indices is essential to computationally tractable CBR. Due to military history (e.g., patterns in the conduct of battles over thousands of years), command decision modeling lends itself to CBR. In particular, for planning COAs, cases comprise the battlefield state, mission goals, constraints, necessary actions, etc. Problems with CBR in this arena include representing complex tactics and reasoning behind certain actions.

Constraint satisfaction treats a problem as a graph-theoretic set of constrained variables. A solution involves searching each variable's domain for valid values. However, exhaustive search is generally exponential with the number of variables, so heuristics based on domain knowledge are used to minimize the space. In developing applications to command decision-making, some researchers have extended the technique to include not only discrete scalar-valued variables, but also arbitrary-typed (e.g., tasks and routes) and continuous variables by utilizing generator functions that produce discretized values for consideration during search.

FL is a formal system for representing and reasoning with imprecise or uncertain information. Fuzzy set theory and models can be used to model complex systems that can be only approximately specified. FL has been used in control theory, pattern recognition, natural language understanding, and many other areas. For our purposes, perhaps the most important applications are in decision support. There are several approaches to fuzzy inference, mostly generalizations of approximation theory or logical deduction. The nature of FL makes it a good technology for command decision modeling; all humans use daily imprecise information and approximate reasoning. It also has potential for application to autonomous intelligent agents in this and other arenas.

GAs provide a robust optimization method for large, difficult search problems. They are based on Darwinian natural selection and iteratively modify an initial data set via cross-over and mutation operators analogous to those of biological genetics. The resulting "chromosomes" are ranked according to a fitness function. Then, the less-promising solutions are removed from the population; the more-promising are retained for additional combination and mutation toward a global optimum. The complexity and quick reaction time required in much command decision modeling appears to make the use of GAs somewhat problematic. However, the technique may be used for path planning, logistical optimization, and some C2 procedural analysis. Also, as discussed elsewhere in this report, valuable work has been done on COA generation utilizing GAs.

Lattice automata comprise one of three techniques synthesized in the design of intelligent realtime agents able to operate in a simulation environment. The other two are isomorphic representation systems and dynamic programming algorithms. The lattice architecture is a locally connected network of automata and has two dimensions representing surface space and a third representing time. The architecture can support an isomorphic representation system able to encode within a computational formalism spatiotemporal knowledge; in particular, battlefield spatial dynamics can be described graphically. After a scenario has been defined, specialized dynamic programming and relaxation techniques permit goal-directed problem solving. Results thus far show that the combination is a powerful method for multiagent route planning and synchronization.

NNs are systems comprising many simple processing elements with function determined by their individual processing, network structure, and connection strengths. NNs are massively parallel and adaptive. Many training sets of data are fed to an NN, which modifies the weighted pathways among nodes to yield desired outputs. NNs tend to perform best on knowledge-poor yet data-rich domains, like classification problems in which explicit rules cannot be readily derived. However, some new techniques may make it possible to extract rules from the internal machine learning of an NN. NNs can be used for control, forecasting, approximation, pattern categorization, etc. Military applications include sensor fusion and target recognition. There is applicability in capturing cognitive processes. In particular, NNs enable some ability to deal with ambiguous environments and provide generalization and nonlinearity that appear necessary for C2 decision-making. Initial indications are that NNs can provide rapid decision support, if there are sufficient (an unknown aspect) training data.

Petri nets have been used as a tool for modeling distributed systems (such as network protocols) requiring nondeterminism, concurrency, communication, and synchronization. They extend finite-state machine theory by permitting simultaneous events. Object-oriented technology has recently been applied; Petri nets with inheritance and dynamic binding can model complex systems with multiple levels of activity. Most C2 applications have been at a high level. Petri nets are apparently better at describing actions (e.g., information flow and states of a system) than at describing reasons for decisions. They are most useful as an integrating tool in managing information flow and addressing timing issues for coordinated movement.

RBSs, outgrowths of early AI problem-solving research, are based on the underlying idea that problems in a well-understood domain can be solved by having experts structure knowledge into if-then rules. Newer RBSs combine multiple knowledge representations, models, and solution methods and reasoning strategies in attacking different aspects of a problem. Simple rules can associate conclusions that result when premises are true; they can express actions to be taken when situations occur. Also, the fact that such encoding is basically how experts communicate facilitates knowledge acquisition for the system. Problems characterized by scheduling and classifying are generally suited to data-driven reasoning that starts from known facts and has many possible goals. Problems characterized by diagnosis (and, to some extent, military decision-making) are generally suited to expectation-driven reasoning that starts with a desired answer and decides if known facts support its derivation. Complex domains involve much detailed knowledge, and decisions are heavily constrained by various sources that are difficult to model. For real-world command reasoning, involving planning and situational awareness, it appears that RBSs are insufficient; however, intelligent agents dealing with well-defined subproblems may help resolve some of the monolithic brittleness of more traditional systems.

4.6 Wargaming. As we have seen, there are various techniques that we might apply to the analysis/assessment/evaluation of a COA, given that it has already been derived. One of particular interest to traditional analysts is wargaming. Gaming may be manual, mathematical, computerized, or a combination.

There are several approaches, mostly derived from wargaming, that are traditionally feasible in examining changes to battle space parameters (weapons and tactics). These include combat ratios, firepower potential, history, unit effectiveness, rate of advance, casualties, and vehicles lost. There are, of course, any number of ways of measuring or calculating such things. Moreover, there are other methodologies that utilize these battle statistics as inputs for subsequent numerical or symbolic analyses: decision trees, BBNs, expert system advisors, etc. What we seek is an optimal technique or a (possibly combined) set of measures, probably situation dependent, that is useful for evaluating COAs in general.

We intend to use two versions of a single wargame program to develop techniques for transferring real-world data and simulation results back and forth among systems. For example, Wargame A (using as input a certain COA) would be monitored to provide actual execution battlefield information. This information would be used to simulate portions of the battle in Wargame B, the results of which would be fed back into the real battle. We can thereby explore algorithms for determining divergence of combat from the fight and for expeditiously developing modifications to the plan, including fragmentary orders. We propose to use ModSAF, a well-known and truly modular simulation with which we have some experience. Other reasons for utilizing ModSAF are its ample documentation and consulative ability of local colleagues. We will arrange for additional detailed training for the group in this software and will transition our work to the emerging OneSAF at an appropriate time.

We would like to develop a procedure, automated if possible, for indicating the effectiveness of forces, COAs, and tactics in various scenarios. The intent is to utilize the killer-victim scoreboards (or other measures of effectiveness) extracted from computerized wargame outputs as inputs to the procedure. A theoretical problem is whether there could be a way to evaluate the general utility of forces, without regard to specific situations.

4.7 Differential Equations. For years analysts have used deterministic differential equations (De) to model aspects of combat (in particular, attrition). Parts of Lanchester theory are fairly well developed, and increased effort has been placed on nonlinear and stochastic formulations. Many such models are solved through computerized difference equations.

Using DEs, we can predict the winner and duration of a conflict and track the history of force levels. Of particular interest to our group is the possibility of parameterized studies to optimize tactics, force deployments, and weapon characteristics. For instance, suppose friendly forces face an enemy in two echelons. Is Red better served by committing the second echelon at some particular time or by continuous reinforcement? How should Blue counter such tactics?

New types of DE models may permit other kinds of investigations. One aspect that might be pursued by our group is the application of the multivariate control theory to determine (even the existence of) optimal responses in combat situations. Perhaps we can characterize, through proper variables, the state of the battlefield and what might be meant technically by an objective state. Then, we can analyze whether the conflict system can be controlled (via feedback loops) and whether any state is optimal. Ultimately, such work might be applied to multistage optimization for monitoring and managing battle execution.

This research could also yield reduced or increased complexity for large simulations. Perhaps sensitivity analyses may show the relative importance of parts of the model, even allowing for reduction of scope if certain items are "superfluous." In any event, it would be useful to investigate situations and parameters for which greater "fidelity" may not necessarily be better for the analysis.

A related effort would be investigating methodologies for developing numerical values for the Lanchester coefficients. Such empirical population of the abstract formulation might be based on historical data or records of field experiments. There are also problems of perception and measurement noise (associated with the "fog of war"), both in the formulation of equations and determination of coefficient values.

In a sense, the traditional Lanchester approach is analogous to Lagrangian fluid dynamics. However, for modeling, the distribution and movement of forces in Eulerian equations are arguably more appropriate. In particular, attrition of forces as a result of the FEBA motion lends itself to use of partial DE, which can naturally handle densities and geometry. In particular, such formulations may permit analysis of interpenetration of forces and unusual battles that may occur in Army 2010 and Beyond scenarios. However, they are often mathematically intractable.

We would like to consider methods for dealing with battles in which the combatants are distributed in space according to density functions. For example, in a general formulation, each differential element of force would engage the enemy according to a kill rate function (e.g., of distance to points within the enemy mass) and would be killed at a rate comprising some kind of summation over the enemy elements. Advancement of one or both of the forces would be a function of ongoing combat, as well as of mission/strategy.

Dr. Mary Anne Fields of the ARL Weapons and Materials Research Directorate (WMRD) and Dr. Greg Spradlin of the U.S. Military Academy (USMA) Mathematical Sciences Department have been working on an intelligent model for battlefield simulations using reaction-diffusion equations. Troop movements can be simulated by modeling each soldier discretely. Large numbers of soldiers render this somewhat intractable, so the aggregation is considered a mass represented by a density function. Movement is then based on equations similar to those used for chemical diffusion studies. In guiding troop movement, many factors (attrition, terrain, mission, visibility, and obstacles) must be included, so computation of the vector field is generally difficult. This work has been pursued for some time, but improvements to the method are needed for more realism. Such improvements include reaction prior to contact, instantaneous communications, learning from mistakes, etc. Perhaps we can even investigate the notion of applying Cauchy analysis to controlling a battle by means of controlling its boundary.

4.8 Statistical Implications. One approach to evaluating COAs might involve application of statistical hypothesis testing, allowing a confidence level to be attached to the results. A null hypothesis that the COA is valid is assumed. A confidence level for a particular statistical test is established, thereby fixing the probability of rejecting a valid COA (Type I error). Perhaps more important for COAA is minimizing the probability of accepting an invalid COA (Type II error). Its magnitude can be determined by the power function of the test; the power is the probability of rejecting a false, null hypothesis. However, power cannot be computed against an alternative as general as "the COA is invalid"; it must be examined against an array of different specific alternatives. Moreover, if there are no numerical data available that are associated with actual battle, it may be impossible to quantitatively evaluate a COA. This is one reason why both historical cases and monitoring actual battle execution are important to this research.

Along these lines, we are interested in the ancillary goal of exploring experimental design techniques to allow simulation exercises to be used as experiments, particularly for application to COAA. If execution of a series of simulations is considered an experiment, statistical experimental design and optimization may provide techniques for deciding particular configurations to simulate so that desired information can be obtained with the fewest runs. However, when the study is not well-structured (as in subjective COAA), formal statistical analyses and precise probabilistic statements may be impossible. Moreover, many variance-reduction techniques developed for Monte Carlo simulations have been found not to be applicable to complex dynamic systems (as in battlefield conflict). Therefore, there are research opportunities for extending formal statistical design/optimization methodologies into the realm of combat simulation and COAA.

COA assessment can be performed by measuring departures in areas such as time, space, and force, as well as in terms of critical events. It appears that control charting techniques superimposed on the battle plan may be appropriate. Control charts, although usually thought of in terms of one measure, may be used to track several process parameters at one time. Work has been done in both parametric and nonparametric multivariate control charts. There are various quantitative measures on the battlefield that could be captured in control charts.

Attribute charts will handle judgments regarding conformance to specifications. For example, the commander, when viewing several simultaneous unit activities over a sequence of battlefield tasks, may be able to visualize defects in execution. Control limits can bound the number of defects that can be withstood and still leave the success of the mission likely. The basic idea in such an attribute control chart is that if a certain number of defects in the process are seen, intervention (in our case, alternative COA) is necessary.

Of course, to implement these charts we must have some way to determine control limits and some reference distribution on which to base them. There has been work in large deviation theory that may be applicable. Consider the lack of a unique rule for data ordering to help one decide when an extreme value has been encountered. To provide the specific reference distribution, we suspect simulation would play a large role in generating pseudo-data. The statistical bootstrap resampling from this pseudo-data is one tool that could be used to help establish control limit estimates. An extension would involve adjustment for time-sequenced data. If sufficient battle data existed, perhaps stochastically interpolated observations over time could be used.

Moreover, we note that COA comparisons are based on data from disparate sources. It would be interesting to consider data fusion techniques as a basis for combining data for the commander. Frequentist, Bayesian, and fuzzy methods are used in the sensor arena, and may be applied to help the commander deal with different bases, variations, and distributions in making his decisions.

As to COA development tools, perhaps some aspects of the plan could be supported by using factorial designs and evolutionary operation, which have some advantage over linear programming in that the objective function need not be linear. A statistically-based routine might be developed to continuously update the multivariate direction to move toward some optimum.

4.9 Display Aspects. There are several technologies that enable interactive display and facilitate decision-making. For instance, heterogeneous database management, query optimization, three-dimensional visualization, and natural language understanding are all areas of CISD research that might be brought to bear on our C2 problems. Other techniques we might investigate are prioritization of information to be presented to the user and methods of intelligently relating such information (including agent-based alarms) to ease the user's cognitive burden.

A soldier-machine interface could essentially be implemented separately from the planning and analysis applications. This would facilitate development and maintenance, support flexibility, responsiveness, and adaptability in user interaction with the software, and leverage ongoing graphical user interface (GUI) development work (e.g., within FedLab).

Ongoing work at ARL and elsewhere involves battlefield visualization. However, additional decision support might be provided by the commander via visualization of the plan itself. Implications about space, time, attrition, consumption, etc., that are made clear to the staff (who make them clear to the commander) would be invaluable. The human operator may be able to see patterns in the data that do not meet rule-based tests or NN tests that an automatic analyzer might apply (despite a counterpoint made elsewhere).

Another possible project (one that, in a sense, is already being undertaken by the Visage group, an R&D consortium investigating dynamic display generation for visualization, search, and analysis of large amounts of information) is a system that could fuse gathered data into a readily interpretable summary, probably mostly visual/graphical, for the commander and his staff. This is useful, but may be considered somewhat controversial because it appears as a filter that permits, or even requires, new kinds of mental manipulations on the part of the decision-maker. This refers back to an earlier point about enabling access to the system's mechanisms and even the raw data. An area of research for us that we believe is not being addressed by the Visage group is detection and correction of incongruous pieces of information that do not readily fit into such a scheme and might get averaged, improperly manifested, or even eliminated in a lesser system. This is an important problem because anomalous data might be vital for alerting the commander to defects (or opportunities) in his battlefield picture.

5. Other Programmatics

5.1 Introduction. There are various related tasks that will require interfacing with other R&D groups, both inside ARL and externally. Such tasks, some of which are ongoing as well-developed projects in their own right, include software infrastructure to build tools, architectures for networked distributed computing, database access and manipulation, multimodal human-computer interfaces, intelligent software agents, intelligent physical agents (e.g., to acquire data), and soft computing methodologies (e.g., to analyze fuzzy data).

There are also funding or partnering vehicles that may be retuned to facilitate some of these projects. For instance, the TCAT effort mentioned elsewhere is certainly germane. The intelligent agents contract with Grambling State University and others may be a way to leverage good basic research, particularly by faculty members, for military C2 applications. There is a large C2 information systems program (under the auspices of the Defense Advanced Research Projects Agency [DARPA], with CECOM executive agent) that impacts our work. Of course, the developmental command post of the future is of vital importance, and CISD has been participating in this effort for some time.

5.2 Outside Agencies. We are aware that other researchers have investigated the development and analysis of COAs. For instance, the AI literature is replete with theoretical results concerning planning and plan recognition. Many organizations are applying new technology to C2 problems. Great effort is placed on gathering as much real-time and background data as possible that might conceivably help the commander's staff. Some are placed on modifying or summarizing the overwhelming amount of information into a (usually graphical) form that is, at least in theory, more easily comprehended by the stressed user. It seems that everyone is looking into development of command posts with tools like graphic displays and database access. Perhaps we can leverage CISD involvement in DARPA's command post of the future (CPOF) effort to bring some of our COA evaluation proposals to greater fruition.

Along these lines, and more important for us, DARPA has a COAA concept exploration program that is examining technical approaches to better the timeliness and quality of COA development. It focuses on identifying technologies that can be embedded in planning systems to aid in COAA (and eventually in the planning itself) and in evaluating effects of technology insertion on doctrinal planning. Likely, technologies are being prototyped to explore their potential for Army division-level COAA. An experiment utilizing the 101st Airborne is being developed to quantify benefits and help implementation. Also, studies of other types of COAA (e.g., various techniques, database requirements, services, echelons) are being pursued.

There are basic mathematical aspects that could be dealt with by graduate students. For instance, application of calculus of variations to determine if objective functions could be an interesting extension of battlefield control research, especially since the parameters are so interdependent. Application and enhancement of computerized DE solvers would be useful not only in this C2 work, but also in other areas of ARL research. There are similar investigations into methodological tradeoffs of, say, heuristic search vs. simulated annealing. Perhaps Dr. Lyle Unger at the University of Pennsylvania could be brought in as a consultant and distinguished lecturer on optimization.

LTC Jack Marin should be contacted with regard to possible interactions with USMA. There is ample availability of faculty/students (many quite experienced in tactical analysis or M&S techniques) to work on our problems. LTC Marin, who directs the AI Center, is working on a functional description of the battle space (for STRICOM) and a wargaming data structure. His intent is to build a 21st-century TOC at USMA.

5.3 CECOM. There are major Army programs that could eventually provide vehicles for transitioning our basic research and exploratory development into demonstrations or experiments. Some headed by CECOM are discussed briefly to give a flavor for such work; as our efforts grow in maturity, we will investigate them further.

The combined arms command and control (CAC2) effort has as its objective development of a digital information systems architecture to demonstrate C2 for horizontal information exchanges for brigade and below combined arms task forces. Major technical challenges are development of a database architecture, distribution designs, and creation of an information processing and management technology product that will integrate with the emerging seamless communications infrastructure. Although we believe much of this work is beyond the scope of our proposed investigations, a critical issue is development of measures of combat effectiveness for comparison of solutions to the user's information needs. Moreover, simulation is to be used as a basis for verification.

Battle Space C2 is to expand information management and distribution capabilities to division, corps, joint, and coalition forces. It is to provide an integrated situation awareness and force synchronization capability via a seamless communication system and distributed database architecture. Technical challenges here involve development of the information management and distribution architectures, building on various predecessor and concurrent programs. Another challenge is correlation and integration of massive amounts of situation data flowing down from national/joint assets and up from lower echelons. Some germane work involves improvement of system engineering tools developed under CAC2, development of a corps tactical information architecture, and demonstration of a prototype platform for command, control, and communications (C3). The platform is to include decision and planning aids, with seamless connectivity to upper echelons.

The Rapid Force Projection Initiative (RFPI) has as an objective demonstration of enhanced C2 capabilities for light close combat. There is focus on defining a system architecture for extending the region of target engagement, controlling battle tempo (via situation awareness), reducing time lines, and increasing the probability of successful engagements. A technical challenge involves development/adaptation of data compression techniques and decision-aiding software. The approach makes use of leveraged products from other technical demonstrations as well as commercial items.

5.4 University of Virginia. Professor Don Brown is Chair of the University of Virginia (UVA) Systems Engineering Department. Moreover, he is a former Army intelligence officer who did signals intelligence in Berlin during the Cold War. He pursues research in planning, replanning, data fusion, simulation optimization, forecasting, tracking, etc. He has worked on a variety of systems engineering activities, such as a tactical electronic intelligence analyzer, crime analysis, rail logistics, and sensor placement. He does contractual work for the national agencies, such as the National Ground Intelligence Center's (NGIC) Pathfinder. He also collaborates with USMA; indeed, Brown was Marin's advisor. Dr. Brown should be contacted for information about methodology leveraging and collaboration on ARL projects (e.g., master's and doctoral theses).

One project that UVA is developing is a way of incorporating road networks into dispersal of a probability mass over actual terrain. Based on analogy to the potential surface of electrostatics (via construction of a prior likelihood map from information on slope, vegetation, obstacles, etc.), it also utilizes notions of state space and cellular automata. An application is, given sensor data (say, from JSTARS), to predict where the detected objects are going. There is some work being done on modification of the potential surface to incorporate the postulated destinations. It would seem that other factors could similarly be included, such as avoidance of probable enemy sensor locations or killing zones and positive weighting of areas that friendly intelligence has cleared.

Dr. Brown is interested in a kind of battlespace architecture. Knowledge sources would feed a structural blackboard (comprising a hierarchy of units, systems, and entities) and a parallel temporal blackboard (comprising situations, events, and behaviors). Perhaps we can help develop the mathematics of the architecture. In any event, we should obtain his design document and object model.

5.5 Internal Considerations. As part of the C2 project development for CCSD, we contracted with TCAT to conduct a study [5] that develops an overview of Army C2 and intelligence processes, simulation and wargaming practices, computer tools used in the operational and wargaming environments to identify hardware, software, information architectures, communication protocols, and standards, discerned incompatibilities, barriers, and obstacles in the operational and simulation and wargaming worlds, champions and concerned commanders, staffs, and operators, and a preliminary identification of methods to address any incompatibilities identified. We planned, through the TCAT contract, to develop a comprehensive understanding of the real-time (operational), simulation, and wargaming environments. Although the study initially focused on the brigade level, it could eventually be extended to incorporate other echelons and joint and coalition practices. The investigators interacted (by visits, conferences, briefings, etc.) with the Command and General Staff College, the Training and Doctrine Command (TRADOC) installations battle labs and Research, Development, and Engineering Centers (RDECs), which are developing tools for C4I and simulation, as well as with ARL researchers.

One possibility for CCSD interbranch cooperation on improving the C2 process involves extension of the Software Technology Branch's collaborative planning project. With the modified group decision support system, a planner or staffer could provide input, including positive requirements and negative constraints, to the overall "blackboard." As these pieces of the plan come together, an automated reasoner should be able to provide near real-time feedback on the validity and consistency of the inputs. If problems are found, then the planning staff can work on fixing them as part of the ongoing process, again probably with assistance from computerized wargaming or other decision aids.

Another such possibility involves utilizing the Battlefield Visualization and Processing Branch's graphics rendering engines. By combining tactical/terrain visualization tools like Chart with simulations like the dismounted infantry simulation (DISim) and ModSAF, the commander and his staff should be able to examine almost any aspect of the battle, be it planned or unfolding.

6. Conclusions

The very complexity of COAA provides fertile ground for development application of various technologies. Although the feasibility of M&S is yet to be determined, we believe it has great potential for improving C2 in the near term and especially for Army 2010 and Beyond.

Our research is intended to be an integral part of the CCSD strategy for developing tools for battle analysis, planning, and monitoring. We are concerned with theoretical approaches to and exploratory applications of methods for situation assessment, COAA, simulation and wargaming, battle-planning/replanning, and monitoring plan execution. Similarly, we intend that our work lead to development of improved simulations, tools to assist in generating forecasts of battle events, and information technology devices to assist the commander, his staff, and the soldier in the field. We will utilize, as appropriate, existing software (e.g., DISim) and hardware (e.g., the Virtual Sand Table Platform). However, we do not want to redevelop well-known types of tools, such as tactical overlays, or implement techniques into emerging battlefield systems (as RDECs have this mission).

This sort of R&D is corroborated by the Army Science Board (ASB). For instance, the work supports battlefield visualization critical paths, terrain data, synthetic environments, and (in particular) COA development and analysis. The ASB has noted that, for presentation of battle activity, synthetic environment is the principal capability, and (in particular) for planning and collaboration, COA development and analysis is the principal capability. It appears that the Battle Space C2 Advanced Technology Demonstration and the Rapid Terrain Visualization Advanced Concept Technology Demonstration have limited capabilities for visualizing the current battle and do not support COA development and analysis.

We must aggressively pursue research in M&S for C2. The technology base program must focus on critical needs and opportunities that provide underpinnings. Army technology base efforts are vital to R&D. We must focus on next generation/future systems to evaluate technical opportunities. We must focus technology on lethality, survivability, deployability, and C2. We will contribute to the ARL mission of executing research to provide the Army with key technologies and analytical support for future land warfare.

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List of Abbreviations

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AOA	Avenue of Approach
AOO	Area of Operations Overlay
API	Application Programming Interface
ARI	Army Research Institute for the Behavioral and Social Sciences
ARL	U.S. Army Research Laboratory
ASB	Army Science Board
BBN	Bayesian Belief Network
BDST	Battlespace Decision Support Team
C2	Command and Control
C3	Command, Control, and Communications
CAC2	Combined Arms and Control Center
CAS	Close Air Support
CBR	Case-Based Reasoning
CCIR	Commander's Critical Information Requirement
CCSD	Computer and Communications Science Division
CECOM	U.S. Army Communications and Electronics Command
CERDEC	Communication-Electronics Research, Development, and Engineering Center
CIP	Combat Information Processor
CISD	Computational and Information Sciences Directorate
C4I	Command, Control, Communications, Computers, and Intelligence
COA	Course of Action
COAA	Course of Action Analysis
COATI	Course of Action Technology Integration
CPOF	Command Post of the Future
DARPA	Defense Advanced Research Projects Agency
DE	Differential Equation
DIS	Distributed Interactive Simulation
DISim	Dismounted Infantry Simulation
FEBA	Forward Edge of Battle Area
FedLab	Federated Laboratory
FL	Fuzzy Logic
FLOT	Forward Line of Own Troops
FM	Field Manual
Fox-GA	Fox-Genetic Algorithm
GA	Genetic Algorithm
GUI	Graphical User Interface
HLA	High-Level Architecture
HRED	Human Resources and Engineering Directorate
IEW	Intelligence and Electronics Warfare

IPB	Intelligence Preparation of the Battlefield
ISTD	Information Science and Technology Directorate
JSTARS	Joint Surveillance Target Attack Radar System
LD/LC	Line of Departure/Line of Contact
ModSAF	Modular Semi-Automated Forces
MOE	Measure of Effectiveness
MOUT	Military Operations in Urbanized Terrain
M&S	Modeling and Simulation
NAI	Named Area of Interest
NBC	Nuclear-Biological-Chemical
NGIC	National Ground Intelligence Center
NN	Neural Network
OneSAF	One Semi-Automated Forces
OOTW	Operations Other Than War
OPORD	Operations Order
ORSA	Operations Research/Systems Analysis
PIR	Priority Intelligence Requirement
RBS	Rule-Based System
R&D	Research and Development
RDEC	Research, Development, and Engineering Center
RFPI	Rapid Force Projection Initiative
SAF	Semi-Automated Forces
SCB	Simulation Concepts Branch
STRICOM	U.S. Army Simulation, Training, and Instrumentation Command
TCAT	Texas Center for Advanced Technology
TOC	Tactical Operational Center
TOE	Table of Organization and Equipment
TRADOC	U.S. Army Training and Doctrine Command
USMA	U.S. Military Academy
UVA	University of Virginia
WMRD	Weapons and Materials Research Directorate
XO	Executive Officer

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 2000

3. REPORT TYPE AND DATES COVERED
Progress, Oct 98 - Sep 99

4. TITLE AND SUBTITLE
Research in Modeling and Simulation for Command and Control

5. FUNDING NUMBERS
61102H44

6. AUTHOR(S)
Richard Kaste, Barry Bodt, Joan Forester, Charles Hansen, Eric Heilman, Thomas Korjack, Mark Thomas, and MSG Henry Wells

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U. S. Army Research Laboratory
ATTN: AMSRL-CI-CD
Aberdeen Proving Ground, MD 21005-5067

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-SR-97

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report is intended to stimulate discussion on both the general nature of and specific projects for the evolving command and control analysis mission of the Simulation Concepts Branch, with emphasis on course of action analysis/evaluation. This is a "living document" that will be expanded and modified as our research gels. We focus on project possibilities most directly associated with course of action analysis tools.

14. SUBJECT TERMS
command and control, course of action analysis, modeling and simulation, wargaming

15. NUMBER OF PAGES
70

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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