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SYSTEM THEORETIC CHALLENGES AND RESEARCH OPPORTUNITIES IN MILITARY C^3 SYSTEMS*

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ABSTRACT

The purpose of this paper is to discuss, in an informal way, some of the challenging research opportunities that arise in the analysis and synthesis of Command, Control, and Communications (C^3) systems. It is concluded that significant advances in the theory of distributed decision theory under dynamic uncertainty are necessary to properly understand and synthesize complex military C^3 systems, and to advance the state-of-the-art.

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1. INTRODUCTION

The purpose of this paper is to examine certain generic problems of military Command, Control and Communications (C^3) systems from the viewpoint of modern systems engineering and to suggest research avenues that appear to be promising in advancing the state-of-the-art for C^3 processes.

The field of Command and Control has received a lot of attention in the past few years (see ref. [1] for a recent collection of views on the subject by several high level DOD and industrial contributors). The reason for this flurry of interest appears to be due to several factors:

(1) There seems to be some dissatisfaction with C^3 related procurements. To a certain degree this dissatisfaction may stem from unrealistic expectations on the part of the military user community on potential performance. There have been several comments voiced that the hardware specifications and system-wide performance were decided by engineers that are not aware of the "true" needs of operational commanders.

(2) There is an increasing awareness that it is very difficult to arrive at rational design specifications for the performance of a C^3 system under a variety of peacetime, crisis-management, and war conditions. The integration of specifications for individual hardware components into a system-wide performance index is a very complex task, and there does not exist a systematic methodology to aid the systems engineer to carry out the necessary cost-performance-reliability tradeoffs.

(3) The increasing range, speed, and accuracy of sophisticated weapons systems enlarge the volume of responsibility of task force commanders, thus necessitating an increased geographical dispersion of the commanders assets.

(4) The increased speed of weapons systems have reduced the time available for making tactical decisions by human decision makers. This requires an ever increasing use of automation at all levels.

(5) Centralized command posts are vulnerable to enemy attack. This necessitates the geographical distribution of the command hierarchy, and requires increased tactical communication among command centers for force coordination.

(6) The necessary secure and reliable communications links represent a very vulnerable component of the C^3 system. Modern electronic warfare (EW) disrupts communications through jamming during the time that tactical communications are needed most for force coordination. Similar communications constraints can occur due to environmental conditions (terrain, weather, etc.). High power communications are also undesirable because the emitted electromagnetic energy can be detected by enemy sensors, such as high-frequency direction finders (HFDF), and can be used my missiles that home-in using the radiation energy (ARM).

(7) Active, high signal-to-noise ratio sensors, such as radar, although excellent in the surveillance problem suffer from similar electromagnetic detection problems. Passive sensors are less vulnerable, but they do not provide accurate information, unless they are internetted with a high-bandwidth communications network.

The above remarks indicate some of the complex systems engineering issues that have to be addressed in C^3 processes. It should be self-evident that one deals with very complex large-scale distributed estimation and decision processes with a high degree of uncertainty due to environmental variables and enemy actions. Clearly, if a relevant set of theories and tools are developed for military C^3 systems, then these results would be applicable to similar problems arising in the civilian sector (power systems, transportation systems, etc.) which operate in a less stressful and less hostile environment.

The function of the C^3 system is to provide relevant, accurate, and timely information to the commanders so that they can make correct decisions regarding the deployment and movement of their forces and resources, carry out the necessary resource allocations, and achieve the objectives assigned to them. To accomplish their missions the commanders must establish a functional organizational structure that can deal effectively with rapidly changing tactical situations. The necessary organizational structure is very much dependent upon sensors, communications, and weapons technology. This is a key point to keep in mind. For example, in the absence of tactical communications the organizational structure must be such that each human decision maker can operate in an open-loop manner (or according to doctrine in military language). Clearly, a different organizational structure will be more effective if communications are available, so that force and resource coordination can be carried out in real time (closed loop command and control).

The distributed nature of the sensors and the distributed nature of human decision makers obviously interact with the architecture of the C^3 system. It is unrealistic to expect that all relevant information is transmitted in a timely manner to all decision makers; this would consume valuable (and vulnerable) communications resources and require a large time-delay.

Even if such "global" information could be transmitted to all human decision makers, they would be "swamped" with information, and they would be unable to use it effectively under the stringent time constraints that commanders operate in a stressful tactical engagment.

The above remarks illustrate the fascinating system-theoretic issues that arise in military command and control. These problems suggest new and unexplored avenues for theoretical research in modern systems, estimation, and control theory. The problems are clearly of the large-scale system variety, but quite different from those considered in the system-theoretic literature.

2. HUMAN DECISION ASPECTS

In this paper, the tactical aspects of command and control will be discussed leaving aside the strategic and planning issues; these are extremely important and quite often the success of a mission will crucially depend upon careful planning, resource allocation and logistic support. These set up some of the goals and constraints that a commander must operate under in any given tactical situation.

The purpose of a C^3 system is to provide the necessary information to a team of human decision makers so that they can carry out the mission assigned to them.

It is very important to appreciate that tactical decisions in a modern warfare environment are carried out by a team of commanders, rather than by a single commander. The reason for this is obvious. Weapons technology has progressed to the point that no single human decision maker can be an expert on all offensive and defensive options; even if he were, there would be no time to absorb all information and execute all decisions. To be sure, there is and there always will be the traditional military command hierarchy; however, from a functional point of view, modern warfare requires a much more fluid structure as far as tactical decision making is concerned.

To illustrate this concept, let us consider a naval battle group or task force consisting of at least one aircraft carrier together with several other platforms (cruisers, destroyers, etc.) and support vessels. Such a task force is capable of conducting simultaneously anti-submarine warfare (ASW), anti-air warfare (AAW), and anti-surface warfare (ASUW) in the sense that it possesses both the sensor and weapons resources, distributed among the platforms, to engage simultaneously submarines, aircraft, ships and missiles (which can be launched from submarines, airplanes, and ships as well as land bases). In order for the task force to be successful in such a complex engagement requires the coordinated decision making of several commanders, which may not necessarily be colocated. The U.S. Pacific Fleet has adopted the concept of Composite Warfare Commander (CWC) who oversees the actions of an ASW Commander (ASWC), an AAW Commander (AAWC), and an ASUW Commander (ASUWC). Each of the three subordinate commanders has a functional responsibility for defensive and offensive decision and actions in his area of "expertise". Interestingly enough the CWC "governs by negation;" the CWC monitors the decisions of the ASWC, AAWC, and ASUWC and he only intervenes when either an inappropriate (in his mind) decision is contemplated or when there is obvious need to resolve conflicts related to resource allocation. Such resource allocation conflicts may arise due to the fact that the relative location of the platforms in the task force can have a significant impact upon the capability of the task force to conduct ASW or AAW, especially since certain platforms have significant capability in carrying out ASW, AAW, ASUW as well as electronic warfare (EW) missions simultaneously. Another type of resource allocation conflict arises in the allocation of air resources to ASW, AAW, and ASUW.

The three main commanders (ASWC, AAWC, ASUWC) are those that issue orders. However, their actions are influenced by inputs of coordinators (such as the screen coordinator, electronic warfare coordinator, helicopter coordinator etc.) who have responsibility for a certain function associated with resources controlled by the commanders (ASWC, AAWC, and ASUWC). These coordinators monitor the status of the specific problem assigned to them and provide recommendations to the commanders on what to do. Interestingly enough one can abstract the objectives of the coordinators in terms of specific detection, survival, deception, and kill probabilities in their specific area of responsibility. Also note that the coordinators do not serve necessarily as staff to one of the commanders; rather they assess situations and generate recommendations that may involve the assets of more than one commander.

The above discussion illustrates that although there is a clear cut command hierarchy (e.g. admiral, captain, etc.), the team-decision mechanism in a tactical situation is <u>not</u> hierarchical in nature (where the word hierarchical is used in the strict system theoretic context).

Such team coordination issues are not unique to the Navy. Even more complex tactical coordination issues arise when one consider a land warfare scenario which involves the coordinated actions of both Air Force and Army assets. In this case the problem of tactical coordination are further complicated by the existence of traditional chains of command between two services as well as necessary coordination with Allied ground and air assets, [2], [3].

Thus, if one examines tactical warfare one must immediately come to grips with problems of distributed decision making by teams of expert commanders. For maximum effectiveness the resources available must be coordinated in time and in space. The complexity of the problem requires a division of responsibility and a certain autonomy in the decision making process of an individual commander. On the other hand, the commanders must communicate selectively for best resource utilization; communications may be subject to constraints especially when the commanders are geographically distributed to decrease vulnerability. It is precisely the function of the C^3 system to provide to each commander the right information at the right time so that he can accomplish the mission assigned to him, and to allow for the necessary coordination of the team resources and decisions.

The most important information that a commander needs is the location, velocity, and identity of his own, the enemy's and neutral objects. Past motion history is often important in deducing the enemy intentions. Fuel and weapons availability related to one's own assets is obviously also important. Such information must be gathered by the C^3 surveillance system.

It is important to stress that in a tactical situation surveillance and tracking information can be collected by a variety of sensors. Often the sensor measurements must be "fused", i.e. correlated with each other so as to provide an accurate situation estimate (some sensors such as radar provide very good position information but not identity; others, such as HFDF can provide some identity information but poor position accuracy). Because the sensors are geographically distributed there is a significant time delay before an accurate situation plot can be generated and transmitted to the commanders.

In a tactical situation each commander is presented with a view of the "state of the world" which he knows can be inaccurate and not necessarily very timely. Nonetheless, on the basis of this incomplete information each commander must make decisions consistent with the constraints imposed by the preplanned actions. Typical decisions involve:

(a) Control of surveillance resources (e.g. turn on a radar, launch a reconnaissance aircraft, etc.) to gather more information or clarify ambiguous information.

(b) Control of electromagnetic radiation (e.g. communicate or not, jamming strategies, etc.).

(c) Control of resources (e.g. relative position of ships, aircraft, tanks, troops, etc. and control of their movements).

(d) Assignment of weapons to targets (e.g. sortie planning by deciding what aircraft, from what bases, should be armed with what weapons, to attack what targets or other objects of military value).

(e) Weapons control.

These decisions are always made by human commanders. Some of the decisions are strategic in nature, i.e. they are the outcome of extensive preparation and planning. In a system-theoretic context the strategic decisions and planning are roughly equivalent to the establishment of desired open-loop controls and trajectories, and one can argue that such strategic or command decisions are the outcome of a static or dynamic deterministic optimization problem. In this phase, intelligence information is crucial. In the planning phase many details are not taken into account. Uncertainty is usually handled by planning in detail alternate options; specific and unambiguous objectives and directives are commanded for execution and implementation by the appropriate commanders. Generally [5], [6] subordinate commanders are told "who", "what", "where", "when" and "why". In general, subordinate commanders are not told "how"; it is up to the subordinate commander to develop a detailed tactical plan of action to accomplish the objective assigned to him.

It is useful, in the opinion of the author, to think of the "command" function in C^3 systems as being completely analogous to the open-loop control concept of modern control theory. The command function effectively specifies the reference trajectories in time and space (and alternate ones) for the mission to be performed. Although the tactical actions will be executed by a geographically distributed set of subordinate commanders according to their best decisions (remember the "how" is not specified), the availability of a global open-loop plan provides valuable open-loop coordination among distinct units. For example, neighboring platoons in a land warfare scenario will know the planned location and plans of adjacent units, as well as the time and place of close air-support operations. This helps a platoon commander plan his own course of action by correctly allocating his own defensive and offensive resources.

The word "control" in C^3 systems refers to the function that indeed the preplanned courses of action are more or less being accomplished in a tactical situation. In the author's opinion, the "control" function is completely analogous to "feedback". Real-time surveillance provides the commander with an estimate of the "state of the world"; he compares this with the desired state associated with the command process, and real-time decisions are made to control in real time the available resources to correct for undesirable deviations.

The nature of real time information by the tactical surveillance system can impact the overall decision process in different ways. A crucial piece of "global" information is one that violates a key assumption* under which the operational battle plans were made. This may necessitate the implementation of alternative operational plans at the highest level. If such a contigency were taken into account in the planning process the alternate plans can be sent easily and rapidly to the subordinate commanders. If, on the other hand, this contgency was not anticipated and there is no

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*A good example is the naval battle at Midway Island during World War II. The Japanese plans to invade Midway were based upon the intelligence assumption that the U.S. carriers were at Pearl Harbor. By breaking the Japanese code the U.S. Naval forces knew of the intended invasion of Midway, and Admiral Nimitz dispatched a three carrier force near Midway. The presence, location, and size of the U.S. task force did not become apparent to the Japanese until the battle started. This may have been a deciding factor in the battle outcome, in which the Japanese lost four of their large aircraft carriers, and abandoned the invasion plan.

time for drawing another set of plans (or if the communications environment does not permit transmission of the commands) the tactical situation will become chaotic at least in the short run.

The feedback "control" function requires the real-time reallocation of the resources of, and by, an individual commander to meet his commanded objectives. Sometimes he can accomplish this with the resources alloted to him; in certain cases, the situation necessitates the real-time coordination of the resources of two distinct commanders, and this obviously requires tactical communications.

The above discussion illustrates the nature of the decisions that have to be carried out by individual commanders, at different levels of the command hierarchy. The quality of the decisions made by an individual commander depend on the following key factors:

(a) The nature, quality, and especially timeliness of the available information (this can be greatly influenced by a superior C^3 system.

(b) The rules of the engagement (these act as constraints upon the commander's decision process).

(c) The goals and objectives assigned to him by superior commanders at the strategic planning phase.

(d) The commander's available resources (these again act as constraints to his decisions).

(e) The planning horizon time.

(f) The complexity of the tactical situation vs. the time available to arrive at a satisfactory decision (computer decision aids for the commander can help him to either arrive at better decisions within a given time limit and/or complete his decisions sooner).

The overall global outcome of any engagement will clearly depend upon the quality of the decisions of the distributed commanders.

3. SYSTEM -THEORETIC RESEARCH ISSUES

In the above section we discussed generic issues associated with the Command and Control process. In this section we outline some relevant research directions, from a system-theoretic viewpoint, that are necessary to develop methodologies and theories for C^3 systems.

Clearly military C^3 systems fall in the category of large-scale distributed decision systems. In spite of the many advances in large-scale estimation and control systems (see the survey paper of Sandell, et al [9]) we do not have a unified theoretical methodology for such systems.

Although C^3 systems fall in the category of large scale systems, nonetheless they are characterized by certain key properties and attributes that must be taken in account. These are:

(1) They are event-driven.

(2) The dynamics* tend to be trivial and there is not a significant dynamic coupling among the system elements.

(3) The coupling occurs primarily at the resource allocation level and the coordination of the resources in time and in space.

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*By this we mean the trajectories of aircraft, ships, missiles, tanks, etc. The motion of these resources does not create a dynamic coupling as in the case with, say, large scale power systems.

Military C^3 systems are characterized by geographical dispersion and phenomena that involve multiple time scales (for example, ASW operations are slow as compared to AAW operations). This spatial and temporal decomposition naturally leads to command distribution without the nned for extensive coordination in many cases.

From a technical point of view, the distributed detection and estimation problems that arise in the surveillance area and in the sensor tasking area, appear to be those that are most amenable to analytical treatment. Unified theoretical and algorithmic approches are needed in the generic problem of multiple geographically distributed sensors tracking multiple geographically distributed objects, the networking of these sensors, the necessary distributed data base management issues, and the communications requirements. A recent paper [7] discusses some of the issues in the C^3 surveillance functions, so no more comments on that topic will be given here.

The greatest challenge by far is to understand the interactions of a distributed team of human decision makers with the mechanistic and electronic components of the C^3 system. Fundamental understanding is required of the proper functional organizational structure of human commanders with the organization and architecture of the underlying C^3 system. It should be stressed that technological advances in the mechanistic and electronic components of the C^3 system (weapons, sensors, computers, communications, etc) will have a definite impact upon the organizational structure of the commanders, including their geographical distribution to reduce the vulnerability of centralized command and control centers. Tactical coordination will increase as multi-purpose platforms (ships, aircraft, etc), capable of performing simultaneously many functions (e.g. ASW, AAW, ASUW, EW), become increasingly available.

One cannot avoid facing squarely the issue that we must develop normative mathematical models for individual decision making. One approach that is under consideration [10] is to attempt to model the decisions a well-trained expert human commander as the output of a constrained optimization (static or dynamic) problem. In this formulation, the constraints on the optimization problem are related to the information available to the commander, the rules of engagement, the assigned resources, the desired mission, the planning horizon, and time-deadlines. The greatest problem area is to quantify the objective function used by the human consistent with his limitations in problem solving. A key constraint that must be included in the problem formulation is the limitations of human short-term memory (STM) (see the discussion by Simon on cognitive simulation in [11]). Information that is being processed by the central nervous system has to be held in STM, which represents a memory of notoriously short term capacity; human performance on congitive tasks is dramatically sensitive to the limits of STM. On the other hand, an experienced well-trained expert has stored a tremendous amount of information in long term memory (LTM). As Simon points out [11], "the accumulation of experience may allow humans to behave in ways that are very nearly optimal in situations to which their experience is pertinent, but will be of little help when genuinely novel situations are presented". It may very well be possible to abstract the human's objectives by suitable combinations of conditional

(a) detection probabilities

(b) deception probabilities

(c) survival probabilities

(d) kill probabilities

to properly take into account the risk-taking and risk-aversion characteristics of human decision making (see the discussion by Wohl [3] and [11], [12], and [13]).

Normative models for humans are not new in control theory. There have been several successful (and validated) models of human acting as a controller [8], [14]. Recently, these normative models have been extended to the case of a single decision maker having to accomplish a multiplicity of dynamic tasks under time deadline constraints, [8]; these results are very encouraging, not only because there is good agreement between the theoretical predictions of the normative optimal decision model for the human and the experimental data, but also because they demonstrate that for rapid tactical like problems with significant uncertainty the planning horizon of the human tends to be short. This is consistent with the limitations of human short-term memory, discusses above, which precludes the human from solving in his head stochastic dynamic programming problems with long planning horizons!

Needless to say, the very issue of developing normative models for human decision makers, and especially military commanders, is a very controversial one. Assuming for the time being that such models can be developed and validated, they can be used to represent the most probable decision of an ensemble of well trained human commanders in the same area of expertise, together with a measure of variability (e.g. standard deviations). Thus, such normative models cannot be used to model any particular commander. Also, it is unlikely that such normative models can provide us with cules on how "great military geniuses" think.

One can engage in endless discussions on modeling human decision making. It is the opinion of the author that such arguments, although intellectually interesting, have little to do with the problem of properly designing the architecture of a C^3 system that is intended to support the decisions of many commanders. If we do develop adequate normative models, these will be very useful in carrying out engineering and cost/effectiveness tradeoffs on the C^3 system hardware and architectures. They can also be very useful in carrying out computer aided war games, in which the functions of low-level subordinate commanders are replaced by computer algorithms, thus allowing the war game to be played realistically at a global level with many fewer human resources. This would result in significant savings. (A complex Naval war game, of the type played at the Naval War College in Newport, R.I. may involve 150 players; the computer is primarily used for bookkeeping purposes.)

Much needed research is needed to combine such normative models of individual commanders into a distributed team decision model. This will allow the study of alternate organizational structures in conjunction with the architecture of the C^3 system, as a function of the tactical situation. Very little military doctrine has been developed in defining the command and organizational structure best suited to coordinate forces with a significant content of multipurpose platforms. If a relevant command organization theory could be developed, then it would be very useful in defining suitable adaptive changes in command following an initial engagement in which some resources, including those associated with the C^3 system, were destroyed. It would also be useful for counter-C^3 studies, by isolating most vulnerable interfaces between the command organizational structure and the C^3 components. From a system-theoretic viewpoint very little has been done along these lines. The methodology in [15] (which deals with issues of team decision making by a distributed set of "expert" decision makers, each with a limited model of the world) could be a useful first step in this class of complex problems.

4. CONCLUDING REMARKS

In this paper a brief discussion of some generic decision problems in military command and control organizations was presented. The need for normative models of both individual and team decision processes was discussed, so that one can understand how to most effectively structure the human organizational command and control structure in unison with the architecture of the C^3 system so as to best support the decisions of the commanders.

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