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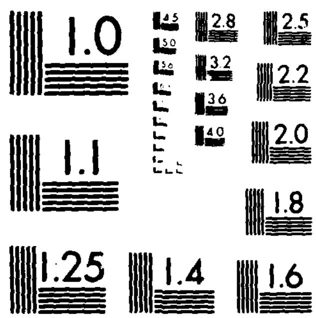

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THE EXPERT TEAM OF EXPERTS APPROACH TO COMMAND-AND-CONTROL (C^2) ORGANIZATIONS*

by

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ABSTRACT

This paper presents a concept which helps in understanding the Command and Control (C^2) process associated with a well-trained team of military commanders each being an expert in problem-solving in his particular tactical warfare area, and has been delegated C^2 responsibility and authority over his resources by his superior commander. It is argued that due to his individual training a commander develops a principal expert model (PEM) of the warfare area in which he has specialized, which allows him to make superior tactical C^2 decisions based upon the tactical information available to him. In addition, as a consequence of centralized mission planning and team-training of the entire C^2 organization, each commander develops aggregated mutual expert models (MEM) of the PEM's of the commanders that he strongly interacts with and competes for common team resources. This concept is refered to as the expert team of experts (ETOE) methodology.

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1. Introduction

The motivation for the ideas presented in this paper arose from the increased tendency to decentralize the military C^2 process in complex tactical situations involving several types of warfare. An excellent example of such doctrinal changes is the so-called Composite Warfare Commander (CWC) C^2 doctrine for Naval battle group operations; the CWC doctrine has been used by the U.S. Pacific Fleet for the past several years, and in April 1981 it was adopted by the Chief of Naval Operations (CNO) as the doctrine for all U.S. Naval battle group operations. Similar attempts to decentralize the C^2 process are under examination by other services. A more decentralized method [1; p.13] for artillery fire direction is being developed by the U.S. Army Field Artillery School to reduce reactions times. Similarly the U.S. Marine Corps are investigating the distribution of the C^2 process for increased survivability [2].

This trend toward decentralization of the C^2 tactical decision making function and the geographical distribution of specialist warfare commanders (WC) is primarily driven by technological advances in sensor and weapons systems; more "things" are moving faster and quiter;but sensors can see further thus necessitating rapid decision-making for the detection, classification, and localization of an enemy threat. In addition, geographical distribution of the WC's offers some protection from simultaneous destruction of the global C^2 process, by tactical (nuclear or conventional) weapons.

The decentralization of the C^2 process would be efficient, and would require a minimum of tactical radio communications for force coordination if the decisions of a particular WC regarding the location, motion, and function of the physical assets assigned to him did not influence to any significant degree the decisions and objectives of other WC's and vice-versa. However, this is almost never the case in modern warfare. In spite of careful mission planning, due to unforseen enemy tactics one WC may need more assets than he has to successfully carry out his individual mission and thereby contributing to the success of the overall mission.

The asset reassignment problem is only one example that points out the required coordination between distinct WC's. A more subtle interaction takes place when at least one particular asset has significant cabability in more than one warfare area. We list two examples to illustrate this point.

Example 1. In an Air Force context think of close air support (CAS) and interdiction (INT) as two separate warfare areas. Consider two specialist commanders one who is an expert in CAS tactics (call him CASC) and another who is an expert in INT (call him INTC). Particular aircraft, such as an F-16, can be used for either CAS or INT or both depending on the mix of armament that they are loaded with. One can imagine tactical scenarios in which the CAS problems in a sector suddenly becomes much more critical than the corresponding INT problem. In this case if the C^2 organization was set up right, and if the INTC had a reasonable aggregated version of the CASC's problem, then he could command one or more CAS-capable F-16, under his control to carry out a CAS mission without necessarily relinquishing his C^2 authority over these aircraft.

Example 2. Modern ships tend to have significant cababilities in all Naval warfare areas*, namely antisubmarine warfare (ASW), antisurface warfare (ASUW), and antiair warfare (AAW) both with respect to the sensors (passive and active sonar, radar, etc.) as well as the weapon systems. Normally, a TASS equiped destroyer will be assigned to the ASW commander (ASWC), while a cruiser will be assigned to the AAW commander (AAWC). However, although the motion of the destroyer will be controlled by the ASWC, nonetheless the destroyer can still carry out AAW function (radar surveillance, fire SAM's) and hence it certainly impacts the AAWC's problem. Similarly, the motion of a guided-missile cruiser will be controlled by the AAWC, but the cruiser can still carry out ASW functions (sonar search, fire torpedo, etc.) and thereby it is very much a contributor to the ASWC's problem. If the AAW threat increases significantly, the AAWC can ask to relinguish control of a particular ship (say, an AAW capable destroyer); the ASWC may or may not grant this request, and the CWC may veto the ship exchange (or lack of exchange).

The above examples demonstrate some very important issues that arise when coordination among WC's is desirable and beneficial in a decentralized C^2 tactical decision making environment. Assuming that such coordination is desirable so as to maximize to the extent possible the warfare effectiveness of a limited set of assets, each with a multiwarfare cabability, it certainly follows that:

(1) The C^2 organization must adopt a tactical doctrine that encourages such coordination of multiwarfare-capable assets, while preserving the C^2 responsibility and authority delegated to subordinate WC's.

(2) The physical C^3 system must provide the appropriate information to each WC so that not only he can make superior decisions in his own warfare area, but also coordinate with other WC's especially in the motion and utilization of multiwarfare-capable assets.

The problem is clearly very complex. From a scientific point of view it certainly contains subproblems of decision-making under stochas[illegible] dynamic uncertainty. Also, it certainly represents a distributed** [illegible]on problem. It contains elements of decision-making by individual human

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*Admiral Doyle's directive is in fact to have each ship have increased cabability in their secondary warfare areas.

**The word "distributed" in this paper is used in the same sense as "decentralized with coordination".

decision makers, the warfare commanders. It is also a problem in distributed team decision making. There are several interfaces between mean and machines; the quality of the collective tactical warfare decisions will clearly depend upon the real-time tactical information generated by intelligence and by sensors organic to the organization. The effectiveness of the tactical decisions will certainly impact the targeting of the weapons systems; delays between decision making and weapons release significantly degrade any reasonable measure of effectiveness (MOE).

In short, the tactical military command and control problem is a very challenging one. The absence of a "C^2 theory" has been recently recognized [4] as a significant gap in the system theory and system engineering disciplines. The lack of systematic methodologies for evaluating C^3 systems hinders the development of high-quality and meaningful specifications for C^3I related procurements. Technological advances in sensors, computers, and weapons systems may indeed require changes in tactics; how to train WC's and how to evolve C^2 doctrine in response to such technological advances is (or should be) a major issue for concern.

2. Some Definitions

The works "command-and-control (C^2)", "command, control, and communications C^3)", "command, control, communications and intelligence C^3I)" have different meanings to different people, and their indiscriminate use can create a great degree of confusion. For this reason, in this paper some distinction between the C^2 and C^3 terms will be made.

C^2 Process: The means by which a team of human military commanders make decisions that relate to the deployment and motion of the resources and assets assigned to them to carry-out a military mission specified by higher authority.

C^2 Authority and Responsibility: This refers to the fact that a particular commander can instruct, direct, position, move and, in general, control the human and physical assets assigned to him by his superior commander. His responsibility is to accomplish the specific objectives spelled out to him by his superior commander.

C^2 Organization: The semihierarchical way and organizational rules by which the human commanders organize themselves in terms of C^2 authority and responsibility by warfare are and/or geographical sector. Rules of engagement and tactical doctrine are an integral part of the C^2 organization.

We remark that in this paper we shall use the term C^2 to primarily relate to human decision making. Obviously commanders need real-time information to make decisions, and weapons systems that eventually implement a subset of their decisions. This leads us to the following definitions:

C^3 System Elements: The physical and technological hardware and software that generate, manipulate, communicate, and display information and the weapon systems. Thus typical C^3 System Elements are

(a) Sensors (Fixed or Moving)
(b) Communication Links (mostly radio for tactical C^2) and related devices
(c) Computers and Displays (hardware, software, firmware, decision aids) viewed as systems
(d) Weapon platforms and weapons systems.

C^3 System: The physical system and its architecture that defines the interconnection of the C^3 elements. Thus it is the C^3 system that

(a) generates data and information for different WC's in the C^2 organization
(b) allows for coordination among several WC's
(c) provides means for implementing the decisions generated by the C^2 process.

3. Some General Issues

It should be noted that the physical elements of the C^3 system as well as the WC's are naturally and/or intentionally geographically distributed; geographic distribution reduces the vulnerability of the C^2 organization and of the C^3 system to enemy attack but strains the radio communication requirements* necessary for coordination among WC's and to carry out the C^2 process.

Figure 2.1 represents a highly simplified schematic of the C^2 process interacting with the C^3 system. It represents a highly multivariable dynamic and stochastic feedback control process or a cybernetic process. The emphasis of Fig. 2.1 is upon the functions of the organic C^3 system as providing information (not data!) to the C^2 organization and acting as an actuator or effector that suitably transforms the collective decisions of the WC's into physical events.

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*Radio Communications bandwidth is the most precious and vulnerable element in the C^3 system because of its susceptibility to jamming. Spread spectrum techniques can reduce the jamming vulnerability but there is just so much bandwidth in the universe·UHF communications are less susceptible to enemy intercepts and localization, but constrain the system to line-of-sight communications.

Parenthetically we remark that the inclusion of weapons as part of the C^3 system is not a widely accepted convention. It is the author's opinion that they must be included since at a minimum they will generate tracks at a subset of sensors and they must be sorted out from the energy and neutral objects and targets. Also, when we consider coordination problem among WC's with respect to proper utilization of multiwarfare-capable assets, it becomes very difficult to define multiwarfare-cabability at a systems level without explicit consideration of the weapons systems that are carried in that asset. Finally, the whole issue of fratricide cannot be addressed in the absence of weapons.

Figure 2.2 illustrates in a different way the interactions of the C^2 process with the C^3 system. What we attempt to highlight in Fig. 2.2 is the need for a harmonious relationship between the C^2 organization and the C^3 system architecture. The "flood" of information that can be generated by technological advances in sensor technology cannot be indiscriminately be communicated to each WC that may be represented by a node in the C^2 organization. Conversely, the diverse decisions generated by the C^2 process should not be indiscriminately be communicated to the C^3 elements.

Many of the current tactical C^3 system architectures bring all the information into a centralized computer; it is very doubtfull that such a system C^3 architecture can support a very distributed C^2 organization, even ignoring the vulnerability of a centralized computer. The tactical communications requirements would be immense, and the delays* totally unacceptable.

It is the author's assertion that at the present time we do not have (and probably neither the "bad guys") a systematic, analytical, quantitative methodology that can be used to:

(1) Analyze the interactions between a fixed C^2 organization and a fixed C^3 system architecture, and develop really meaningful and relevant MOE's.

(2) Synthesize "harmonious topologies" of a distributed C^2 organization and a distributed C^3 system architectures, so that meaningful and relevant MOE's become "sufficiently good" or even "optimal"

What we do have is:

(1) Huge computer simulations
(2) Semi-artificial war games
(3) Military exercises

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*It is the author's opinion that the delay between the occurence of a hostile event by an enemy asset and the time to put "iron" on that enemy asset is the primary C^2/C^3 MOE.

What we have is valuable, but not enough; they are necessary but by no means sufficient. What we need is a "C^2 theory" which will complement what we can do now, and provide solid theoretical guidance on ways that C^2/C^3 analyses and syntheses should be carried out.

SO WE NEED A C^2/C^3 THEORY!

4. Why a C^2/C^3 Theory is Hard!

Before one can synthesize a harmonious C^3 architecture to support a distributed C^2 organization one must develop at the very least a rudimentary analytical cabability.

The analysis of any complex system requires a set of elements together with a mathematical description of what they do; these can be thought of cause-and-effect relations (or input-output or stimulus-response). The relations may be static or dynamic, deterministic or stochastic. Another requirement is that of a system topology which describes how the basic elements are interconnected. Next one requires a set of consistent variables and rules which define how the output of an element becomes the input to another, description of serial, parallel, and feedback relationships. All of the above allow a global system description by a set of consistent variables and mathematical expressions.

Given such analysis tools one can carry qualitative and quantitative analyses at the system level; for example, global stimulus-response dynamic characteristics can be deduced. Sensitivity analyses can be used to isolate bottlenecks and pinpoint to vulnerable C^2/C^3 system elements. MOE's can be defined and evaluated as functions (or function(s) of the consistent variables. Validation studies can be carried out provided that data is available.

Given an analytical model of the type that was described above synthesis questions can be posed. Thus optimization techniques can be used to improve selected MOE's. Impact of alternate C^2 organizations and/or C^3 system architectures can be quantified.

There are several stumbling blocks in the development of models for the generic elements of the C^2/C^3 system, and the main difficulty stems from the distributed nature inherent in a C^2/C^3 system. Even in the surveillance area in which the sensor (radars, sonars, HFDF's,ESM gear etc.) characteristics are well understood from a physical and engineering viewpoint, the problem of distributed detection arises and requires advances at a purely conceptual and mathematical level; some new (often counterintuitive) phenomena arise in distributed detection theory that have no counterparts in classical detection theory (see ref. [4] for a very simple example). Within the surveillance area, the theory and algorithms necessary to solve the multiple-target problem, including issues of data association and false measurements has not been resolved.

The same theoretical bottlenecks arise in almost every part of the C^3 system. For tactical radio data communication networks one must develop theories and algorithms for distributed routing and flow control for networks with changing topology, i.e. nodes and links may dissappear and reappear due to line-of-sight considerations. Issues of imbedding a redundant distributed data base within a changing radio communication network have received very little attention.

All of the above issues do impact the time delay between the occurence of an event (say position and identity of an object) and the presentation of this information to the appropriate warfare commander.

Although the distributed nature of the physical C^3 system requires advances in theory and algorithms before analysis and design can be really carried out, it is the author's opinion that the most difficult stumbling block relates to the appropriate modeling of the human commanders in the C^2 organization. Since the whole purpose of the physical C^3 system is to provide information to the C^2 organization and to implement the decisions generated by the C^2 process, such an interface cannot be ignored. Thus, at the most rudimentary level we need to model the information-processing and decision-making processes associated with:

(a) *a single military decisionmaker,*

(b) a warfare commander (WC) augmented by his staff, and

(c) the entire C^2 process by a team of cooperating WC's with a C^2 organization.

To successfully develop models for the C^2 process generated by the distributed C^2 organization one needs to blend system theory* and cognitive psychology concepts. It is argued that unless we develop suitable models for the C^2

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*The author's definition of system theory is broad; it includes all disciplines that relate to normative aspects of decision theory. Thus traditional disciplines that form system theory include: detection theory, estimation theory, control theory, game theory, operations research, communication theory, information theory, statistical decision theory, certain parts of computer science, and artificial intelligence in particular. As Simon [5 ,p.497] points out "...Artificial Intelligence is a normative discipline. Like operations research, its goal is to find powerful problem-solving algorithms, and no holds are barred. In fact, there is no real boundary between these disciplines, and today the theory of heuristic search is being pursued vigorously by both."

process we will never be able to develop suitable tools that will help us analyze current C^2/C^3 systems, point the way for superior evolutionary changes (through changes in hardware or doctrine) in existing C^2/C^3 systems, and synthesize superior future C^2/C^3 systems that can meet advanced threats and take advantage of technological innovation in C^3 elements.

5. Models for Commanders in C^2 Organizations

Modeling the behavior of human beings is a subject that has an enormous literature and certainly gives rise to very controversial arguments. To clearly delineate the boundaries, the author wishes to stress that the need for models that represent the information processing and decision making of a commander should be restricted to the fundamental issues of military warfare "Did the military objective got accomplished?" "Did we shoot down or drove away his airplanes?" "Were we successful in protecting the carrier from submarine threat?" etc.,etc.

In military C^2 organizations Warfare Commanders are delegated C^2 authority and responsibility by their superior commander because of the complexity of modern warfare. If the superior commander made all the tactical decisions in a superior manner then he would be required to

(a) absorb, and interpret all the tactical information

(b) be a true expert tactician in all warfare areas

(c) have a sufficient amount of time to correlate correctly the real-time information with the tactics that he has stored in his brain to arrive at the correct decisions.

All of the above exceed the fundamental limitations of even super-intelligent well-motivated and well-trained human beings. The main limitations of a human are summarized as follows:

Short Term Memory Limitations. These show up repeatedly in learning and decision making (problem solving) experiments as to the amount of information that can be stored in the highly serial short term memory (STM). In a classic paper Miller [6] argued that approximately seven independent "items" can be stored in STM. Simon [7 ,p.81] refers to these items as "chunks" because some "chunks" contain easily correlated information than others; for example, if the items are three letter English words the two words "DOG" and "FKN" correspond to four chunks "DOG" and "F", "K", "N".

The retention of 5 to 9 "chunks" in STM is true only if no other spurious activity or task, however simple, is interposed between the human subjects hearing the items and repeating them, then the number of retained chunks drops down to 2 [7, p.81].

The above strongly supports the clear preferences of military commanders to see the disposition of their military forces, and those of the enemy in a geographical plot. In naval battle groups a "chunk" may represent a pattern of warships with respect to a carrier; the same information presented in numerical longitude and latitude format would saturate the STM.

Learning Time: Once we have a "chunk" in the STM, then it takes 2-10 seconds (average about 5 seconds) to learn this chunk in the sense of placing it in the long term memory (LTM) [7, p.77].

Long-Term Memory (LTM): The human LTM is essentially infinite; there is no evidence that human beings have an upper bound on what they can learn. It is a highly associative memory with information stored in interlinked list structures, with extensive cross-referencing and indexing [7, p. 104]. In the case of a military commander all the relevant information that he brings to bear is stored in his LTM (tactics, prefereable asset distributions, effectiveness of weapons, etc.). An expert WC becomes trained by the accumulated experience gained through training, war games, exercises, etc.

Retrieval Time From LTM: Information stored in LTM can be retrieved relatively quickly; retrieval times range from about 50 milliseconds to 2 seconds.

The limitations of the human brain lead to the fact that even a highly motivated well trained human has his limitations, and these are primarily reflected to notions of human bounded rationality [5]-[8] and the fact that men are satisficers rather than optimizers (in the strict system theoretic sense). Simon [7, p. 36] asserts that "what a person cannot do he will not do, no matter how much he wants to do it". This leads to the notion of satisficing solutions which represent "good enough" decision but not mathematically optimal ones. Because of the limitations of the STM and any decision deadlines (which are prevelent in tactical warfare) the human is incapable in general of arriving at mathematically optimal solutions. Simon [5, p. 503] however, states that "... accumulated experience is indeed a very large component of high-level skill... . This accumulation of experience may allow people 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. That conclusion is consistent with our general belief that the limits of human rationality become particularly important in explaining behavior under uncertainty where we translate "uncertainty" here to mean any kind of significant novelty."

Keeping in mind the fact that tactical military decision making is carried out only in the context of a C^2 organization, it is very very difficult, if not outright impossible, to develop an empirical and repeatable data base on the basis of which empirical models of the decision process carried out by a single warfare commander can be developed. For example consider the naval war games that take place at the Naval War College in Newport, R.I. In such war games it is easy to quantify the final outcome of a naval engagement in terms of the initial and remaining assets. However, it is very difficult to properly define intermediate "epochs" in which the collective decisions, even before the battle starts, have given one side a particular advantage, and to use the empirical data so as to assess the quality of the human decisions that lead to a particular epoch.

It is the author's contention that we need to develop normative models to explain and quantify the decision process of a warfare commander, with particular emphasis upon his interactions with the tactical information provided to him by the physical C^3 system and his assigned mission within the C^2 organization.

The author proposes the term humoptimization as the process by which normative optimization-based models which actively reflect human limitations, such as bounded rationality and "the human is a satisficer," into the constraints of a suitable mathematical optimization problem. This type of constrained optimization problem must reflect

(1) the expertise of a well-trained warfare commander to arrive at superior tactical decisions in his own warfare area,

(2) the constraints imposed by the STM and its interactions with the LTM, and

(3) stochastic elements that reflect and capture the variability of the human decision making process.

Figure 5.1 illustrates in a highly simplified manner what a normative model, based on humoptimization, should capture. The set of decisions generated by such a model must be within the set of the satisficing solutions. The limitations of the STM would limit the search strategies in the tree generated by alternative hypotheses generation-response selection mechanism, and introduce a certain degree of stochastic variability in the humoptimization solution.

It is important to stress that such normative models of warfare commanders cannot be developed in a vacuum; they must be developed in the context of the physical C^3 system. An expert naval anti-air warfare (AAW) commander would not do a very good job if all of a sudden 100 Backfires appeared 50 miles from the carrier; this would represent a "novel" situation. However, such an event is extremely unlikely; it is precisely the intelligence and surveillance function of the C^3 system to prevent having the AAW commander having to face such novel situations.

There do exist normative humoptimization models of human decision making that have been validated. For the past decade several such models that accurately model the human as an element of a control system (e.g. landing an airplane, pointing an AAA weapon etc.) have been developed using the tools of stochastic dynamic optimization theory incorporating human perceptual and neuromuscular constraints; see, for example, Kleinman [9] and Levinson and Baron [10]. More recently Kleinman et al [11] have developed and validated a dynamic decision-oriented model of a well-trained human who is faced with carrying out several dynamic and stochastic tasks, under decision deadlines; once more the tools of stochastic dynamic optimization were used. Needless to say a great deal of basic and applied research is needed to develop the normative humoptimization-based models of different warfare commanders, and to validate them, that are needed to model the interactions of the C^2/C^3 process.

We shall refer to such normative models of an individual warfare commander as his Principal Expert Model (PEM). The PEM reflects the superior (expertise) of a well-trained commander to make tactical decisions in the warfare area/sector of his C^2 authority and responsibility.

Figure 5.2 illustrates the key elements of the PEM. The "blocks" within the PEM are those that must be reflected in the humoptimization model.

1) The Model of the World in the area of the WC expertise must include as a minimum the disposition of his own assets, enemy assets, and cababilities of the sensor and weapon systems under his control. His mental model in his LTM will be updated by tactical information, processed by his STM. The tactical information and the interaction between STM and LTM leads to a small set of alternate hypotheses which correspond to situation assessment. One can indeed argue that one of the key functions of the physical C^3 system would be to provide quality and timely information to the WC so as to minimize the situation assessment hypotheses (through reduction in uncertainty) since the generation of multiple "what is going on" hypotheses stresses the limitations of the STM.

2) Based on the situation assessment a set of decision options must be generated and eventually a particular decision option is selected. This process clearly involves the correlation of tactical training stored in LTM and is influenced by :

   (a) the objective function which abstracts the mission responsibility and objectives dictated by his superior commander,

   (b) the planning horizon that dictates the time-urgency of the WC's tactical decisions,

(c) any constraints on his allowable decisions imposed by the C^2 organizations (rules of engagement, EMCON status, use of tactical nuclear weapons etc.),

(d) Available resources (platforms, sensors, weapons etc.) and dynamic constraints (speed, maneuvarability).

Obviously the decision option generation is one of the most complex aspects of human decision making. It has been claimed* that experienced commanders tend to generate fewer options as compared to more novice commanders. This can only be explained that superior tactics are better organized as "patterns" in the expert commander's LTM, thus minimizing the "chunks" that are transfered in the STM.

It should be noted that the above qualitative description of the Principal Expert Model (PEM) represents a mild extension of the SHOR model (Stimulus-Hypothesis-Option-Response) proposed by Wohl [12]. Once more the quality of the information presented by the physical C^3 system can have a significant impact upon the decision option generation process. For example, gridlock errors among different surveillance platforms can cause a single target to appear as two or more targets; the WC must assess this possibility in his option generation and selection. Similarly any delay in communicating a weapons-release command to the actual weapon release will influence the tactical decision process.

The PEM must be by necessity a detailed model and even in a single warfare area the amount of tactical information may saturate a single WC; it is for this reason that a major WC is augmented by his staff to avoid information overload. This has led Boetcher and Levis [13] to develop information-theoretic models of humans.

The normative models that represent the PEM of a particular WC are not necessarily complex. The reader should keep in mind that the only reason that these models are necessary is to understant the interactions between the physical C^3 system and the commanders within the organization. The decision variables of the commanders are relatively simple at each instant of time since they relate to:

(a) positions and motions of assets
(b) turning on or off sensors and other surveillance assets
(c) communications with other commanders
(d) timing of above decisions.

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*Based upon private communications with Dr. A.H. Levis, Mr. J.G. Wohl and Gen. Cushman, U.S. Army (ret.)

The process by which decisions are arrived at are complex; but these are carried out in the mind of the commander who is modeled as an expert in this decision-making task. The only degradation in his decision making is due to the C^3 system that may give him too much or too little information, delayed information, conflicting information, and only partial information about the enemy's assets and their motion.

Therefore, the PEM's must be stochastic and dynamic models, and must have a feedback mechanism. Thus, they cannot be purely prescriptive and open-loop (e.g. modifications of linear programming algorithms); rather they must represent adequately the cybernetic feedback process of Fig. 5.1.* The successful human control and decision models developed to date [9] to [11] provide a conceptual framework on which future modeling efforts may expand upon, but they cannot address in their current form the complexity of the C^2 tactical decision process of an individual WC.

Individual models of WC's are necessary, but by no means sufficient, to provide guidance in structuring the architecture of the physical C^3 system. A good model of the PEM of an individual WC would clarify the detailed tactical information that he needs to carry out his decision process and perhaps quantify the efforts of innacurate and/or untimely tactical information upon the quality of his decisions. However, the physical C^3 system cannot be designed to serve only one WC, but the collection of the WC's that operate as a team in the overall C^2 organization. A particular bit of tactical information is often necessary for many WC's, perhaps for different reasons. Thus, in order to understand the interactions between the distributed C^2 organization and the physical C^3 system architecture one must understand the interactions of the collective decision processes of the C^2 organization.

6. Modeling the C^2 Organization

The interactions among different WC's are best illustrated if one assumes that the assets controlled by one WC have warfare capabilities in more than one warfare area.

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*This is in philosophical agreement with the central hypotheses proposed by Simon in [7],p.65: "A man, viewed as a behaving system is quite simple. The apparent complexity of his behavior over time is largely a reflection of the complexity of the environment in which he finds himself". Indeed one could argue that a "good" C^3 system should not increase the complexity of the true tactical scenario through the information that it transmits to the WC's.

The simplest example is a modern destroyer whose position and motion is controlled* by the ASWC. The destroyer has sensor and weapons capabilities that impact AAW, ASUW, and electronic warfare (EW). Hence, its position impacts the problem faced by the AAWC and the ASUWC as well as that of the EW coordinator. The fact that, say, the AAWC does not have C^2 authority over the motion of that particular destroyer does not preclude him from using the AAW sensors and weapons of that particular destroyer. In particular, the decisions of the ASWC as reflected in the position of that particular destroyer (which is the output of the PEM of the ASWC) will certainly impact the decision process of the AAWC. Hence, to fully utilize all available resources for each warfare area, the WC's must somehow coordinate their tactical decisions.

This need for coordinating the multiwarfare sensor and weapon capabilities of a particular asset creates new requirements for the physical C^3 system. Clearly the WC's must communicate among themselves so as to coordinate their tactical decisions. In addition, the C^3 system must deliver to each WC tactical information, differing in detail, about assets not directly under his C^2 authority.

Extensive joint team training of the WC's and joint centralized mission planning prior to execution are the key elements that will determine the success of a particular military mission. The tactical warfare expertise of a particular commander is a necessary but not a sufficient ingredient for a smoothly functioning C^2 organization. The different WC's must, through team training, become aware of the tactical problems faced by the other WC's so that tactical coordination takes place, without having to always resort to the superior commander for conflict resolution (a process that introduces delays, increases communications, and disrupts the superior commander from accomplishing his own global objectives).

For the reasons outlined above one can argue that the effect of team training** of the WC's turns a "team of experts" into an "expert team of experts (ETOE)".

Within the C^2 team context, the decisions of one WC impact the decisions of another, and vice-versa. Thus, we cannot simply model each WC by only his detailed PEM. Rather, we must augment his problem solving process by including yet another model that captures his interactions and decision-coordination with the other commanders.

We therefore postulate that as a result of team training each commander;

(a) retains his principal expert model (PEM) which models his individual tactical expertise in solving problems in his particular warfare area, and

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*See example 2 in Section 1.

**Team training is not unique to the military. The most familar example is the training of athletes in an All-Star team.

(b) develops a set of mutual expert models (MEM); each MEM represents a suitably aggregated version of the PEM of each other commander.

The relationship between the PEM's and MEM's is illustrated abstractly in Figure 6.1 for two interacting commanders. Prior to team training the expertise of each commander is captured in their respective PEM's, denoted by P_A and P_B respectively. As a consequence of team training Commander A develops a MEM denoted by M_{BA} which represents an aggregated version of P_B, the PEM of Commander B. Consistent with the cognitive limitations discussed in Section 5 we cannot expect the mutual model M_{BA} to have the same complexity and detail as the principal model P_B. In a similar fashion, through joint team traning Commander B develops a MEM denoted by M_{AB} which represents an aggregated version of P_A, the PEM of Commander A.

The mutual expert models do provide the common view of the global tactical situation between the two commanders, and capture all important variables and decisions that must be coordinated. The MEM's are necessary to define the common language (and protocols) by which the two commanders communicate and coordinate their tactical decisions.

A diagram of a hypothetical C^2 organization is shown in Figure 6.2. Commander A can be thought as the superior commander, while commanders B and C can be thought as warfare commanders each controlling their assigned multiwarfare capable assets. Each commander is characterized by his PEM (denoted by P_A, P_B, and P_C in Figure 6.2) and a set of PEM's (denoted by M_{BA}, M_{CA}, M_{AB}, M_{CB}, M_{AC} and M_{BC} in Figure 6.2). As illustrated in Figure 6.2 the coordinated decisions of the C^2 organization, related to the positioning and even the tactical reassignment of an asset from one WC to another, can only be carried out on the basis of the MEM's.

A mathematical model of the C^2 organization decision process should include both the principal expert model (PEM's) and the mutual expert models (MEM's) of the different commanders, since both are necessary to describe the individual decisions of the commanders and the coordination by which the commanders have arrived at their decisions. Since both the PEM's and the MEM's are strongly influenced by information provided by the physical C^3 system (through the surveillance assets and communications assets), such models of the C^2 decision processes may be used to define the suitable architecture(s) of the C^3 system.

The PEM's would define the nature and level of detail of the tactical information needed by each commander to properly utilize his expertise in his own particular area. It would also define the tactical communications requirements necessary so that the particular commander can effectively exercise C^2 authority over the assets assigned to him and directly controlled by him.

The MEM's would define the nature and minimal level of aggregation of the information necessary to be common knowledge to all commanders in the C^2 organization so that suitably coordinated decisions can be made related to the location, motion, and even reassignment of the assets. This in turn would specify the subset of tactical information* that must be common information to all appropriate commanders in the C^2 organization. Also it would define the requirements of the communications network that must link the commanders so that they can reach coordinated decisions.

It is the author's opinion that most military organizations are indeed informally arranged in the structure suggested by the expert team of experts concept, at least as far as their communications requirements are concerned. Cooperating commanders at the same level of C^2 authority and responsibility communicate among themselves using distinct telephone circuits or radio frequencies. Different communication channels are established to allow a commander to communicate with his assets. This semi-hierarchical structure acts as a buffer on the amount of information flow that reaches the top levels of the C^2 organization; it is also consistent with the overall doctrinal requirement that subordinate commanders must report evaluated information to their superiors. One can make the plausible argument that the aggregated tactical information is that necessary to support the MEM's of the cooperating commanders.

The challenge is, at least in the author's opinion, to suitably structure the flow of relevant tactical information and its storage in (redundant) distributed data bases to support the needs of both individual commanders and of the entire C^2 organization. Advances in electronic sensors and computers, have drastically increased the amount of tactical data available at each instant of time. Tactical communications limitations preclude the indescriminate transmission of this data to the computer data bases that support different commanders decisions, also, the communication requirements to solely keep the information in the distributed data bases consistent is prohibitive. Finally, the cognitive limitations of humans in absorbing new information must be observed.

7. Concluding Remarks

In this paper we have discussed the need for mathematical models that describe;

(1) the tactical decision making process of an individual commander, and

(2) the collective coordinated decision process of commanders operating within a C^2 organization

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*An example of common information is the geographical display of platforms by the NTDS systems in Naval battle groups.

Such models are needed if one wants to define the architecture of the physical C^3 system whose function is to provide

(a) suitably aggregated tactical information to specific commanders,

(b) means for reliable tactical communication between a commander and his assets,

(c) means for communication between commanders for coordination purposes, and

(d) mechanism for storing consistent information in diverse redundant distributed data bases.

The contribution of this paper lies in viewing the C^2 organization as an "expert team of experts". Each individual commander is viewed as an expert in his warfare area, in the sense that given a detailed tactical situation he is capable of directing the assets under his direct control to accomplish the mission objective assigned to him by his superior commander. We abstract the commander individual expertise by defining his Principal Expert Model (PEM).

We argue that a well-functioning C^2 organization is more than a team of individual experts. We postulate that as a consequence of joint mission planning, joint C^2 team training, and availability of common tactical information, each commander develops a mental picture which represents an aggregated version of the tactical decision making process of his fellow commanders with whom he must coordinate, exploit multiwarfare capable assets, and compete for scarse resources. This is abstracted by defining for each commander a set of Mutual Expert Models (MEM's); each MEM is an aggregated version of other commanders PEM's and is a consequence of joint team training; in this manner the "team of experts" gets transformed into an "expert team of experts".

The physical C^3 system must have the physical elements and the architecture to provide to each commander the necessary tactical information to support both his PEM and his MEM's. Otherwise, one would expect a deterioration of the quality of

(a) individual warfare tactical decisions via the PEM's, and

(b) collective coordinated C^2 organization decisions via the MEM's.

A great deal of fundamental and applied research is needed so as to develop scientific methodologies related to constrained distributed decision making problems of this nature before a more concrete set of theories and quantitative results can be obtained.

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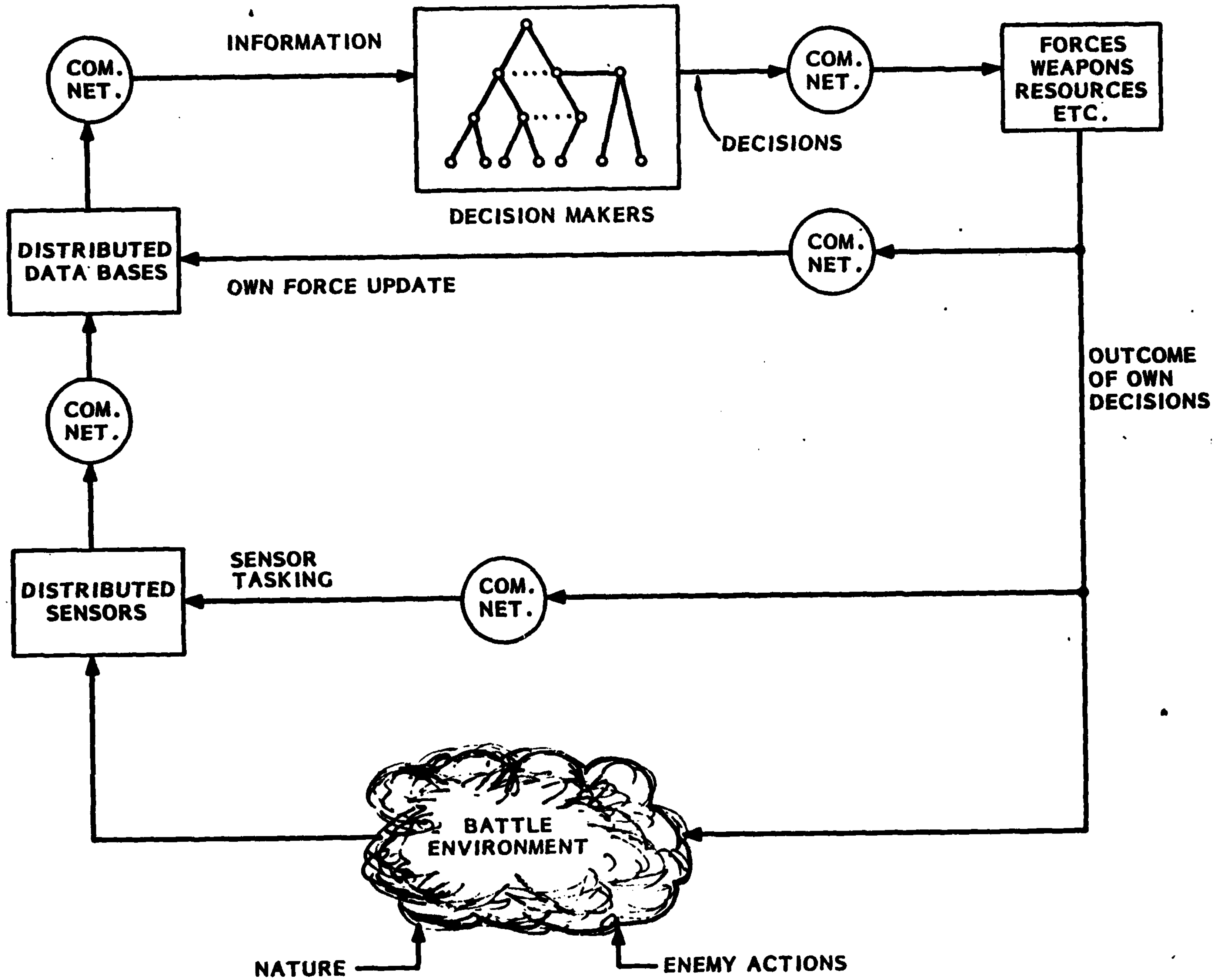

FIGURE 2.1 The C^2/C^3 Interface

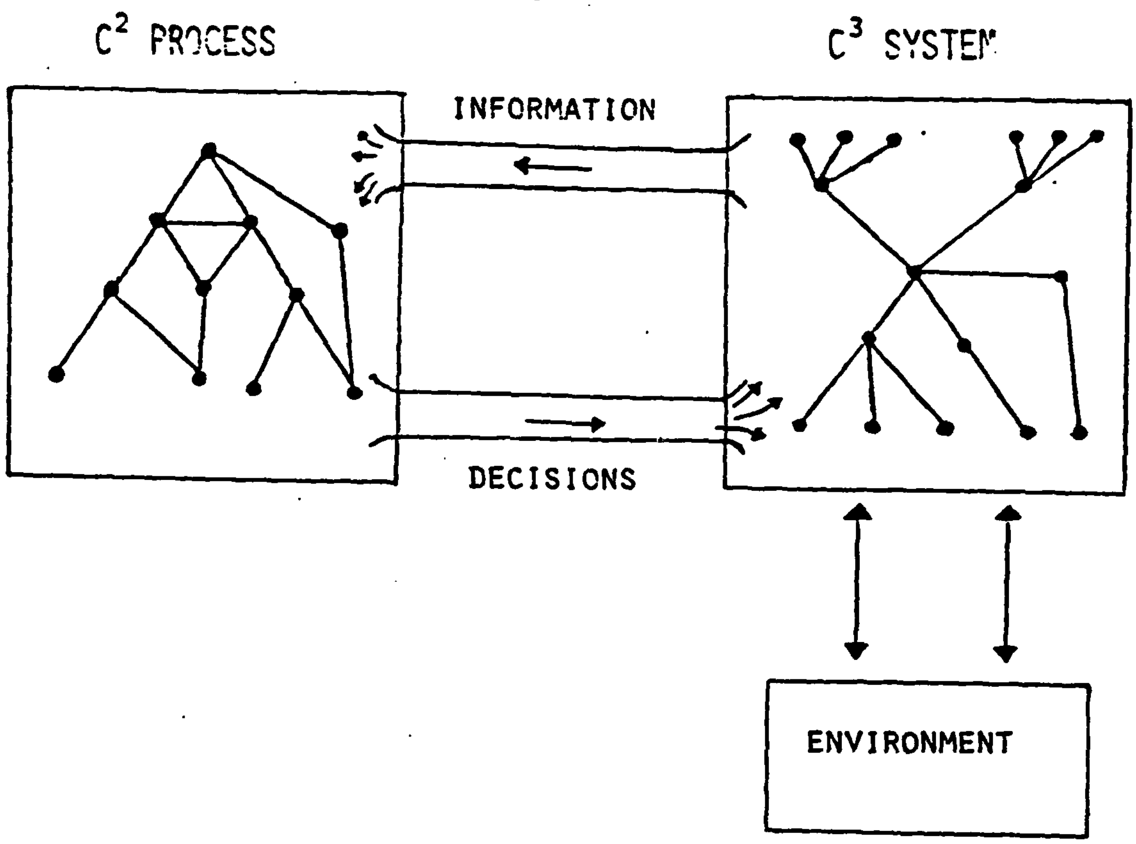

FIGURE 2.2 Interactions between the C^2 process and the C^3 system

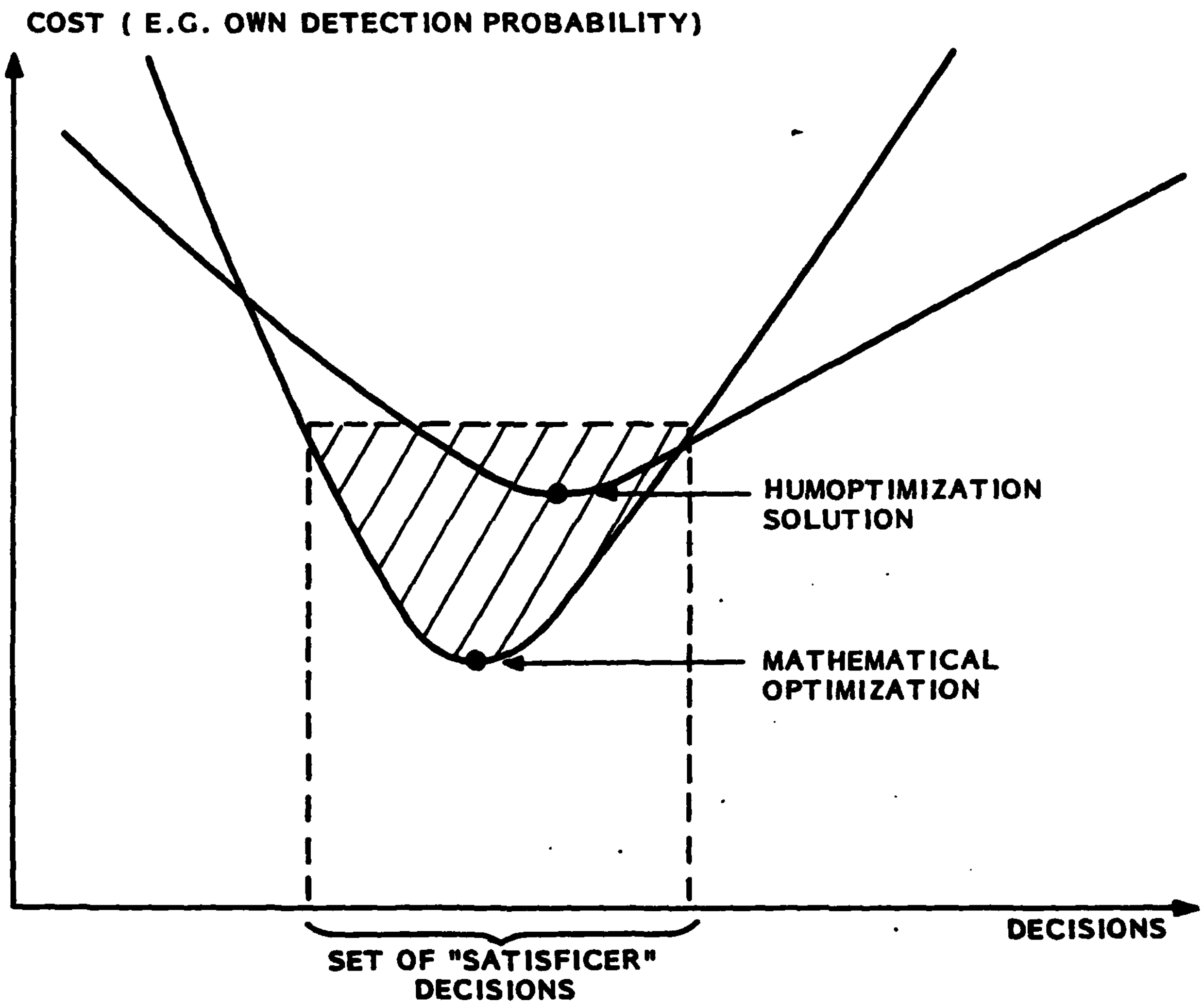

FIGURE 5.1 Illustration of the Humoptimization Concept

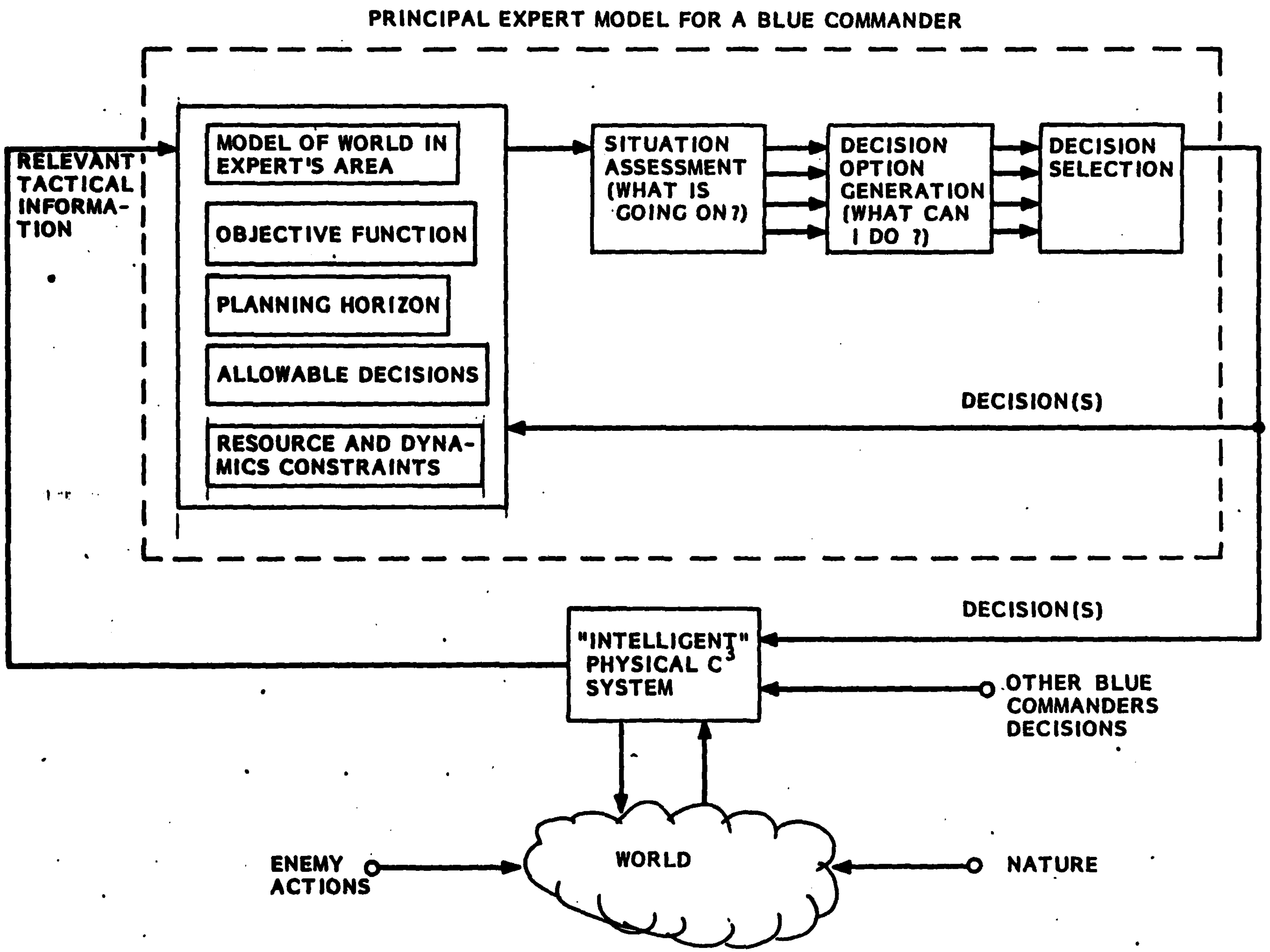

FIGURE 5.2 Modeling the tactical decision processes ‥ a **Warfare Commander by his PEM**

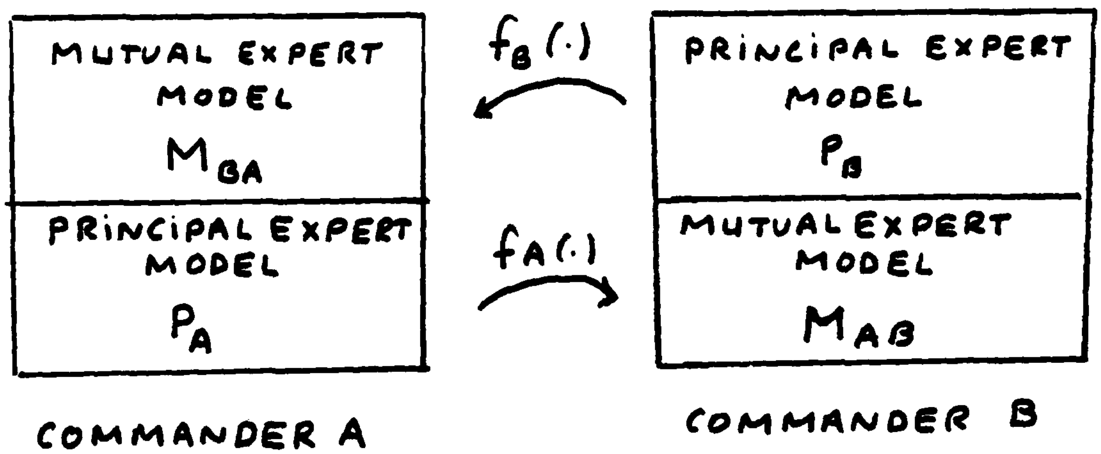

FIGURE 6.1 Modeling two interatcing commanders

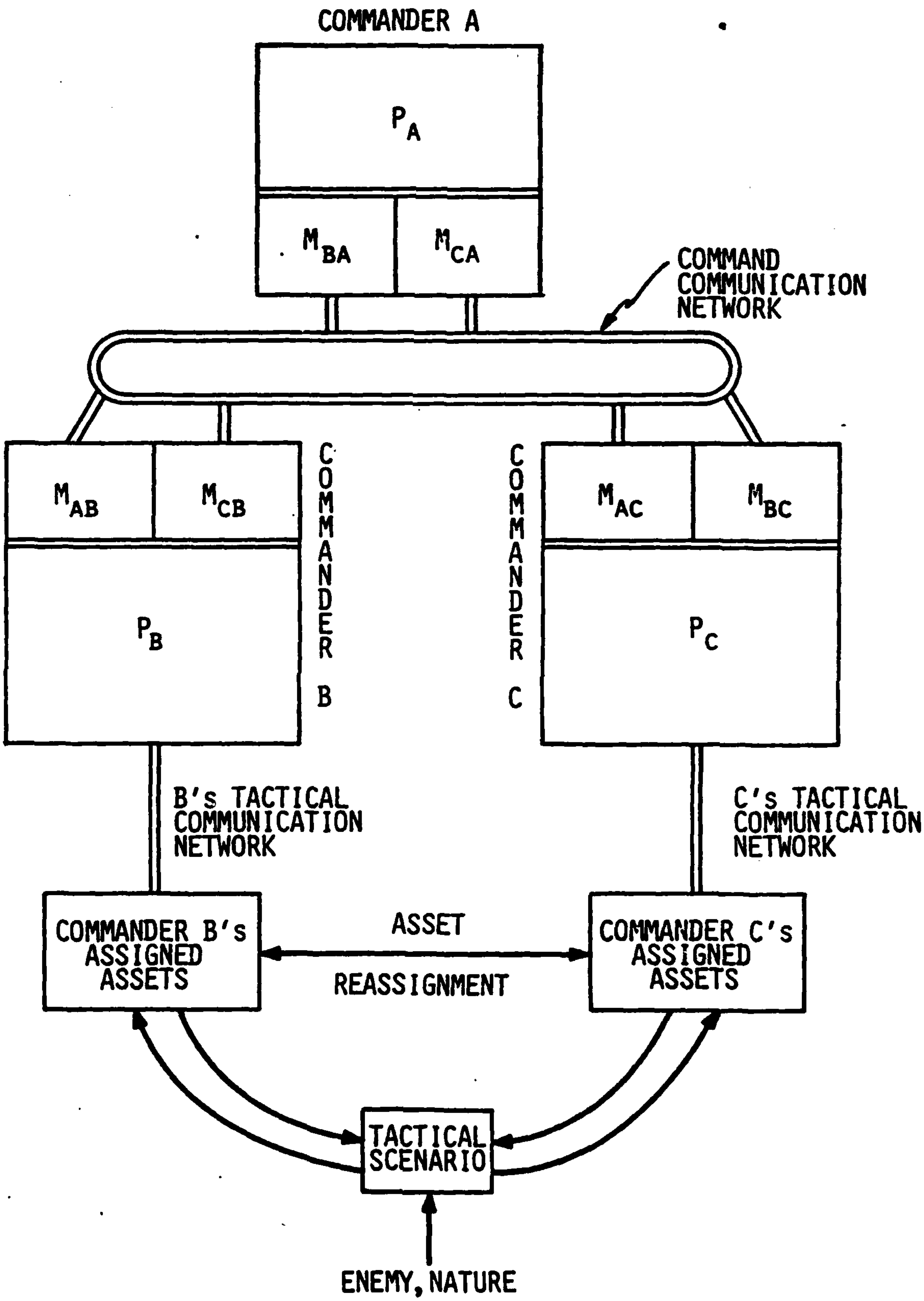

FIGURE 6.2 Hypothetical C^2 Organization