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DISTRIBUTED DECISION AND COMMUNICATION PROBLEMS IN TACTICAL USA--ETC(U)
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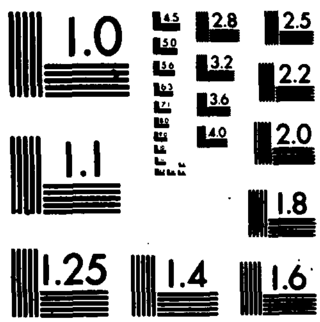

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DISTRIBUTED DECISION AND COMMUNICATION PROBLEMS

IN TACTICAL USAF COMMAND AND CONTROL

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I. INTRODUCTION

The inherent complexity of C^3 systems and the rapid implementation of technological changes in the acquisition, processing, storage, and dissemination of data, present problems that existing theory and available tools do not address adequately. The analysis of generic aspects of C^3 systems represents an area of research that requires the integration of diverse concepts and theories, if progress is to be made toward the development of a theoretical basis for their analysis and design. Furthermore, while many of the generic problems are relevant to the C^3 systems of all services, the unique missions of each service introduce constraints that need to be understood and design considerations that must be exploited to produce more effective systems.

In June 1979, the Laboratory for Information and Decision Systems (LIDS) of MIT undertook a twelve month effort with two main objectives:

(a) identification of relevant theoretical problems in Air Force C^3 systems and initial problem formulation for subsequent basic research; and

(b) Basic research on specific problems in areas such as distributed surveillance and multiobject tracking, dynamic distributed data bases and communication networks, resource allocation problems, and C^3 system structure.

The technical effort was directed toward generic, long range, basic, unclassified research. The emphasis was on general methodological and technical issues, but from the perspective of the unique needs and requirements of the Air Force. The latter requirement led to extensive interaction with the Air Force C^3 community to obtain the necessary background information, both technical and operational, needed to understand the issues and to abstract research problems. In section II of this report, four research areas are described and progress achieved to date in formulating specific problems is summarized. In section III, a brief review of interactions is presented.

II. THE RESEARCH EFFORT: PROBLEM IDENTIFICATION AND FORMULATION

Research in control and communication system theory, operations research, organization theory, and computer science is all relevant for tactical command and control problems. Four different research areas are presented in this section - each one addressing distinct aspects of tactical command and control systems. The selection has been influenced in part by interactions with the C^3 community (Section III), in part by the research interests and qualifications of the LIDS research staff, and in part by reviewing selected literature on the function and basic doctrine of the United States Air Force, e.g. [1]. They are:

(a) C^3 System Structure and Organizational Forms;

(b) Information Storage and Flow in C^3 Systems;

(c) Distributed Estimation; and

(d) Evasive Trajectories for Tactical Aircraft.

Each research area is described briefly in the following sections.

2.1 C^3 System Structure and Organizational Forms

The structure of a C^3 system, the links that it establishes between various elements of an organization -- whether to transmit sensor data or intelligence information, or propagate decisions -- is dependent on the structure of the organization it is designed to serve. The converse, however, is less obvious, but equally important. The structure of the tactical C^3 system affects the structure of the functioning organization. An effective C^3 system is well matched to the organization it serves, and for an organization to be effective it should be well matched to its C^3 system. This interrelationship, this coupling between organizational forms and C^3 systems constitutes a basic topic of research in C^3 system theory.

In order to study the interrelationship between the structure of an organization and its C^3 systems, it is necessary to model the task the organization is to perform and the elements of the organization (men, machines, data). Consider, for example, an air interdiction operation. Sensors, processors, decision makers, and weapons systems can be organized in different ways (depending, or course, on the choice of the specific equipment used) to achieve the objective. The question of how to organize these resources is a problem in organizational form. It consists of specifying the decision structure, i.e., the assignment of decisions to different elements of the organization, and of specifying the information structure associated with the decision structure. (The specification of the standard operating procedures and the enforcement rules constitutes the problem of organizational control.)

Two lines of inquiry have been identified and research problems have been formulated in each one.

(a) Mathematical Model of Organization Member

Since an organizational unit may consist of such diverse components as an unattended sensor (e.g., a radar), a single decision maker, an aircraft and its pilot, or a whole GTAC, it is important that the mathematical model of the organization unit be able to represent them adequately. The macroscopic view of the organization unit is of an element that receives inputs (data, information, commands) from a finite set -- the input alphabet -- and produces outputs [2]. The decision process is modeled as the selection of the output signal that is the desired response to the input signal. The internal processing -- the microscopic view of the organization member -- can be modeled using the partition laws of information flow [3]. The general stochastic case in which the decision maker exhibits bounded rationality and also has internal information sources has not been treated in the past.

(b) Information Structures

The class of organizations considered are those characterized as teams. As with the organization member, the task of the organization as a whole is to receive inputs arriving from various sources, process them, and produce outputs that are then dispatched to various destinations. The question of information structure can be formulated as the assignment of sets or subsets of the input symbols to specific decision makers and the specification of the rules by which they are dispatched. The relevant concept is that of partitions; alternative information structures will be expressed in terms of partitions of the input alphabets. Notions of parallel processing, sequential processing, or specialization can be formulated in terms of partition rules. If the team members are assumed to have bounded rationality (to be error prone when overloaded) then an optimization problem can be formulated for the determination of optimal or satisfactory partitions. The selection of a partition rule constitutes the design of an information structure.

It should be stressed that the key notion generally missing from past formulations is that of bounded rationality for the decision maker. Without it, the problem of information structure can still be formulated in an information theoretic setting using channel capacity constraints, but it leads to unrealistic simplistic organizational forms.

2.2 Information Storage and Flow in C^3 Systems

A C^3 system may be viewed in terms of its ability to transfer and store information, i.e., it may be visualized as an information flow network. This view encompasses not only the communications system that transmits data and messages, but also the components that process, present, and use the information - whether to make decisions or to summarize, expand, and even translate it. One measure of performance of the C^3 system is its ability to deliver at designated points the desired information so that, upon arrival, it is timely, accurate, complete, and easy to use.

The vulnerability of this information flow network -- subjected to both external and internal stresses -- has long been a subject of concern. External stresses derive from direct attacks on the network elements or, through disruption, deception and manipulation, on the information itself. Internal stresses may follow from the external ones or may be due to an inherent mismatch between the realization of the information flow system and the demands made upon it.

Efforts to deal with the factors of internal stress focus on such aspects as the reliability of system components, suitability of message structure, coding procedures and protocols, adequacy of system elements in terms of storage, speed, complexity or transmission/processing capacity and the effectiveness of routing and reconfiguration procedures. Despite the future technological advances likely to result from these efforts, the effectiveness of the overall system will be limited because of the increasing load it must support. Two components of this load are recognized - one derived from the potential escalation in the availability of large volumes of data (near-real-time intelligence, surveillance, and reconnaisance data); the other from the increase in the demand for service to support the processing and analysis of that data, as well as in the flow of status, command and communication information. Both components tend to increase the load as the "action" intensifies - often conflicting for the same resources for processing, storing and displaying information. The additional information activity and demands on the system slow the response time for honoring even simple information requests.

Thus, the system response is perceived to degrade exactly when it is most important that it operate well: when battle information is flowing in and the time available for decision making is short. It follows, then, that there is need to modify the desired information transfer to match it to the facilities and the time available for processing. Two aspects of this problem are of particular interest: the relationship between the dynamics of network congestion and the action taken, and the development of models for that action in terms of the various users, situations, and levels of detail. In order to relate a view of the data and the information flow to the situation, the user requirements, and the level of system congestion, techniques must be developed by which the methods for the analysis of data and presentation of information may be altered to permit the automatic aggregation of information less critical to the performance of a specific mission.

The development of adaptive techniques for modifying and reducing the flow of mission- and engagement-dependent information in a C^3 system operating under stress is the key research objective. Recent advances in flow control of computer networks and distributed data base processing will be examined to gain insight into how measures of system congestion and constraints on the time available to make a decision might be incorporated into the choice of models applied to the information flow. The aggregation problem, particularly those aspects relating to the retention and use of partial assessment of a given situation will also be investigated.

2.3 Distributed Estimation

The surveillance elements are an integral part of C^3 systems. Typically, they are distributed over a region of interest and may be active only during specific intervals of time. This gives rise to a number of interesting estimation problems concerning the processing of data collected by these elements. Local data processing serves to compress the amount of communications required to transmit information to users, at the expense of losing the ability to correlate data from different sites for improved accuracy and identification capabilities. On the other hand, the delays inherent in complete data transmission and central processing make centralized processing of all data undesirable.

The basic distributed estimation problem arises when a number of sensors are distributed over a geographic region; these sensors report to local processing stations, which in turn communicate with each other and with upper level processing stations. Speyer [4] analyzed the computational requirements for a decentralized implementation of a Kalman filter using a model similar to the one shown in Figure 2.1. Along the same lines, Castañon, [5] and Willsky et al [6] studied more general problems in distributed estimation for linear systems, which incorporated some transmission restrictions and centralized coordination. However, in all these studies, it is assumed that the models of the observation processes and their statistics are available to all processing stations. This assumption is unrealistic in the context of C^3 applications, since the sensors and objects of interest can be moving rapidly in space, with observation errors which are a product of configuration; thus, the a priori statistics of the models used for observation cannot include the observation errors, as in [4]. Two research problems have been identified in the context of tactical Air Force C^3 systems. The first one arises from the relative navigation system used in conjunction wtih JTIDS [7]. Each user in that system processes independently local information as it arrives on the JTIDS network. The results of this processing are used to form the next message transmitted to other users. This is an example of distributed estimation with a highly interconnected communication scheme.

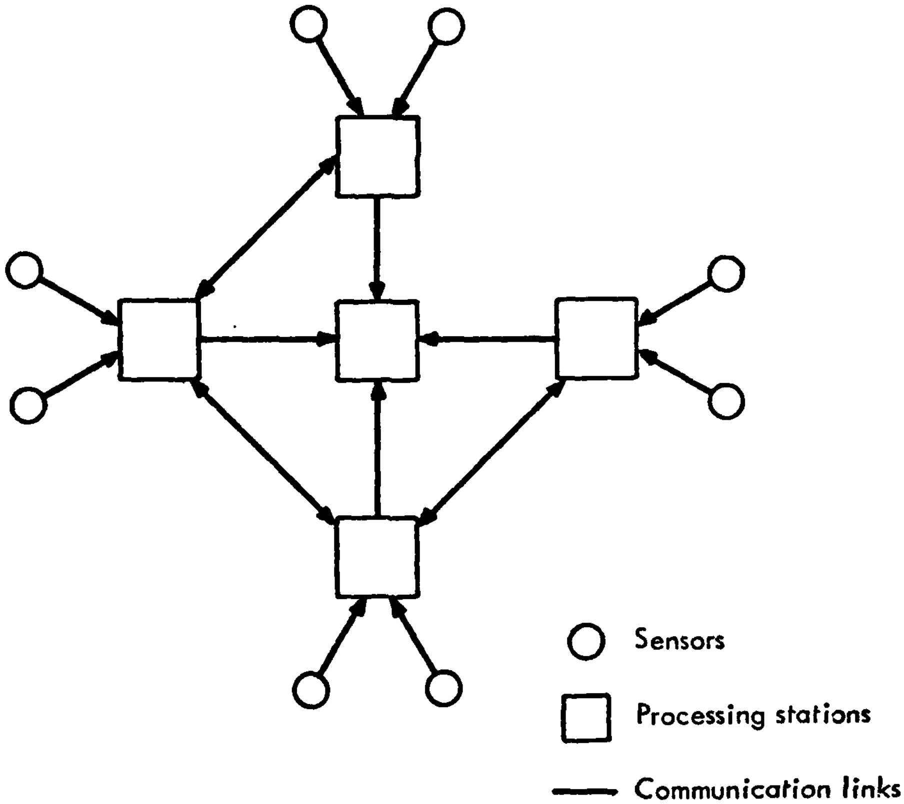

Figure 2.1 Model of Distributed Estimation Network

Several issues can be examined in the context of this application:

- What are the minimal transmission requirements to ensure convergence of the relative navigation system?
- What is the effect of using different local processing algorithms? Currently, the local processors are based on Kalman filters processing selected measurements.
- What are efficient ways of correlating the output of these local processors with other sources of information?

A second problem addresses issues in distributed estimation arising from tracking problems where the tracking is done by a network of interconnected sensors. Because of the speed of some objects of interest, it is essential to be able to communicate tracks along the network; on the other hand, it is both burdensome and inefficient for all sensors to keep a track on the same object. Thus, the research objective is the development of a theory for determining efficient data processing algorithms and communications schemes for each alternative architecture of the type shown in Fig. 2.1.

Both research problems fall outside the mainstream of current basic research in estimation theory. The main difference is the element of communications requirements introduced by the distribution of the sensors as a network interconnected with communication links.

2.4 Evasion Trajectories for Tactical Aircraft

The research problems identified in the three previous sections, although in different disciplines, have strong common themes: the distributed nature of the resources; the limited overall capacity for information storage and flow, the vulnerability of the decision and information flow networks. A desirable design feature of C^3 systems is their ability to degrade gracefully. For this to be effective, it is also necessary that procedures exist for force management in the battlefield even when communications capabilities have been reduced to a minimum. Furthermore, procedures that decrease the vulnerability of component elements contribute to the robustness of the overall system.

A research topic in this general area has been identified; it deals with optimum control techniques for enhancing the survivability of tactical aircraft engaged in interdiction or close air support missions. The immediate objectives of this work are (a) to devise 4D attack trajectories that represent the best compromise between accomplishing a mission successfully and surviving, and (b) to prove that the 4D attack trajectory does result in an improved survival rate against surface-to-air missiles. If the value of such techniques can be established, other elements of the C^3 process will be affected by the new set of control requirements.

The first step in the analytical formulation, the main effect has been to set up the equations of motion and guidance laws for a typical surface-to-air missile. This model must be quite accurate, particularly with respect to the dynamic limitations of the missile, if a realistic measure of miss distances as a function of the aircraft's evasive maneuvers is to be achieved.

III. INTERACTIONS

One of the major concerns in formulating methodological research in C^3 systems is that it be relevant and reflect an in-depth understanding of the tactical C^3 problem. Much of this understanding exists in the C^3 community of the Air Force. Thus, a series of visits, interactions, and attendance at symposia took place by members of the MIT/LIDS project team.

1. RADC/SUNY Symposium: Command, Control, Communications - Managing Tomorrow's Resources, June 25-27, 1979, Rome Air Development Center, Griffiss Air Force Base, New York, 13441.

Professor Michael Athans and Dr. Alexander H. Levis attended the RADC/SUNY Symposium. Professor Athans was one of the speakers in the session "Perspectives on Science and Technology."

2. Second MIT/ONR Workshop on Distributed Communication and Decision Problems, July 16-27, 1979, Naval Postgraduate School, Monterey, California.

The workshop, chaired by Professor Athans, contained presentations based on work being carried out at MIT/LIDS, presentations from research laboratories of the Navy and reviews of work in progress in industry. Most of the staff of LIDS involved with C^3 research, either for AFOSR or ONR, attended at least a portion of the workshop.

3. Visit: October 18-19, 1979

William A. Myers, III, Rear Admiral, U. S. N. (Ret.), visited MIT/LIDS. Amont the subjects discussed were the basic types of control structures and the impact they have on the design specifications (or performance requirements) of a C^3 system.

4. Visit: October 19, 1979

Drs. Levis and Castañon and Mr. Connelly of LIDS met with John H. Cushman, Lt. General, U. S. Army (Ret.), at MITRE in Bedford, MA to discuss C^3 systems from the commander's point of view.

5. Visit: November 13, 1979

Dr. Donald B. Brick, Technical Director, Development Plans, Electronic Systems Division and Dr. Fred I. Diamond, Technical Director, Communications and Control Division, RADC, visited LIDS and reviewed research problems in C^3 systems of current interest to the USAF.

6. Visit: January 9, 1980

Dr. Levis and Mr. Connelly met with Col. Adrian V. Polk, Director of the Office of Aerospace Studies at MIT. Col. Polk discussed USAF organization and doctrine and provided the project team with relevant documents.

7. Visit: January 17, 1980

Prof. Athans visited Dr. Harry VanTrees, C^3I, OSD to discuss problems of common interest in the Air Force and Naval C^3 area. The concept of netting aircraft for a tactical scenario was discussed as well as recent developments in JTIDS. The requirement that aircraft know their relative positions leads to some unconventional network structure problems. Other subjects of discussion were the status of M on N aircraft engagements, and the use of the force multiplier concept in cases where the aircraft are coordinated for tactical operational missions using JTIDS.

8. Visit: Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, February 7, 1980

Mr. Mark E. Connelly discussed various AFFDL research programs with Morris Ostgaard, James Guckian, Finley Barfield, Fred Unfried, Lt. Scott Yeakel, and Terry Emerson. The emphasis was on advanced tactical aircraft such as the control configured F-16, the AFTI-15 concept evaluation and validation program, and tactical cockpit displays.

9. Visit: MITRE Corporation, C^3 Division, Bedford, MA February 13, 1980

A full day briefing, organized by Dr. Donald B. Brick, was attended by most of the MIT/LIDS C^3 study group including Prof. Athans, Dr. Levis and Mr. Connelly. The morning technical presentations on tactical C^3I consisted of:

a) Overview of ESD C^3I, by Dr. Brick, (ESD)
b) TAFIIS Master Plan, by Mr. M. Cannell (MITRE)
c) Assault Breaker, by Mr. C. Hunter, (ESD)
d) USAFE Architecture, by Capt. S. Robinson, (ESD)
e) Tactical Operations Planner, by Maj. J. Harvey, (ESD)

The afternoon session consisted of two parts. In the first one communications problems were described. First, Mr. S. Sternick (ESD) gave an overview of problems in communications. He was followed by Maj. R. Sutton (ESD) who presented MILSATCOM architecture, Maj. C. Anderson (ESD) on Adaptive HF, and Lt. S. Enke on C^3 Systems Analysis. The second part of the session included a presentation on Communications Netting and JTIDS by Mr. Ellingson (MITRE) and Radar Netting by Mr. O. Wech.

10. Visit: March 4, 1980

Dr. Levis met with Mr. J. G. Wohl of MITRE to discuss the latter's report on "Battle Management Decisions in Air Force Tactical Command and Control."

11. Third Annual Symposium on Command and Control: Information Processing And Decision Making for Battle Management, March 11-12, 1980, MITRE Bedford, MA.

Professor Athans, Dr. Levis and Ms. Ducot attended the two-day symposium sponsored by the Assistant Chief of Staff, Studies and Analyses, HQ USAF and by the Commander, Electronic Systems Division, AFSC.

12. Visit: April 11, 1980

Dr. Levis visited Mr. Dennis K. Leedom, Tactical Systems Division Assistant Chief of Staff, Studies and Analyses, HQ USAF and discussed research problems in tactical command and control.

13. Visit: Rome Air Development Center, Griffiss AFB, NY 13441, May 1, 1980

Drs. Levis and Castañon and Ms. Ducot visited the Rome Air Development Center and held technical discussions on C^3 problems with Dr. Fred I. Diamond, Technical Director, Communications and Control Division, Mr. Richard Metzger of the Information Systems Division, Mr. Frank Rehm of the Surveillance Division, and with other members of the RADC technical staff.

14. Visit: May 22, 1980

Lt. Col. R. Hodgkinson visited LIDS and gave a seminar on tactical command and control from the Air Force pilot's point of view.

15. Third MIT/ONR Workshop on Distributed Information and Decision Systems, Silver Spring, MD, May 27 - June 6, 1980.

Most of the staff of LIDS involved with C^3 systems research attended at least a portion of the workshop. Professor Athans, workshop chairman, presented an "Overview of MIT Research in C^3 Related Problems;" Dr. Levis gave a talk on "Organization Theory and C^3 Systems;" Dr. Castañon talked on "Goal Coordination for Hierarchical Structures in Game Theory;" and Ms. Ducot presented "Some Thoughts on Information Flow in C^3 Systems." The presentations will appear in the workshop proceedings that will be issued by MIT/LIDS.

IV. PERSONNEL

The following faculty and staff of LIDS participated in the identification of the research areas and the formulation of research problems.

Professor Michael Athans, Co-principal Investigator
Dr. Alexander H. Levis, Co-principal Investigator
Dr. David A. Castañon
Mr. Mark E. Connelly
Ms. Elizabeth R. Ducot

A graduate student/research assistant, Mr. Kevin Boettcher, is carrying out research toward a thesis for the degree of Master of Science in Electrical Engineering. He is expected to complete his thesis by February 1981.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Four relevant theoretical problems in tactical Air Force C^3 systems are identified and described briefly. They are: (a) C^3 system structure and organizational forms, (b) information storage and flow in C^3 systems, (c) distributed estimation, and (d) evasive trajectories for tactical aircraft. A summary of the interactions that led to the identification and formulation of the research problems is included.

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