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NAVAL C3 DISTRIBUTED TACTICAL DECISION MAKING(U)
MASSACHUSETTS INST OF TECH CAMBRIDGE LAB FOR
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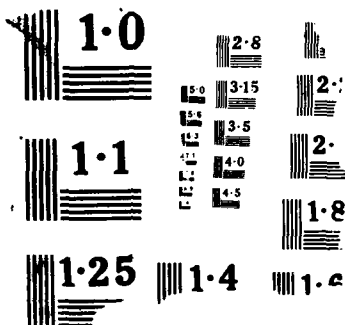
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139**

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QUARTERLY TECHNICAL REPORT

for the period

1 January 1988 to 31 March 1988

for

NAVAL C³ DISTRIBUTED TACTICAL DECISION MAKING

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April 22, 1988

structures for distributed decision problems, aggregate solution techniques and coordination.

- 2.3 Impact of Informational Discrepancy: The effect on distributed decisionmaking of different tactical information being available to different decisionmakers will be explored. The development of an agent model, the modeling of disagreement, and the formulation of coordination strategies to minimize disagreement are specific research issues within this task.
- 2.4 Constrained Distributed Problem Solving: The agent model will be extended to reflect human decisionmaking limitations such as specialization, limited decision authority, and limited local computational resources. Goal decomposition models will be introduced to derive local agent optimization criteria. This research will be focused on the formulation of optimization problems and their solution.
- 2.5 Evaluation of Alternative Organizational Architectures: This task will address analytical and computational issues that arise in the construction of the generalized performance-workload locus. This locus is used to describe the performance characteristics of a decisionmaking organization and the workload of individual decisionmakers.
- 2.6 Asynchronous Protocols: The use of asynchronous protocols in improving the timeliness of the organization's response is the main objective of this task. The tradeoff between timeliness and other performance measures will be investigated.
- 2.7 Information Support Structures: In this task, the effect of the C³ system on organizational performance and on the decisionmaker's workload will be studied.
Keywords: (to p A)
- 2.8 Integration of Results: A final, eighth task, is included in which the various analytical and computational results will be interpreted in the context of organizational bounded rationality.

3. STATUS REPORT

In the context of the first seven tasks outlined in Section 2, a number of specific research

problems have been formulated and are being addressed by graduate research assistants under the supervision of project faculty and staff. Research problems which were completed prior to or were not active during this last quarter have not been included in the report.

3.1 DISTRIBUTED TEAM HYPOTHESIS TESTING WITH EXPENSIVE COMMUNICATIONS

Background: In Command-Control-and-Communication (C^3) systems multiple hypothesis testing problems abound in the surveillance area. Targets must be detected and their attributes must be established; this involves target discrimination and identification. Some target attributes, such as location, are best observed by sensors such as radar. More uncertain target locations are obtained by passive sensors, such as sonar or IR sensors. However, target identity information requires other types of sensors (such as ESM receivers, IR signature analysis, human intelligence etc). As a consequence in order to accurately locate and identify a specific target out of a possibly large potential population (including false targets) one must design a detection and discrimination system which involves the fusing of information from several different sensors generating possibly specialized information about the target. These sensors may be collocated on a platform (say a ship in a Naval battle group) or be physically dispersed as well (ESM receivers exist in every ship, aircraft, and submarine). The communication of information among this diverse sensor family may be difficult (because of EMCON restrictions) and is vulnerable to enemy countermeasure actions (physical destruction and jamming). It is this class of problems that motivates our research agenda.

To put it another way the fusion of information derived from dispersed sensors and decision nodes requires communication. To discourage nonessential communication we would like to put a price on each transmitted bit. In this manner, extensive communications would occur only if the decision warrants them.

Research Goals: We are conducting research on distributed multiple hypothesis testing using several decision-makers, and teams of decision-makers, with distinct private information and limited communications. This is the simplest possible non-trivial distributed decision problem, whose centralized counterpart is well understood and straight-forward to compute. The goal of this research is to *unify* our previous research in situation assessment, distributed hypothesis testing, and impact of informational discrepancy; and to *extend* the methodology, mathematical theory and computational algorithms so that we can synthesize and study more complex

organizational structures. The solution of this class of basic research problems will have impact in structuring the distributed architectures necessary for the detection, discrimination, identification and classification of attributes of several targets (or events) by a collection of distinct sensors (or dispersed human observers).

The objective of the distributed organization will be the resolution of several possible hypotheses based on many uncertain measurements. Each hypothesis will be characterized by several attributes. Each attribute will have a different *degree of observability* to different decision makers or teams of decision makers; in this manner, we shall model different specialization expertise associated with the detection and resolution of different phenomena. Since each hypothesis will have several attributes, it follows that in order to reliably confirm or reject a particular hypothesis, two or more decision-makers (or two or more *teams* of decision-makers) will have to pool and fuse their knowledge.

Extensive and unnecessary communication among the decision-makers will be discouraged by explicitly assigning costs to certain types of communication. In this manner, we shall seek to understand and isolate which communications are truly vital in the organizational performance; the very problem formulation will discourage communications whose impact upon performance is minimal. Quantitative tradeoffs will be sought.

Progress during the past quarter: We have been studying distributed hypothesis-testing teams using different models for expert and novice decision makers. For binary hypothesis testing the so-called Receiver Operating Characteristic (ROC) relates the probability of detection to the probability of false alarm. For the same false alarm probability an expert decision maker has a higher detection probability. Thus, by observing the dominance of the ROC curves one can rank the decision makers so that one is clearly better than another.

Mr Papastavrou and Professor Athans have been studying different ways of organizing a given set of decision makers, each defined by an individual ROC curve. Then one can define the overall ROC for the distributed organization, and thus compare organizations. We are seeking theoretical insights so as to avoid direct numerical comparisons since this involves the solution of NP-complete problems.

Mr Pothiwala and Professor Athans are studying the team performance improvement in a simple organization consisting of two decision makers involved in binary hypothesis testing. The

upstream decision maker, based on his own uncertain measurement, transmits one out of M possible messages to the downstream decision maker (this requires that the upstream decision maker computes $M-1$ likelihood ratio type of thresholds). The downstream decision maker will make the global team decision on the basis of (a) his own measurement and (b) the message received from the upstream decision maker, so as to minimize the team probability of error. The solution of this problem will quantify the cost/effectiveness of additional discrete communications upon the global performance of this team.

Documentation: None as yet. A paper is in preparation for the JDL C2 Symposium, Monterey, California, June 1988

3.2 DISTRIBUTED HYPOTHESIS TESTING WITH MANY AGENTS

Background: The goal of this research project is to develop a better understanding of the nature of the optimal messages to be transmitted to a central command station (or fusion center) by a set of agents (or sensors) who receive different information on their environment. In particular, we are interested in solutions of this problem which are tractable from the computational point of view. Progress in this direction has been made by studying the case of a large number of agents. Normative/prescriptive solutions are sought.

Problem Statement: Let H_0 and H_1 be two alternative hypotheses on the state of the environment and let there be N agents (e.g. intelligent sensors) who possess some stochastic information related to the state of the environment. In particular, we assume that each agent i observes a random variable y_i with known conditional distribution $P(y_i|H_j)$, $j = 0, 1$, given either hypothesis. We assume that all agents have information of the same quality, that is, the random variables are identically distributed. Each agent transmits a binary message to a central fusion center, based on his information y_i . The fusion center then takes into account all messages it has received to declare hypothesis H_0 or H_1 true. The problem consists of determining the optimal strategies of the agents as far as their choice of message is concerned. This problem has been long recognized as a prototype problem in team decision theory: It is simple enough so that analysis may be feasible, but also rich enough to allow nontrivial insights into optimal team decision making under uncertainty.

Results: This problem has been studied by Prof. J. Tsitsiklis. Past results [1-2] can be summarized as follows:

Under the assumption that the random variables y_i are conditionally independent (given either hypothesis), it is known that each agent should choose his message based on a likelihood ratio test. Nevertheless, we have constructed examples which show that *even though there is a perfect symmetry in the problem, it is optimal to have different agents use different thresholds in their likelihood ratio tests*. This is an unfortunate situation, because it severely complicates the numerical solution of the problem (that is, the explicit computation of the decision threshold of each agent). Still, we have shown that in the limit, as the number of agents becomes large, it is asymptotically optimal to have *each agent use the same threshold*. Furthermore, there is a *simple effective* computational procedure for evaluating this single optimal threshold.

We have also shown that if each agent is to transmit K -valued, as opposed to binary messages, then still each agent should use the same decision rule, when the number of agents is large. Unfortunately, however, the computation of this particular decision rule becomes increasingly broader as K increases.

We have also investigated the case of M -ary ($M > 2$) hypothesis testing and constructed examples showing that it is better to have different agents use different decision rules, even in the limit as $N \rightarrow \infty$. Nevertheless, we have shown that the optimal set of decision rules is not completely arbitrary. In particular, it is optimal to partition the set of agents into at most $M(M-1)/2$ groups and, for each group, each agent should use the same decision rule. The decision rule corresponding to each group and the proportion of the agents assigned to each group may be determined by solving a linear programming problem, at least in the case where the set of possible observations by each agent is finite.

Finally, results have been obtained which cover the Neyman-Pearson (as opposed to Bayesian) version of the problem, in the case of $M=2$ hypothesis. The asymptotically optimal solution has been found and involves the Kullback-Liebler information distance.

In the past quarter, the following research has been completed by Prof. J. Tsitsiklis and a graduate student, Mr. George Polychronopoulos:

- (a) We have considered a class of symmetric detection problems in which given any hypothesis H_j , each sensor has probability ϵ of making an observation indicating that some other hypothesis H_j is true. A simple numerical procedure has been found which completely solves this problem.

Furthermore, a closed form formula for the optimal decision rules has been found for the case where the "noise intensity" ϵ is very small.

(b) In the context of the above symmetric problem we have posed problems of the following type: "Is it preferable to have N sensors each one transmitting D bits, or N/K sensors, each one transmitting KD bits? A complete solution has been found. The formulation represents a fundamental design problem in the design of distributed sensor systems.

We have also completed numerical experiments on the validity of asymptotic considerations, when the number of agents N is moderate ($N \approx 5$), with encouraging results. It has been founded that even when N is as small as 5, the decision rules derived for the case where $N \rightarrow \infty$ come very close to the truly optimal ones, in terms of performance. The above results will be reported in the Masters thesis of Mr. Polychronopoulos, which will be submitted in May 1988. A journal paper is in preparation.

The above results will be reported in the Masters thesis of Mr. Polychronopoulos and on a subsequent journal paper.

Documentation

- [1] J. N. Tsitsiklis, "On Threshold Rules in Decentralized Detection," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986; also LIDS-P-1570, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, June 1986.
- [2] J. N. Tsitsiklis, "Decentralized Detection by a Large Number of Sensors," LIDS-P-1662, April 1987; to appear in *Mathematics of Control, Signals and Systems*, 1988.

3.3 COMMUNICATION REQUIREMENTS OF DIVISIONALIZED ORGANIZATIONS

Background: In typical organizations, the overall performance cannot be evaluated simply in terms of the performance of each subdivision, as there may be nontrivial coupling effects between distinct subdivisions. These couplings have to be taken explicitly into account; one way of doing so is to assign to the decisionmaker associated with the operation of each division a cost function which reflects the coupling of his own division with the remaining divisions. Still, there is some freedom in such a procedure: For any two divisions A and B it may be the responsibility of either decisionmaker A or decisionmaker B to ensure that the interaction does not deteriorate

the performance of the organization. Of course, the decisionmaker in charge of those interactions needs to be informed about the actions of the other decisionmaker. This leads to the following problem. Given a divisionalized organization and an associated organizational cost function, assign cost functions to each division of the organization so that the following two goals are met: a) the costs due to the interaction between different divisions are fully accounted for by the subcosts of each division; b) the communication interface requirements between different divisions are small.

This line of research, described in detail in earlier progress report is now essentially complete. Most results have been reported in the Masters thesis of Mr. C. Lee [1]. A journal paper covering both the philosophical and the technical aspects of this work, is in preparation.

Documentation:

- [1] C. Lee, "Task Allocation for Efficient Performance of a Decentralized Organization, LIDS-TH-1706, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, September 1987.

These results were also overviewed at the annual ONR/DTDM contractor meeting, Newport, RI, September 1987.

3.4 COMMUNICATION COMPLEXITY IN DISTRIBUTED PROBLEM SOLVING

Background: The objective of this research effort is to quantify the minimal amount of information that has to be exchanged in an organization, subject to the requirement that a certain goal is accomplished, such as the minimization of an organizational cost function. The problem becomes interesting and relevant under the assumption that no member of the organization "knows" the entire function being minimized, but rather each agent has knowledge of only a piece of the cost function. A normative/prescriptive solution is sought.

Problem Formulation: Let f and g be convex function of n variables. Suppose that each one of two agents (or decisionmakers) knows the function f (respectively g), in the sense that he is able to compute instantly any quantities associated with this function. The two agents are to exchange a number of *binary* messages until they are able to determine a point x such that $f(x) + g(x)$ comes within ϵ of the minimum of $f+g$, where ϵ is some prespecified accuracy. The objective is to determine the *minimum* number of such messages that have to be exchanged, as a function of ϵ and to determine *communication protocols* which use no more messages than the minimum

amount required.

Results: Several variations of this problem have been studied and solved by Professor J. Tsitsiklis and a graduate student Zhi-Quan Luo. Results have been reported in [1].

An interesting qualitative feature of the communication-optimal algorithms discovered thus far is the following: It is optimal to transmit aggregate information (the most significant bits of the gradient of the function optimized) in the beginning; then, as the optimum is approached more refined information should be transferred. This very intuitive result seems to correspond to realistic situations in human decisionmaking.

More recently, we have considered a new formulation in which the messages are real-valued, rather than discrete. A prototype problem is to assume that each one of two agents knows a $n \times n$ matrix A_i , $i = 1, 2$. The objective is to compute a particular entry of $(A_1 + A_2)^{-1}$. This problem arises, for example in distributed optimization of a cost function of the form $x'A_1x + x'A_2x + x'b$. An obvious solution is for agent 1 to transmit all of the entries of A_1 to agent 2 who then performs the required computations. This scheme requires n^2 communications. We have succeeded in showing that there exists no method which will do with fewer than $O(n^2)$ communications. That is information must be centralized. On the technical side, we have restricted to communication protocols which are smooth rational functions of the original data A_1, A_2 . (Otherwise n^2 numbers could have been coded in a single real number). The proof of our result uses novel techniques and makes use of certain results in algebraic geometry. A journal paper on the subject is in preparation.

A new result has also been obtained which states the following: if the computation of $f(x_1, x_2)$ requires a lot of communication [here agent 1 (respectively, 2) knows x_1 (respectively, x_2)], then the computation of $f(x_1, x_2)g(x_1, x_2)$ also requires, in a certain generic sense, a lot of communication. This result (valid when x_1, x_2 are real vectors and when f , and the messages are rational functions) uses some recent results in algebraic geometry. Collecting more such results should lead to a better understanding of communication complexity issue.

Documentation:

- [1] J. N. Tsitsiklis and Z.-Q. Luo, "Communication Complexity of Convex Optimization," LIDS-P-1617, Laboratory for Information and Decision Systems, MIT, October 1986; *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December, 1986;

also an invited talk was given at the *2nd Symposium on Complexity of Approximately Solved Problems*, Columbia University, New York, April 1987; also, *Journal of Complexity*, 3, 1987, pp. 231-243.

These results were also overviewed at the annual ONR/DTDM contractor meeting, Newport, RI, September 1987.

3.5 DISTRIBUTED ORGANIZATION DESIGN

Background: The bounded rationality of human decisionmakers and the complexities of the tasks they must perform mandate the formation of organizations. Organizational architectures distribute the decisionmaking workload among the members: different architectures impose different individual loads and result in different organizational performance. Two measures of organizational performance are accuracy and timeliness. The first measure of performance addresses in part the quality of the organization's response. The second measure reflects the fact that in tactical decisionmaking *when* a response is generated is also significant: the ability of an organization to carry out tasks in a timely manner is a determinant factor of effectiveness.

The scope of work was divided into three tasks:

- (a) Evaluation of Alternative Organizational Architectures;
- (b) Asynchronous Protocols; and
- (c) Information Support Structures.

During this year, the research effort has been organized around three foci. In the first one, we continue to work on the development of analytical and algorithmic tools for the analysis and design of organizations. In the second, we are integrating the results obtained thus far through the development of a workstation for the design and analysis of alternative organizational architectures. Finally, the experimental program, initiated last year with the objective of collecting data necessary to calibrate the models and evaluate different architectures for distributed decisionmaking, has been continuing and is expanding.

In order to design an organization that meets some performance requirements, we need to be able to do the following:

- (a) Articulate the requirements in qualitative and quantitative terms;

- (b) Generate candidate architectures that meet some of the requirements;
- (c) Evaluate the candidate organizations with respect to the remaining requirements;
- (d) Modify the designs so as to improve the effectiveness of the organization;

The generalized Performance Workload locus has been used as the means for expressing both the requirements that the organization designer must meet and the performance characteristics of any specific design. Consider an organization with N decisionmakers. Then the Performance Workload space is an $N+2$ dimensional space in which two of the dimensions correspond to the measures of the organization's performance (say, accuracy and timeliness) and the remaining N dimensions correspond to the measure of the workload of each individual decisionmaker. Two loci can be defined. First, the Requirements locus is the set of points in this $N+2$ dimensional space that satisfy the performance and workload requirements associated with the task to be performed by the organization. The second, the System locus, is the set of points that are achievable by a particular design. The design problem can then be conceptualized as the reshaping and repositioning of the System locus in the Performance Workload space so that the requirements are met.

3.5.1 Synthesis of Decision-making Organizations

Objective: Given a feasible organizational architecture, develop a methodology for (a) identifying the functions that must be performed by the organization in order that the task be accomplished, (b) selecting the resources (human, hardware, software) that are required to implement these functions, and (c) integrating these resources - through interactions - so that the system operates effectively.

Progress to Date: This research problem has been investigated by Stamos K. Andreadakis under the supervision of Dr. A. H. Levis. A doctoral thesis was completed during this period. The problem statement and a description of the results follow:

For a complex information processing and decisionmaking task, there exists a multitude of ways to partition the processing of the task into subtasks (functions), to define the schema of information exchange among the functions, to allocate functions to decisionmakers, and to specify the supporting system (software and hardware).

Synthesis Problem Formulation

The synthesis problem is formulated as follows: Given a mission and a set of tasks to be performed, design a decision-making organization that is accurate, timely, has a task throughput rate higher than the task arrival rate, and whose decisionmakers are not overloaded. The quantitative formulation is:

Accuracy greater than or equal to a given threshold, or equivalently, expected cost J less than or equal to some threshold J_0

$$J \leq J_0$$

Timeliness measure greater than or equal to some threshold T_0

$$T \geq T_0$$

Processing capacity measure greater than or equal to some threshold S_0

$$S \geq S_0$$

under the constraint that decisionmakers are not overloaded, i.e., that each decisionmaker's information processing rate is less than or equal to his rationality threshold $(F_0)_i$

$$F_i \leq (F_0)_i$$

An alternative formulation is obtained when the second and third requirements are expressed as:

Response time T_r less than or equal to some threshold $(T_r)_0$

$$T \leq T_{r0}$$

Processing rate R greater than or equal to task arrival rate R_0

$$R \geq R_0$$

The approach taken in this work decouples the decomposition of the decision-making process and the exchange of data among the functions from the function allocation to decisionmakers, and the selection of the supporting systems. Thus, the methodology tackles the synthesis problem at two levels: the *data flow structure level* and the *decision-making organization level*. The data flow structure design focuses on information processing schemata, while the organization architecture design focuses on function allocation to decisionmakers and on the development of the supporting systems.

The synthesis methodology has four phases (Figure 1). In phase 1, the procedure for generating data flow structures produces a set of candidate designs. In phase 2, each data flow structure is augmented and transformed to one or more decision-making organizations, in which the

functions have been allocated to decisionmakers, and the supporting hardware and software have been incorporated. In phase 3, the measures of performance and the measure of effectiveness are computed. The designs obtained in this manner, are revised in phase 4, to increase their measure of effectiveness by changing function allocation, introducing decision aids, modifying the database design, and improving the communications links. Finally, a decision-making organization is selected on the basis of the highest MOE value.

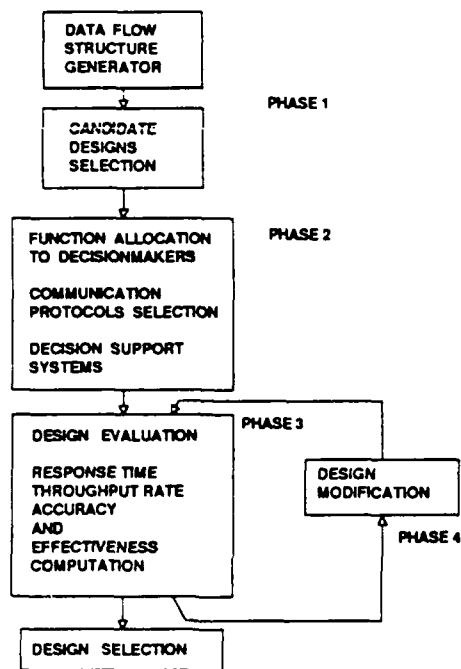


Fig.1: The Synthesis Methodology

Data Flow Structure Design

The information processing is decomposed into five stages (functions): Initial Processing [PI], Data Fusion [DF], Middle Processing [MP], Results Fusion [RF], and Final Processing [FP]. As data are received, they are processed in the IP stage to assess the situation. Information (local or partial situation assessments) of several IP stages are combined (fused) in the DF stage, which produces global situation assessment. The global situation assessment is fed to the MP stage which develops results (options or courses of action). The results are combined (fused) in the RF stage to eliminate conflicting options-courses of action. Finally, a response is selected from the available options in the FP stage. Each processing stage is represented in the Petri Net of the data flow structure by a transition.

The generation of data flow structure takes into account the complexity and redundancy of information processing that is required by the task, and the organization's objectives. Depending on the degree of centralization of decision-making for global situation assessment and the magnitude of the geographical area for which global situation assessment is desired, the data fusion stage may be more or less complex. Similarly, depending on the degree of centralization for global response selection, and the magnitude of the geographical area where the response needs to be coordinated, the results fusion stage may be more or less complex.

The *degree of complexity* of a DF transition is defined as the number of transitions that feed data to the DF transition. The degree of complexity of the DF stage is defined as the maximum of the degree of complexity of the DF transitions. The term complexity is justified by the observation that the more data that are fed to a fusion node, the more complex the processing that takes place.

The need for redundancy of information within the structure arises from survivability considerations and topological factors. The *degree of redundancy* of a IP transition is defined as the number of fusion stages that receive the output data of the IP transition. The degree of redundancy of the DF stage is defined as the maximum of the degrees of complexity of the IP transitions. The term redundancy is justified by the fact that the same information is communicated to more than one fusion nodes, and is therefore redundant in the data flow structure.

The degree of complexity of a RF transition, the degree of redundancy of a MP transition, and the degrees of complexity and redundancy of the RF stage are similarly defined. i.e., those that are appropriate for the task, the designer must consider the adaptability of the structure to the information processing functions must be developed, and then be associated with the transition of each structure. During this stage, some links may be removed from the structure. If it is not possible to associate the algorithms with the transitions of a structure, then the structure is discarded.

Organization Architecture Design

From each data flow structure one or more decision-making organizations may be developed through function allocation to decisionmakers. Functions allocated to a decisionmaker must observe three requirements:

- 1) must be connected through an input-output relationship, i.e., the output of the one must be the input to the other, so that the decisionmaker processes information relevant to the same subtask;
- 2) must belong to different slices of the Petri Net, so that they observe concurrency; and
- 3) must conform to the specialization of the decisionmaker.

When a set of functions is allocated to a decisionmaker, a resource availability place is introduced.

Next, communication links are introduced and the decision support system are incorporated. The data flow structure is augmented by the addition of the transitions that represent the communication processes and the decision support systems access, and of the places that represent the corresponding protocols.

Design modification

If the computed Measure of Effectiveness is not satisfactory, then the organization is modified in order to increase the MOE value. The procedure for the modification depends on the location of the organization locus with respect to the requirements locus. The existing cases are described in Table 1.

Table 1: Design Modification Cases

case	$J < J_0$	$T > T_0$	$S > S_0$	must improve	modification required
1	false	true		accuracy	introduce decision aid
2	true	false		response time	better communications improve database access improve decision-aids
3	false	false		accuracy and response time	introduce decision aid better communications improve database access
4	true	true	false	throughput rate	modify function allocation

Application

The methodology has been applied to the design of C^2 organizations for the outer air battle. A simple model has been developed to describe the decisionmaking pertinent to the outer air battle. The model incorporates the following features:

1. Threat identification on the basis of emitter signature and threat velocity.
2. Development of courses of action based on the strenght of the incoming raid and the type of enemy aircraft.
3. Response selection from the available courses of action based on the availability of resources.

The following decisionmaking functions were defined:

1. local (sector) situation assessment
2. local courses of action development
3. global situation assessment
4. global response selection (resource allocation)
5. local (sector) response selection.

Fourteen data flow structures were created by the DFS generation algorithm (phase 1). Two of these structures were selected for the application of phases 2 and 3 of the methodology. From each Data Flow Structure two organizations were developed through different function allocation. The MOPS and MOE were computed for each organization and a quantitative and qualitative comparison led to the selection of the best design.

Documentation:

- [1] A. H. Levis and S.K. Andreadakis, "Computer-Aided Analysis of Organizations," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.
- [2] S.K. Andreadakis and A. H. Levis, "Accuracy and Timeliness in Decision-Making Organizations," *Proc. 10th IFAC World Congress*, July 27-31, 1987, Munich, FRG and *Proc. 9th MIT/ONR Workshop on C^3 Systems*, LIDS-R-1624, MIT Cambridge, MA, December 1986.

- [3] S. K. Andreadakis and A. H. Levis, "Design Methodology for Decision-Making Organizations," *Proc. of 1987 Symposium on C² Research*, National Defense University, Washington DC, June 1987.
- [4] S. K. Andreadakis, "Analysis and Synthesis of Decision-making Organizations," Ph .D. Thesis, LIDS-TH-1740, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, January 1988.

3.5.2 Evaluation of Decision-making Organizations

In this project, undertaken by Mr. Francois Valraud under the supervision of Dr. Alexander H. Levis, a different kind of problem in organizational design is addressed. The aim of this task is to compare the implementation of a large complex decision-making organization with its supporting C³ system against the functional requirements. An organization consisting of several geographically distributed organizational units, each one with its own architecture, will be considered. A modular building block concept is used to design the system implementing each unit's architecture. Different functions are distributed across the various units to enhance survivability. Communications are needed to perform the functions and to connect the system elements between themselves and the system environment.

More specifically, it is assumed that a C3 system has been specified in terms of the functions it must perform. From the requirements, it is possible to derive information flow diagrams for each message through a combination of functions; other diagrams can be derived focusing on each decisionmaker showing the information and the processes he needs to perform his functions. On the other hand, the design can be represented as a graph in terms of the input and output flows, the communication networks, and the hardware and software implementations. These graphs, which describe the system as designed, and as desired or expected, can be constructed using the Petri Net formalism. This formalism is suitable to model both concurrency and parallelism. Analytical and graphical tools developed in the course of this project will be used to determine the properties of both the designed and the required systems. Examples of such properties, based on the Petri Net formalism, include lines, slices, concuarent paths, subnets, etc. In order to check eventual differences between the representations of the system, scenarios will be derived which reduce the complexity of the representations.

The two compatible representations can then be compared. The comparison should not be made in terms of connectivity (topology), but rather in terms of functionality and of survivability.

Algorithms and associated software will be developed that can compare the two representations and identify their essential differences. Clearly, one objective would be to identify required functionality not available in the designed system (shortfall). A second objective is to identify redundancies in the design that actually degrade performance (overlaps). A typical example of this type is the transmission of data to decisionmakers "just in case" they may need them when that data are not necessary for their assigned functions. This kind of overlap may cause overload or delays that degrade performance.

The establishment of actual shortfalls and overlaps can be achieved only through testing and experimentation of the implemented design. This task is expected to provide a way of designing intelligent experiments - to develop hypotheses that can then be tested in actual experiments. While the problem addressed in this task has wide applicability in C3 system design, part of the effort will be focused on using the results of this research in the design of multi-person experiments, where the final experimental set-up is not identical to the one specified in the requirements.

The completion of the first stage of this effort is expected by December 1988.

3.5.3 Design of Multi-person Experiments

A major task to design a multiperson experiment was initiated by Ms. Victoria Jin under the supervision of Dr. Alexander H. Levis. The basic experimental model was established using the tools of dimensional analysis, as reported earlier. The data from the single person experiment carried out by Casey, Louvet, and Levis in 1987 is being used to validate the model.

There are two major considerations in designing multiperson experiments.

Model-driven experiment: The purpose of the experiment is to validate the mathematical model for designing and evaluating the performance of C³ organizations. The hypotheses to be tested are derived from the mathematical models. The experimental model needs to be established in such a way that the experimental conditions, the controlled variables, and the measured variables are consistent with the mathematical model.

Variable selection: While considering the design of multi-person experiments, one of the difficulties is that too many variables are involved and, consequently, the experiment is hard to

design and control. Therefore, how to choose the variables to be controlled or measured in the experiment is a critical question in the experimental design. Those variables have to capture all significant characteristics of organizational performance, and to be controllable and observable during the experiment.

Based on these two considerations, dimensional analysis has been used and extended during the development of experimental model. Dimensional analysis is a method used in the design and analysis of experiments in the fields of engineering and physical sciences. When a functional relation between variables is hypothesized, dimensional analysis can be used to check the completeness of the relation by considering its dimensional aspects. One of the consequences of the application of dimensional analysis is that it reduces the number of experimental variables. An extension of the approach has been made to include Information and other fundamental quantities pertinent to experiments containing cognitive aspects.

Documentation

A technical paper is in preparation describing the approach and its application to the single person experiment.

MEETINGS

February 2-4, 1988

Dr. A. H. Levis and Dr. S. K. Andreadakis attended the workshop organized by the Basic Research Group of the Joint Directors of Laboratories at the Naval Ocean Systems Center to develop a set of priorities for basic research in command and control.

5. RESEARCH PERSONNEL

Prof. Michael Athans,	Co-principal investigator
Dr. Alexander H. Levis,	Co-principal investigator
Prof. John Tsitsiklis	
Dr. Stamos K. Andreadakis	post-doctoral fellow

Ms. Victoria Jin	graduate research assistant (Ph.D)
Mr. Jason Papastavrou	graduate research assistant (Ph.D)
Mr. Javid Pothiawala	graduate research assistant (MS)
Mr. Francois Valraud	graduate research assistant (MS)
Ms. Sabina Skulsky	undergraduate research assistant (BS)

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