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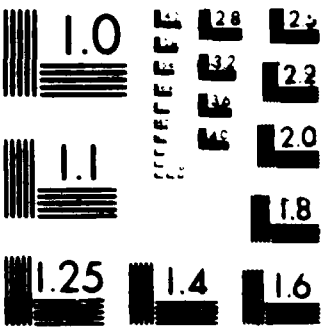
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Progress on 3 research problems in Command and Control Theory is described

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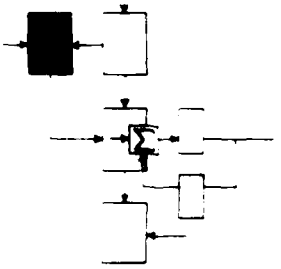

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

Massachusetts Institute of Technology
Cambridge, Mass., 02139, U.S.A.

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QUARTERLY PROGRESS REPORT

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COMMAND AND CONTROL THEORY

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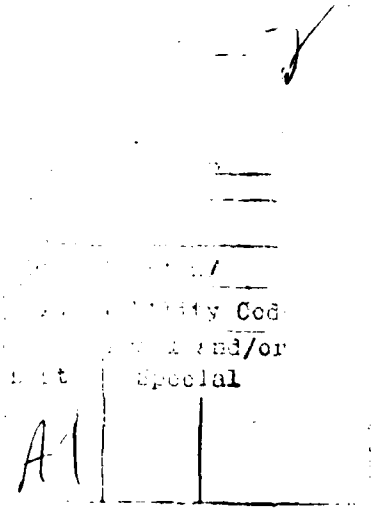

Submitted to:

CDR T. Jones, Code 121
Mr. J. G. Smith, Code 1211
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000

Submitted by:

Alexander H. Levis
Michael Athans

November 22, 1986

COMMAND AND CONTROL THEORY

1. PROJECT OBJECTIVES

The main goal of this research is to start bridging the gap between mathematical theories of command and control and empirical studies. More specifically, the goal is to develop theories on the one hand and to model experimental paradigms on the other, so that realistic problems in command and control (C_{μ}^{2}) can be studied prior to the design of experiments and the collection of relevant data.

The research program undertaken for this project has three main objectives:

(a) The extension of a mathematical theory of C_{μ}^{2} organizations so that it can be used to design an experimental program;

(b) The further development of an analytical methodology for measures of effectiveness, and

(c) The investigation of organizational architectures for distributed battle management (many weapons on many targets resource allocation problems).

The unifying theme of this research is the concept of distributed information processing and decisionmaking. The emphasis is on the development of models and basic analytical tools that would lead to the design of an experimental program as contrasted to ad hoc experimentation.

The project draws upon and contributes to the theoretical developments on naval distributed tactical decisionmaking (DTDM) being pursued in parallel under ONR Contract No. N00014-84-K-0519. The co-existence of these two programs has made it possible to undertake long-range, basic

research on fundamental issues and problems in command and control.

2. STATEMENT OF WORK

The research program has been organized into five tasks, four that address the research objectives and a fifth that addresses the question of disseminating the results of this project both directly to the members of the Basic Research Group of the Technical Panel on C^3 of the Joint Directors of Laboratories and to the C^3 community at large through publications and presentations.

2.1 RESEARCH TASKS

TASK 1: Development of Computer-Aided Design System

1.1 Develop the specifications for the Computer-Aided Design System. Specifically, design the data base, the architecture generator, the performance-workload locus module, and the analysis and evaluation module. The system should be able to handle a generic five member, three echelon organization.

1.2 Implement the design developed in Task 1.1. Design the graphics module to be used in presenting the performance-workload locus and its projections as well as the loci obtained from the analysis and evaluation module.

1.3 Design and implement the user interface. Use the Petri Net formalism for the specification of the interactions between organization members and the design of protocols.

TASK 2: Command and Control Organization Design and Evaluation

2.1 Develop and implement a set of tasks, as well as sets of

information processing (situation assessment) and decisionmaking (response selection) algorithms for use with the decisionmaker models. These tasks and algorithms should be appropriate to future experimental efforts.

2.2 Use organizations with up to five members to exercise and test the CAD system developed in Task 1.

2.3 Analyze and evaluate command and control organizational architectures using the CAD system. Begin developing hypotheses that can be tested through experimental efforts.

2.4 Incorporate in the design system and in the analysis module the theoretical results obtained from parallel research projects.

TASK 3: C^3 Organizations and Architectures for Distributed Battle Management

3.1 Develop a unified theory for complex engagements of several weapons against several targets. Assume imperfect defensive weapons systems so that the elemental "one-on-one" kill probability is non-unity. Also assume imperfect defensive surveillance so that the target/decoy discrimination probability is non-unity.

3.2 Develop several "many-on-many" engagement strategies and evaluate their impact upon decentralized C^3 system requirements and architectures. Develop the necessary tools so as to design distributed C^3 architectures compatible with the engagement strategies.

3.3 Illustrate the tactical doctrine and C^3 interface requirements via computer simulations. Develop hypotheses that could be tested in the field.

TASK 4: Measures of Effectiveness

4.1 Conceptual Development. Develop and refine the concepts and definitions of measures of effectiveness (MOEs), measures of performance (MOPs), and system/mission parameters. Interpret the concept of measure of force effectiveness (MOFE) as a global effectiveness measure in the context of C^3 systems.

4.2 Implementation of the Methodology. Develop a quantitative framework where models of various types can be used to estimate measures of performance (MOPs). Develop analytical, computational and graphical tools for measuring effectiveness (MOEs). Begin the implementation of these techniques on the same workstation used for Task 1 with the objective of developing a system based on MOE evaluation that can be used as an aid in system development and selection. Note that many of the software utilities to be developed are common to Tasks 1 and 4.

4.3 Application of the Methodology. Illustrate the various conceptual and technical developments with examples drawn from actual or planned C^3 systems. Apply the methodology to an evolving C^3 system. While motivated by real systems, the applications will be described in generic terms.

TASK 5: Information Dissemination

5.1 Participate in technical sessions of the Basic Research Group to be held approximately once per calendar quarter.

5.2 Present the research results at technical conferences and meetings and publish articles in archival journals.

3. PROGRESS REPORT

During this quarter, emphasis was placed on the extension of the theory and the development of computational and graphical tools to be used in the design of experiments. In addition, the experimental program has been initiated with the design of the first calibration experiment.

3.1 Development of Computer-Aided Design System

The computer aided design system being developed consists of four major components:

A Data Base which is used to store basic organizational architectures and loci defined by the corresponding Measures of Performance (MOPs).

The Architecture Generator which constructs feasible organizational forms using the Petri Net formalism.

The Locus module that computes and constructs the performance-workload locus of an organizational form that is carrying out a given task.

The Analysis and Evaluation Module contains algorithms for the analysis of organizational architectures and their evaluation.

Highlights of progress made during the reporting period follow.

Graphical Generation of Organizational Architectures (Task 1)

The second component of the Computer-Aided Design System, the Architecture Generator, is being designed and implemented by John Kyratzoglou under the supervision of Dr. A. H. Levis. The objective of this work is the development and implementation of a graphical design methodology for constructing and modifying distributed decision making organizations (DDMO) using the Petri Net formalism. A set of generic

algorithms processes the underlying graphical representation, and generates data structures which corresponds to structural properties of the system. These data structures serve as input to the performance evaluation algorithms in the Analysis and Evaluation Module. Also, the Petri Nets of a special class of organizational forms can be constructed from their data structure.

This work has been organized into six technical subtasks. The first three deal with the design and implementation of a prototype software system. The next two substasks have to do with the revision and completion of the modular parts of the software system. The last subtask has to do with testing and refining the software system.

Subtask 1: Examine the capabilities of the IBM PC/AT, design the applications software specifications, and select the programming environment. A set of symbols, adapted from Petri Net theory, is used to represent the interactions of different decision makers (DMs) and the information exchange among them. The following graphical symbology is used: i) the place node, indicated by a circle, denotes signals or conditions, ii) the transition, indicated by a bar, denotes activities or processes, iii) the switch, indicated by a round bar, a variant of the transition, denotes decisions and iv) the connector or link, indicated by an arrow, denotes direct relationships between places and transitions.

Implement the "assign" function, which activates a command parser and creates a special storage file. In this file, information is stored about the elements of the organizational structure, such as capacity, which is associated with places, probability, which is associated with the connectors, and algorithms which are associated with transitions. The designer can interact with his design using keyboard and mouse commands (the latter have not been implemented yet).

Subtask 2: Generate a prototype software system to test the feasibility of the design. Implement the design framework developed in Subtask 1.

Develop the basic algorithimc tools for revising or modifying the design and for carrying out analysis.

Subtask 3: Revise the design according to the observations made from the operation of the prototype system. Complete the conceptual design of the system. Implement a simple file system service consisting of a file management service, a file table, and a file data base. The data base is used to store and retrieve files containing data structures of organizational forms.

Subtasks 1, 2, and 3 were completed during the last quarter and Version 1.0 of the software system has been demonstrated to faculty, staff, students, and visitors. Current effort is focused on Subtask 4:

Subtask 4: Complete the implementation of the interactive editing function (edit mode) and of nesting (converting a Petri Net structure into a single element). Because of limitations, of the IBM PC/AT, only one level of nesting is permitted for each transition.

In the following quarters, the technical effort will be directed on Subtasks 5 and 6:

Subtask 5: Generate the organizational architecture of a Distributed Decisionmaking Organizations from a data structure in the data base.

Subtask 6: Integrate all software components into a unified Design System. Test, refine and document the software system.

Expected date of completion of the Task is June 1987.

3.2 Organizational Designs

Assessing Human Operator's Bounded Rationality Constraint: An Initial Experiment

In order to develop an experimental program for studying the properties of distributed decisionmaking architectures, it is necessary to carry out some preliminary experiments to calibrate the analytical models. In this section, plans for the first of a series of experiments utilizing human subjects are described. The purpose of this experiment is to demonstrate that the information theoretic surrogate for workload can be used to predict conditions under which performance will deteriorate due to information processing overload. The design of this experiment is being conducted by Anne-Claire Louvet under the supervision of Drs. A. H. Levis and J. T. Casey.

A basic assumption of the approach being taken is that bounded rationality sets a stable upper limit on the amount of information that can be processed per unit time. When this rate constraint, denoted F_{max}, is exceeded, performance should be seriously degraded due to uncontrollable error. The validity of the workload surrogate will be assessed by examining the stability across tasks of an estimate of F_{max}. A novel, computer-simulated air defense task performed by single decision makers has been designed for this purpose. Both the tempo of operations and the number of incoming threats will be varied systematically. Subjects' goal will be to select the incoming threat which would arrive first in the absence of intervention. The critical question is: With decision strategy held constant, does F_{max} remain constant regardless of the source of variation in workload (tempo versus "track load")?

A single, critical requirement underlies the task design and distinguishes it from previous laboratory air defense tasks. This requirement is that subjects' strategies (choice of situation assessment and response selection algorithms) be known a priori. Toward this end, a

process tracing technique has been devised in which subjects use the computer's mouse to make intermediate responses as they evaluate threats and eliminate alternatives. This technique, combined with careful training, is intended to restrict inter-and intra-subject strategic variation to a small set of strategies. These strategies will be modeled usign existing analytic tools.

If the workload surrogate can be validated in this way for the single decision maker case, experiments will be designed (to be carried out at Naval facilities) to extend the results to multi-decision maker organizations and to address other pertinent questions. These first experiments are crucial, because a valid and reliable estimate of F_{max} is needed to calibrate the models. Calibration will make it possible to determine, for task situations in which experiments with human subjects are infeasible, whether the bounded rationality constraint is likely to be exceeded. This ability would constitute a major start toward the goal of designing organizations such that performance requirements are met without pressing individual decision makers beyond their cognitive limits.

Prototype experimental software is currently under development at MIT. Preliminary work will utilize MIT engineering students as subjects.

3.3 C^3 Organizations and Architectures for Distributed Battle Management (Task 3)

Project Objective: The long-range goal of this research is to understand basic issues associated with Battle Managament C3 (BM/C3) architectures associated with many weapons engaging several targets. The defensive weapons are assumed imperfect, and the targets may have a finite probability of being decoys. Thus, the problem is one of wise Weapon-to-Target (WTA) assignment strategies, and their interface with other BM/C3 functions. We also seek the evaluation of centralized, decentralized, and distributed BM/C3 architectures that support such "many-on-many" engagements.

Problem Definition: The major emphasis of the research during the past year has been in the area of problem definition. Professor Athans studied the problem of optimizing the Weapon-to-Target (WTA) function which is at the heart of the "many-on-many" problem. Suppose that we have a total of M weapons which we are willing to commit against the total of N targets. At that most general level, the effectiveness of each weapon can be different against each target; this can be quantified by having a different kill probability p_{ij} for weapon j assigned against target i (j=1,2,...,M; i=1,2,...,N). The WTA function wishes to allocate the right weapons against the correct targets so as to minimize leakage, i.e., the expected number of surviving targets. Thus, if we adopt an optimization framework, we wish to minimize the leak L which is given by

$$L = \sum_{i=1}^{N} \prod_{j=1}^{M} (1-p_{ij}x_{ij}) \qquad (1)$$

by selecting optimally the MxN allocation decision variables x_{ij}, each of which is either 0 or 1. Thus, $x_{ij} = 1$ if the j-th weapon is assigned to the i-th target and 0 otherwise and

$$\sum_{i=1}^{N} x_{ij} = 1 \quad , \quad j = 1,2,...,M \qquad (2)$$

which simply states that each weapon can only engage a single target.

More realistic versions of this problem can be formulated in a similar manner. For example, each target indexed by i = 1,2,...,N can be assigned a value V_i reflecting the importance of that specific target to the defense. In this case, the defense may wish to minimize the expected total surviving value associated with all targets, i.e., minimize the cost function

$$C = \sum_{i=1}^{N} V_i \prod_{j=1}^{M} (1-p_{ij}x_{ij}) \qquad (3)$$

again by selecting optimally the MxN allocation variables x_{ij}, subject to the constraints of Eq. (2).

The solution of such optimization problems for the WTA function is very difficult, because it has a strong combinatorial flavor; in fact, it has been proven to be NP-complete by Lloyd and Witsenhausen in 1986. Part of the complexity relates to the fact that the kill probabilities p_{ij} are different. If the kill probabilities are the same, i.e., $p_{ij} = p$ for all i and j, then the optimal solution (to minimize the leakage) is easy and it requires the maximally uniform assignment of the weapons among the targets. The problem is inherently hard even in the special case that the kill probabilities depend only on the weapons but not the targets, i.e., p_{ij} is independent of i.

Description of Recent Progress: The inherent complexity of the WTA optimization problem suggests that it may be advisable to decompose the centralized WTA function into subfunctions, and accept the collective decisions of the WTA subfunctions as a suboptimal solution to the centralized WTA problem. For example, one can split both the targets and the weapons into subsets so that for each subset the kill probabilities are approximately the same and use a maximally uniform allocation within this subset. Indeed this may turn out to be a reasonable starting point in the definition of distributed BM/C3 architectures that support the WTA function.

We have studied an "easy" WTA algorithm. We call it the Highest Target Value (HTV) algorithm. In the HTV we initially rank the targets according to their values. Then we assign the most effective weapon to the highest value target, delete that weapon from the list, compute the expected

survival value of the target and reintroduce it into the ranked-by-value target list. Thus, we never forget about a target, simple change its expected survivable value and keep it in the list until the damage assessment function declares the target "dead" with probability one. Note that in this manner a high value target will be assigned multiple weapons following a Shoot-shoot-shoot-etc strategy. However, we have been investigating the circumstances that the HTV algorithm will generate "bad" assignments (this can happen if the range of the kill probabilities is wide).

Mr. Walton's doctoral thesis research, under the supervision of Professor M. Athans, will examine additional tradeoffs that arise from decoy considerations, vulnerability of BM/C3 to enemy countermeasures, and delays in decision execution. We foresee highly nontrivial tradeoffs as we move from centralized to distributed and then to purely decentralized (or autonomous) BM/C3 architectures. In particular, we are working on developing analytical models and quantitative approaches to study the following issues:

- Optimal weapon resource utilization deteriorates with increased distribution; however, such degradation will be strongly dependent upon the effectiveness of one-on-one engagements (the kill probabilities p_{ij} defined above).
- The overall vulnerability of the BM/C3 functions will reduce as the degree of its distribution increases.
- The communications requirements for coordination will increase as we distribute the BM/C3 functions more and more.
- The complexity of the coordination strategies will increase as the degree of distribution increases.
- The delay in executing a local BM/C3 function will decrease in distributed architectures, simply because each subfunction will have to handle fewer targets and weapons.

To what extent the improvement in survivability and reduced delays are counterbalanced by increases in communication/coordination and resource misutilization remains a problem for future research.

Documnetation: No formal documentation exists as yet. The Ph.D. thesis of J. Walton is scheduled for completion in 1988.

4.0 RESEARCH PERSONEL

Dr. Alexander H. Levis, Principal Investigator
Professor Michael Athans
Dr. Jeff T. Casey

Mr. John Kyratzoglou,	Research Assistant	(ME Candidate)
Mr. Pascal P. Remy,	Research Assistant	(SM Candidate)
Mr. James Walton,	Research Assistant	(Ph.D. Candidate)
Mr. Scott Weingaertner	Research Assistant	(MS Candidate)

5.0 INFORMATION DISSEMINATION

The following documents were issued as Laboratory Technical Reports or as Technical Papers. There were submitted to ONR, to the Basic Research Group of the JDL Panel on C^3, and to the distribution list specified in the contract. Some aspects of the work contained in these reports were supported by other related projects, such as the one from the Office of Naval Research on Distributed Tactical Decisionmaking (N00014-84-K-0519).

5.1 Theses/Technical Reports

1. C. M. Bohner, "Computer Graphics for System Effectiveness Analysis," LIDS-TH-1573, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, July 1986.

2. P.J.F. Martin, "Large Scale C^3 Systems: Experimental Design and System Improvement", LIDS-TH-1580, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, August 1986.

3. H. P. Hillion, "Performance Evaluation of Decisionmaking Organizations Using Timed Petri Nets," LIDS-TH-1590, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, August 1986.

4. S. T. Weingaertner, "A Model of Submarine Emergency Decisionmaking and Decision Aiding," LIDS-TH-1612, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, September 1986.

5. P. A. Remy,"On the Generation of Organizational Architectures Using Petri Nets," LIDS-TH-1630, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, December 1986.

5.2 Technical Papers

1. P. Remy, A. H. Levis, and Y.-Y. Jin, "Delays in Acyclical Distributed Decisionmaking Organizations," LIDS-P-1528, Laboratory for Information and Decision Systems, MIT, January 1986. (Accepted for presentation at the 10th World Congress of the International Federation on Automatic Control, Munich, FRG, July 1987).

2. A. H. Levis, "Modeling the Measuring Effectiveness of C^3 Systems," LIDS-P-1608, Laboratory for Information and Decision Systems, MIT, September 1986. Presented as an invited paper at the Seventh Annual AFCEA European Symposium on October 30, 1986.

3. M. Athans, "Command-and-Control Theory: A Challenge to Control Science" LIDS-P-1584, Laboratory for Information and Decision Systems, MIT, September 1986; paper will appear in the IEEE Transactions on Automatic Control, April 1987.

5.3 Technical Interactions

On December 2, 1986, two representatives from the Navy Personnel Research and Development Center (NPRDC), Dr. D. Nebeker and C. Tatum, visited the Laboratory to be briefed on our research and discuss possible joint experimental efforts in the future.

Dr. Levis presented an invited lecture on Measures of Effectiveness at the 7th Annual AFCEA European Symposium on October 30, 1986.

Dr. Levis presented the results of the work on Measures of Effectiveness in a Seminar at the SHAPE Technical Center on October 29, 1986.

On August 11 and 12, 1986, 8 faculty and students from the C^3 Curriculum of the Naval Postgraduate School visited the MIT Laboratory for Information and Decision Systems where they had an in-depth presentation of the research results in anticipation of joint efforts in carrying out the experimental program.

In June 1986, Dr. Levis presented the first results on the generation of alternative organizational forms at the 9th MIT/ONR Workshop on C3 Systems.

Dr. Levis attended four meetings of the Basic Research Group in accordance with contractual requirements in which he briefed the Group on the progress of the research effort. The meetings were held at the Naval Ocean Systems Center, At Ft. Monmouth, and at the National Defense University.

Dr. Levis participated in the second workshop on Measures of Effectiveness for Command and Control Systems held at the Naval Postgraduate School in January 1986. His involvement in this workshop led to the use of the IFFN testbed as the illustrative example in Martin's thesis.

Dr. Levis and Mr. P. Martin participated in a meeting organized by Studies and Analyses, USAF, to discuss the applicability of the work to the experimental program of the IFFN Joint testbed (US Army, US Air Force).

These interactions are considered essential for presenting the results of basic, fundamental research to the C^3 community and for receiving feedback -- comments and suggestions -- that increase the relevance of the work.

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