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DISTRIBUTED DECISION AND COMMUNICATION PROBLEMS

Final Report

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SUMMARY

This document is the final technical report on a contract funded by the Office of Naval Research entitled **Distributed Decision and Communication Problems** to the Laboratory for Information and Decision Systems (LIDS) of the Massachusetts Institute of Technology (MIT). The contract number is N00014-77-C-0532 (Task Number NR 041-519).

This contract was initiated on 1 July 1977 and terminated on 30 September 1986. During these nine years we were blessed by three outstanding ONR contract monitors: first, Dr. Stuart Brodsky, then Dr. Charles J. Holland, and finally Mr. J. Randolph Simpson. Much of the success of the research carried out can be traced to the forward-looking ideas of these wonderful contract monitors, their help, their encouragement, their confidence in the MIT/LIDS research team, and their sincere belief that the field of Command-and-Control can benefit from some solid quantitative analyses.

During its tenure this contract provided partial financial support to seven faculty members, three senior research staff, ten doctoral students and over fourteen master's students. Their names together with brief remarks appear in the sequel. Moreover, it provided the resources for an environment that attracted many visiting engineers and scientists to MIT. Last, but not least, it provided the required support for organizing the highly visible and successful annual **MIT/ONR C3 Workshops**. The written documented output of this long-term research effort can be found in the 100 publications (journal and conference papers, technical reports, theses, and the nine C3 Workshop proceedings) cited at the end of this final technical report.

SUMMARY OF RESEARCH ACCOMPLISHMENTS

It is obvious that we cannot provide even a high level technical summary for all the technical achievements documented in the publications. For this reason we shall only provide here a brief technical perspective.

Background.

When this contract was initiated in 1977, there were claims expressed at the early MIT/ONR C3 workshops that the services in general, and the Navy in particular were dissatisfied with the available C3 systems. C3 meant different things to different people. To a commander, the C3 system provided the means to command-and-control his resources. To a communications engineer C3 meant radio communications and the associated hardware. To a computer scientist C3 meant bigger computers and larger colorful displays. To a surveillance person C3 meant radars, sonars etc. Thus, it is fair to state that there were few generally agreed definitions or research priorities. It was not at all clear whether or not a "C3 science" or a "C3 theory" even made sense, much less whether or not it would be possible to prove some relevant theorems using analytical models. It was in this type of background that the MIT/LIDS research team started its research.

Workshops and Interactions.

Neither the MIT/LIDS research team nor our contract monitor knew too much about command-and-control. So the first order of business was to find out what "it" was about so that we could structure a relevant long-range 6.1 basic research program that could also withstand the rigorous review of the ONR mathematics office.

With the help of our first ONR technical monitor, Dr. Stuart Brodsky, we arranged for several visits to Naval installations and talked to Naval commanders as well as Naval scientists and engineers concerned with issues related to C2 problems. The first MIT/ONR workshop, held for three weeks at MIT in the summer of 1978, exposed us to more military decision makers and expanded our knowledge base to problems faced by the Army and Air Force. During this first workshop we met Dr. Jay Lawson of NAVELEX (now retired) who was one of the very few people to recognize at an early stage the importance of a "C3 theory" and was an active contributor to the emergence of such a theory. Jay Lawson's enthusiasm rubbed on all of us. These valuable contacts continued during the subsequent years and included attendance of war games at the Naval War College at Newport and at NOSC in San Diego, and participation in a two week training course on the Composite Warfare Commander (CWC) doctrine at Training Group, Pacific with the help of Rear Admiral Gerald Thomas (now retired).

The annual C3 workshops continued to be organized by MIT and sponsored by ONR for nine years. Their location alternated between Cambridge, MA, Monterey, CA, and San Diego, CA. One year we held one near Washington, DC in the hope of attracting more government researchers; the opposite happened. The last C3 workshop attracted about 140 attendees and resembled a small conference rather than a workshop. In 1986 we decided that it was time to terminate the MIT organization, and it was "transitioned" to the so-called C3 symposium, presently sponsored by the JDL, and held in June 1987 at the National Defense University.

The MIT/ONR workshops had several purposes. One objective was to expose the long-term needs of the military to the academic system engineering community, as well to other interested industrial researchers. Many of the graduate theses at MIT were directly motivated by these interactions at the C3 workshops. The second objective was to bring to the attention of the C3 practitioners the state-of-the-art in basic research. The author knows for a fact that in the area of multi-target tracking and in the area of communicating over vulnerable networks many applied studies were directly influenced, and benefited from, the academic advances in the state-of-the-art. The third objective was to increase the visibility of the C3 field as an important scientific discipline and to encourage increased academic research in several universities.

After three or four years a solid core of about 35 attendees from government, industry and universities participated in each workshop. A common language and working definitions were developed and documented in the workshop proceedings. Many research groups chose this unclassified forum to present their progress from year to year, since the technical quality of the presentations was maintained at a high level; the attendees could be sure that "viewgraph engineering" and sales pitches would not take place in these workshops. The special classified sessions were designed to provide tutorial expositions of current issues to the research community, and these influenced the research plans of many researchers. As the years went by we increased to content of papers dealing with AI, while maintaining the traditional strength of analytical optimization-oriented flavor. Also, an ever increasing number of presentations dealing with cognitive psychology started to appear; this helped to a significant level the researchers concerned with the unification of normative/prescriptive and empirical/descriptive methodologies. Finally, in the last few workshop years we saw an everincreasing number of 6.2 program managers attending the workshops, a hopeful sign that some of the 6.1 research findings reported were becoming ripe for 6.2 transition. For these reasons we believe that the MIT/ONR C3 workshops met all their original objectives. We sincerely hope that the "follow-on" JDL sponsored C3 symposia will continue the tradition of relevance and excellence that were the hallmark of the MIT/ONR workshops.

The presentations in the annual MIT/ONR C3 workshops is documented in 3, 13, 21, 28, 37, 60, 86, 94, and 99.

Distributed Detection Theory.

The surveillance function is a critical and generic function in C2 processes. Hostiles, friendlies and neutrals must be detected, tracked and identified. A very significant amount of progress was done in the area of distributed detection and the fusion of this detection information with constraints on the amount of communication allowed.

The development of a distributed detection theory represents the first non-trivial class of problems within the more broad framework of distributed decision theory. Distributed detection networks present a degree of computational complexity that is absent in their centralized counterparts (distributed detection problems are NP-complete). Also, they have many counterintutive properties. For these reasons they are excellent paradigms for studying distributed decision architectures, to understand the impact of limiting communication in such networks, and to even suggest empirical experiments for human decision making organizations.

Relevant references in the distributed detection theory area are as follows: 1, 2, 4, 6, 8, 15, 16, 19, 20, 22, 24, 39, 41, 47, 78, 81, 88, and 95. For all practical purposes, this set of publications is the core of the available knowledge in the distributed detection theory area.

Research on Multi-Sensor Multi-Target Tracking.

Another part of the surveillance function is target tracking. Accurate knowledge of the location of a target with minimum error covariance is critical for forecasting its future trajectory and execute impact point prediction. Clearly, such tracking information is critical for battle space management, weapon-to-target assignment algorithms, and target interception. One of the most difficult problems from a technical point of view is how to track many targets based upon diverse low observable signals available to one or more sensors, and how to utilize such low observable signals to execute 3D tracking together with estimation of target attributes (e.g. discrimination) using a hybrid-state estimation framework.

A driving open problem which became apparent at an early phase was the need for distributed implementations of the surveillance function, and the fusion of information generated by many dissimilar sensors. For example, the US Navy initiated studies on how to fuse radar, sonar, ESM etc information on a single ship. The distributed CWC doctrine presented special challenges in obtaining accurate surveillance information in a timely manner.

We made significant advances in developing a unified theory and algorithms for tracking several targets on the basis of returns from many dispersed sensors. We also studied the special problems of crossing targets, data association, multisensor correlation etc. We pioneered the use of AI-based pruning methods to deal with the combinatorial explosion associated with these multiple-hypothesis problems.

Relevant references in this area of decentralized and distributed state estimation and its application to some surveillance problems are as follows: 1, 17, 18, 22, 24, 29, 30, 33, 36, 41, 44, 45, 49, 58, 61, 62, 75, 76, 77, 78, 82, 83, 84, 85, 87, 92, 93, 98, 100.

Distributed Data Networks and Data Bases.

All military C3 systems require data communications and such data resides in distributed data bases. In such networks it is important to develop routing protocols so that information can be transmitted from any origin to any destination node in the presence of multiple link and node failures, provided that a physical path exists. Also, from the viewpoint of accurate decision making it is important that consistency is maintained among the different copies of the distributed data files. However, to maintain a common picture a large amount of communication may be necessary which could tax the data network, especially when its nodes and links are being attacked by the enemy.

Our research on data networks focused on developing failsafe routing algorithms and associated protocols which could be counted upon to deliver data and messages in a failing network. We also pioneered the examination of bandwidth and other communication constraints upon the management of distributed data base systems and networks.

Our research in this area is documented in the following references: 9, 10, 23, 31, 36, 42, 43, 50, 51, 54, 55, 56, 59, 64, 68, 69, 71, 74, 79, 80, 82, 90, 91, 97 and 100.

Distributed Decision Making Algorithms and Organizations.

The design of organizations based on quantitative reasoning is a virgin research area. We used game theoretic, optimization-based, and information-theoretic approaches to such organizations. Some of the research used the distributed detection paradigm discussed above.

Overall we have found that the analysis and design of organizations represents a very difficult research area. Our research has barely scratched the surface. Even in the absence of human decision makers, in which case the organization corresponds to a suite of distributed algorithms it is very difficult to quantify the convergence and rates of convergence of these algorithms. In C2 organizations where both humans and algorithmic decision aids interact the problems are, of course, even more complex.

Our research in this area is summarized in the following references: 1, 4, 5, 7, 11, 12, 14, 16, 20, 23, 24, 25, 26, 27, 32, 35, 36, 38, 40, 46, 48, 57, 63, 65, 66, 67, 70, 72, 73, 82, 89, 96 and 100.

PEOPLE

In this section we provide a brief summary of the MIT faculty, research staff, and doctoral students that participated in the research program and received partial financial support from this contract.

Michael Athans, is a faculty member in the EE&CS department at MIT. He has been the principal investigator since the inception of the contract.

Kevin L. Boettcher, received his Ph.D. at MIT in 1985. He then joined the staff of Honeywell Inc.

David A. Castanon, was a research staff member at LIDS. He then joined ALPHATECH Inc.

Wilbur A. Davenport Jr., was a faculty member in the EE&CS department at MIT. He then became a faculty member at the University of Hawaii. While at MIT he was principal co-investigator of this contract.

Elizabeth R. Ducot, is a research staff member at LIDS.

Leon K. Ekchian, received his Ph.D. at MIT in 1985. He then joined the staff of Optima Inc.

K-T Huang, received his Ph.D. at MIT in 1982. He then joined the staff of IBM Inc.

Norman A. Lehtomaki, received his Ph.D. at MIT in 1982. He then joined the staff of Honeywell Inc.

Alexander H. Levis, is a Senior Research Scientist at LIDS at MIT.

Bernard C. Levy, is a faculty member in the EE&CS department at MIT.

Victor O.K. Li, received his Ph.D. at MIT in 1981. He then joined the faculty of the University of Southern California.

Moses Ma, is a doctoral student at MIT.

Peter Ng, received his Ph.D. at MIT in 1985. He then joined the staff of RCA.

Nils R. Sandell Jr., was a faculty member in the EE&CS department at MIT. In

1979 he joined ALPHATECH Inc. While at MIT he was principal co-investigator of this contract.

Adrian Segall, was a faculty member in the EE&CS department at MIT. He then joined the faculty at Technion (Israel) and continued consulting for the project.

Robert R. Tenney, received his Ph.D. at MIT in 1979 and then joined the faculty in the EE&CS department at MIT. In 1985 he joined ALPHATECH Inc. While at MIT he was principle co-investigator of this contract.

John N. Tsitsiklis, received his Ph.D. at MIT in 1984 and then joined the faculty in the EE&CS department at MIT.

R. Paul Wiley, received his Ph.D. at MIT in 1985. He then joined the staff of the Microelectronics Institute.

ACKNOWLEDGMENT

The author greatfully acknowledges the contributions of his MIT colleagues to the research project. Special thanks are due to Alex Levis. Also, to Lisa Babine who helped with the administrative details of the C3 Workshops.

Special thanks are also due to our contract monitors: Stu Brodsky, Charlie Holland and Randy Simpson for all their help and support over the years.

The author also wishes to thank the following individuals that helped him understand command and control over the years: Mr. J. G. Wohl, Dr. J. R. Lawson, Admiral W. Meyers, USN (ret), Admiral G. Thomas, USN (ret), Capt. S. Landersman USN (ret), Dr. J.M. Wozencraft, Dr. M. Melich, Dr. D. Schutzer, and Cdr. P. Girard USN.

PUBLICATIONS

The following journal and conference papers, theses, and reports were supported in whole or in part by contract ONR-N00014-77-C-0532 (NR-041-519). Copies of these have been submitted to the contract monitors. These publications fully document the technical achievements under this research contract.

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