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MODELING THE ACQUISITION AND REPRESENTATION OF KNOWLEDGE FOR DISTRIBUTED TACTICAL DECISION MAKING

This article discusses research on fundamental issues underlying the design of reconfigurable knowledge-based systems for support of distributed tactical decision making. A concept of distributed knowledge bases interacting in an open communications system to support peer-level decisions is presented. General progress is described in terms of a computer-based three-node interview and test system.

INTRODUCTION

For knowledge to be used effectively in human/computer decision environments, it must be represented in forms most amenable to the problem environment and the decision processes of the human decision makers. We are conducting research on fundamental issues underlying the design of reconfigurable knowledge-based systems to support decision processes of multiple tactical commanders using a common decision-aiding system in which their own tactical knowledge may be represented.

BACKGROUND

In a distributed tactical decision-making (DTDM) system, decision makers who are separated spatially, electronically, and organizationally must develop and maintain an understanding of their dynamic decision environment, which consists of all pertinent factors involved in the exercise of their authority. In cases of incomplete or conflicting decision information, doctrine and experience augment the decision environment.

Doctrine provides commanders "acceptable" courses of action; however, it is generally inadequate to achieve full effectiveness of distributed resources. As doctrine is expanded to accommodate a wider range of preconditions and associated actions, selection among acceptable options becomes increasingly dependent on each commander's perception of existing conditions (in effect, weakening the predictability of doctrine). Thus, doctrine fails to support the effective coordination of distributed resources to the extent that separate commanders are operating with different knowledge of the doctrinal preconditions.

A second failing of doctrinal control of distributed resources results from the limit, in its application, of the "weakest link." By promoting actions compatible with all units, doctrine sacrifices localized effectiveness to achieve uniformity of control. In the worst case, with no external communications, this leads to independent actions at the lowest effectiveness level and may result in the loss of all cooperative or synergistic capabilities of the several units involved.

The experience of individual decision makers, comprising as it does lifelong education, training, and memory of past events, does not necessarily suffer those failings. However, it, too, has its limitations in a distributed decision-making environment insofar as individual decision makers do not know what decisions are being made and what actions are being taken by other decision makers within their regional decision environment. If there were a way to convey continually to his peers the experience and related environmental knowledge of each decision maker, the coordination of decisions to avoid conflicting resource allocation and to exploit opportunities for synergistic action would be facilitated. Such a mechanism for understanding the decisions of others may be necessary but may not be sufficient to achieve optimal decisions in a distributed tactical problem domain. Other requirements for effective decision making by physically separated command peers will likely include compatible representation, processing, and communication of knowledge.

CONCEPT

One possibility we are exploring for improving distributed decision making at a given level of command is for decision makers such as area commanders to use local instantiations of a common knowledge-based decision-aiding system incorporating essential elements of doctrine and expertise from all mission areas. With such a system of knowledge bases operating in reduced-communication scenarios, each participant could, in principle, project and keep track of the best estimate of the likely responses of other system participants to evolving events. As the tactical environment permitted, the system could be calibrated with updates about the actual decisions and related performance of system participants, thereby permitting a decision maker the opportunity to refine his understanding of peer decision processes and the overall situation. Also, should one or more of these decision makers, or his ability to control assigned resources, be lost to the DTDM system, that state change could be recognized (in the form of conflicts with expected behavior) within the system so that mission-essential functions could be reassigned to other decision makers. Similarly, as units departed or joined the organization, the overall control structure could be reconfigured so that new participants in the operation of the system would be recognized. A major potential strength of such a well-defined distributed knowledge-based system would be the ability to reconstruct local inferences and their tactical consequences so that when communication restrictions were subsequently relaxed, each decision peer could be made aware not only of the actual current situation but of its evolution during communication blackouts as well.

PURPOSE OF RESEARCH

Given that concept as a general goal, the purpose of this research is to investigate the nature of the decision processes of experienced Naval tactical decision-making peers who, although spatially and electronically separated, must coordinate their decisions and actions to satisfy several (possibly conflicting) sets of warfare-area requirements within the context of a prescribed mission.

To do this, we have set the following goals for our research:

1. Identify DTDM planning elements that are necessary for the effective coordination of tactical decisions made by peers interacting in an open system.
2. Identify DTDM knowledge requirements in terms of tested psychological, computational, and communicative procedures and levels of problem-solving abstraction.
3. Identify information flow and internode communications requirements that are needed for distributed decision processes and interactions.

METHODS

To improve the likelihood that the Navy DTDM domain is described appropriately and adequately in our research, we have developed a taxonomic structure to identify and organize requirements for Navy DTDM in relation to candidate human and computer process models. The taxonomy is constructed along the three major dimensions of psychological, computational, and communicative processes. Each major dimension carries with it requirements for acquisition, representation, and utilization of knowledge associated with that processing. Also, each dimension is further defined in terms of hierarchical levels of processing.

The choice of models for each processing dimension and the interrelationship of the levels of processing determine the basic knowledge representation requirements at each level. Using the taxonomy, a number of process models can be characterized in relation to other models. For any single or composite model proposed as a candidate to address the combined psychological, computational, and communicative processes of DTDM, the challenge is to identify the processing relationships at increasing levels of complexity in terms that will support the required empirical validation. Given the specification of those relationships, methods of knowledge acquisition, representation, and utilization may then be analyzed in terms of observed performance in fulfilling a complete or generative set of DTDM requirements. In this complex process, we are restricting our focus initially to the knowledge representation required in an open system of Navy command peers when their decisions are characterized as separate psychological, computational, and communicative processes, as described below.

Psychological Processes

In the spirit of the "human information processing" paradigm of modern cognitive psychology,[1-3] we are exploring psychological constructs of time-critical decision making within an adapted form of Rasmussen's empirically derived decision process model.[4,5] The human information processing paradigm is especially appropriate to the effort because it is of current interest in the psychological community and is compatible with current computer science approaches to research in knowledge-based artificial intelligence systems.

Rasmussen's model (Fig. 1) is organized as a hierarchy of levels of abstractness that takes into consideration skill-based, rule-based, and knowledge-based performance and the different ways in which information is perceived, analyzed, and used at each of those performance levels. The model has been developed through studies in the complex environment of nuclear power plant control-room operations and appears to offer a reasonable initial framework within which to structure psychological studies of performance in the Naval tactical decision-making environment.

As abstractions from the investigation of human performance, the skill-, rule-, and knowledge-based levels bear a strong resemblance to problem-solving performance levels of artificial intelligence investigations, where algorithmic solutions, rule-based systems, and other knowledge-based heuristic reasoning approaches are used to solve problems at increasingly abstract levels of performance.[6] Similarly, knowledge engineering techniques associated with the development of expert systems appear to be useful for modeling and studying tactical decision-making processes for and among multiple commanders and also for comparing knowledge representation formalisms.

We are using knowledge engineering techniques to build laboratory tools for acquiring data and exercising decision-making processes. However, the theoretical basis for our experimentation models is a still-developing integration of Rasmussen's model of decision making with a Navy command and control process model and an open system communications model (described below).

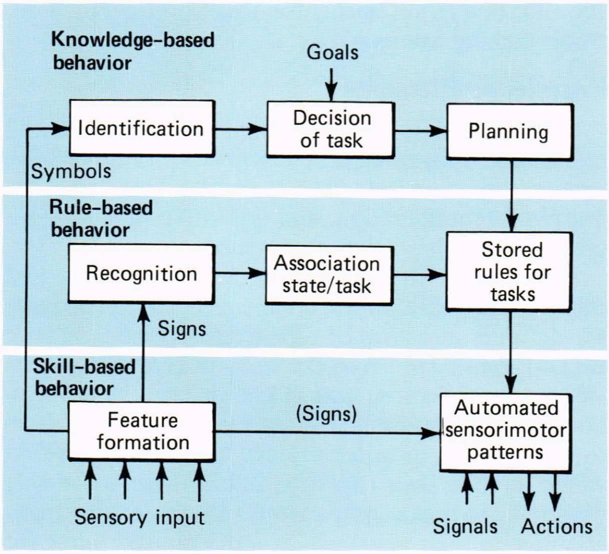

Figure 1—Performance levels of skilled human operators.[4] Task performance at different conceptual levels requires more or less direct conscious application of human knowledge. At the level of skill-based behavior, highly integrated automatic actions can be taken in direct response to the detection of environmental signals or to the matching of feature patterns without conscious control. At the level of rule-based behavior, signs are interpreted by recognition and association mechanisms that relate familiar environmental states to task requirements, and action decisions are made in terms of stored sets of (previously successful) rules that apply to the state/task relationships. At the level of knowledge-based behavior, symbolic information about unfamiliar situations must be interpreted by a human decision maker who can identify the meaning of symbolic information, cast it into task statements related to explicit performance goals, and plan and execute desirable courses of action.

Computational Processes

In 1977, APL was asked to assist in developing a concept for an integrated command and control system to support Naval warfare in the year 2000. A series of processing models and system architectures was produced through an analysis of projected mission requirements identified by senior Naval commanders in open wargaming at APL.[7,8] The models, derived empirically using specific processing capabilities already planned for Navy acquisition, reflect a restricted engineering perspective on command and control that may not be complete theoretically with respect to the general problem domain of DTDM.

As a foundation for much of that analysis of Navy C^3I Year 2000 systems, APL also developed a general model of computational processes supporting current and projected command and control functions (Fig. 2). Known as the Year 2000 C^3I process model, it reflects the Navy command structure and sensor-to-decision processing levels determined by current and planned sensor and computer systems. We are using this model to address computational processes in DTDM in relationship to psychological processes associated with human control of the total system on the one hand and communications processes judged appropriate for the interaction of decision-making peers on the other.

Communicative Processes

The tactical nature of DTDM requires interconnectivity of distributed resources and decision makers in an environment of uncertain and restricted communications where the composition of resources may change drastically as command or casualties dictate. This open

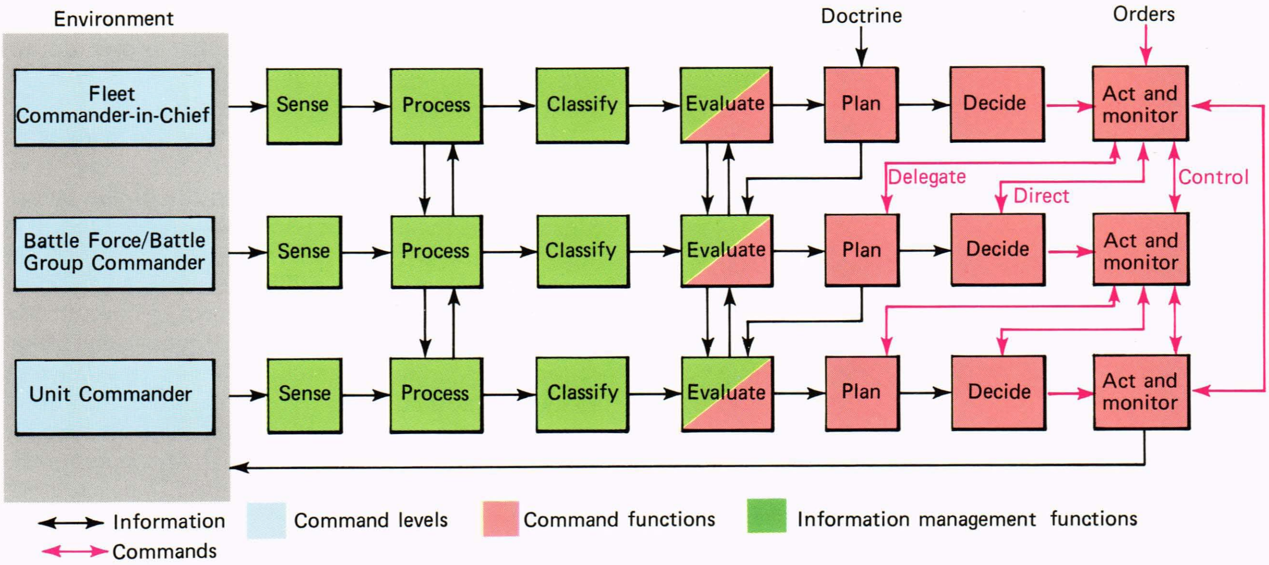

Figure 2—Functional model of the command and control process.[7] Each commander plans, decides, and acts on the basis of inputs from the sense, process, classify, and evaluate functions, from the existing doctrine, and from the orders promulgated by higher level commanders. The decision of the commander may be to delegate authority for a particular action to a subordinate commander (who can then do his own planning), to direct his activities using operational plans or orders, or to control his actions with specific orders. At the same time, the commander (or his staff) monitors the execution of the plans and orders. The actions taken at each level affect the environment, even though only one feedback loop is shown here for simplicity. The resulting events are sensed by the existing system, starting the new flow through the model. Thus, C^2 is a closed-loop process with multiple tiers of interrelated functions and multiple feedback loops.

system thus requires networking of control and information so as to optimize coordinated tactics and error-free exchanges in a dynamically reconfigurable environment.

A reasonable model of open systems interconnection processes that we are using in our investigation is the Open Systems Interconnection model (Fig. 3) developed by the International Standards Organization.[9,10] That model, like the Rasmussen and Year 2000 C^3I models, is a hierarchical process model that has been used successfully to build systems providing reliable interconnection and control of computer processes and reliable exchanges of information in an open system of peers. In a direct extension of these ideas, we are exploring the viability of layered protocol structures to coordinate control and communications in DTDM.

Another potentially strong benefit of using the Open Systems Interconnection approach is in the area of knowledge-base reconstitution (following loss of a node) or reconfiguration (following loss of the computational capability of a node). We are addressing those issues in our analysis of knowledge representation in the composite psychological, computational, and communicative processes by examining information storage and flow requirements for selected distributed decision-making events.

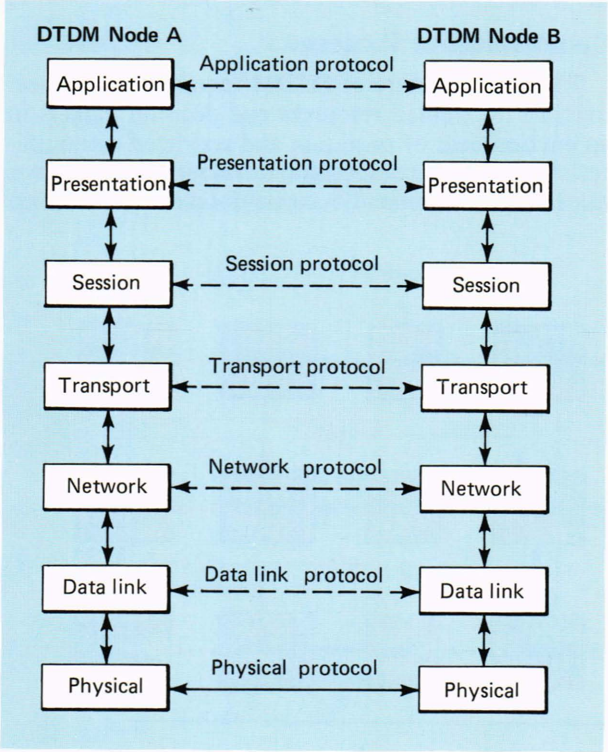

Figure 3—Network architecture.[9] In this layered network architecture, which is based on the International Standards Organization Reference Model of Open Systems Interconnection, a layer has been created where a different level of abstraction is needed. Each layer performs a well-defined function, with layer boundaries chosen to minimize information flow across interfaces. Protocols are defined at each layer to support communications among host nodes at the several levels of abstraction that are represented. (Dashed lines identify virtual or apparent connections; solid lines identify actual or physical connections.)

Knowledge Elements

Our approach to the acquisition, representation, and utilization of knowledge is described in the following sections (see also Ref. 11). Of course, knowledge acquisition, representation, and utilization interact symbiotically, so they must be pursued together.

Knowledge Acquisition. In order to identify and classify representation requirements in terms adequate for defining measures of effectiveness, representative DTDM events are being exercised in controlled interview settings. Because tactical knowledge is largely situational in nature, we pose structured tactical problems to our subjects in order to have a framework within which to elicit their expertise and in order to be able eventually to make comparisons (across decision makers) among their responses in an organized quest for common structures in their decision processes. Existing tactical problems developed at APL are used when possible, and consideration will be given to using problems or scenarios available from Navy laboratories, schools, and other facilities. New scenarios are devised as necessary to meet research requirements and goals if available ones do not meet our needs.

Along with the use of such tactical problems is the use of a computer-based scenario generation, interview, and simulation system that we have developed to acquire and exercise knowledge from experienced tactical decision makers. The associated interview techniques are aimed at eliciting responses about what they are doing and thinking in the course of solving problems and making decisions. The interviews do so in such a way as to be able to derive both explicit and implicit interpretations of the knowledge and processes being used to perform the tasks. We are aware that people do not necessarily do what they think or say they do when solving problems and making decisions.[12]

Knowledge Representation. There are many ways to represent knowledge. Each approach is based on assumptions about the qualitative nature of the knowledge and the mental processes to be represented. It is therefore necessary to determine the nature of the knowledge that a system will be expected to use before decisions can be made about the system architecture and the best way to represent the knowledge within that architecture.[13,14] Our research addresses this issue by analyzing knowledge structures obtained in the knowledge acquisition phase (above) and their relationship to the psychological, computational, and communications process models described earlier. It also addresses the issue in terms of a priori structures derived from relevant psychological literature on the organization of memory for problem solving and decision making.

Candidate psychologically based representation structures include semantic association networks; strict and "tangled" hierarchical taxonomic structures; contextual schemata or "frames"; "script" representations; a skill-, rule-, and knowledge-based human performance model; a "cognitive architecture" form of representation; production rule structures; procedural structures; and various mixtures of these and other such structures. Many of the psychological models have current examples in computer software systems developed by psychologists and computer scientists in the course of their research. The availability of such systems can facilitate the conduct of laboratory and field experiments designed to examine the effects of alternative structural representations of knowledge on problem solving and decision making.

Central to our concept and purpose is the representation of the knowledge of multiple decision makers within the same decision-aiding system framework. Analysis and experimentation must determine which aspects are shared among decision makers and which are idiosyncratic. This dimension of decision-making performance may be a significant factor in establishing a basis for a distributed command decision-aiding system of the kind we have described. We expect that analysis along these lines will yield identifiable qualitative components of the decision processes involved and that some of the components will be quantitatively measurable. The identification of such components should lead to the development of criteria for objective measures of decision-making performance that can be applied within our interview system and, perhaps, to a more general context of decision-making performance analysis in other systems. Objective measures and well-defined component DTDM processes would define benchmarks that could be used by researchers for comparative analyses.

Knowledge Utilization. Knowledge represented throughout a distribution of tactical command nodes for DTDM can be partitioned into local and external knowledge elements. Under the assumption that optimal processing efficiency and accuracy will result when common knowledge structures and processes are used for both local and external knowledge elements (as in the Naval Tactical Data System), we are using them to acquire, represent, and employ knowledge elements in our composite processing model and in our interview system.

Because the value of knowledge is judged by its use, we are concerned with individual and composite knowledge structures (i.e., knowledge elements correlated and combined from several units to form a composite "picture" of an event) that are most amenable to DTDM via separate psychological, computational, and communicative processing. Interactions with tactical experts in our interview system will continue to provide insights in this area. If we can identify knowledge representation formalisms amenable to the major processing models, we plan to extend our tactical analyses to address specific decision-event representations and performance measures.

PROGRESS

The following sections describe our progress after one year of effort on the theoretical framework, the experimental environment, and software and hardware issues.

Theoretical Framework

We have developed a composite process model to describe DTDM in terms of psychological, computational, and communicative processes that are interrelated functionally in three levels of decision-making abstraction. In Table 1, decision making, monitoring, and actuation are modeled for each node in an open system of decision-making peers. The functions depicted for each process area are organized into three levels of abstraction. For example, rule sets, computational evaluation, and communications session management functions have been classified at a level of abstraction labeled "integrated man/machine procedures" for the purpose of knowledge representation and information flow analyses. The selection of the three levels of abstraction to organize all DTDM processes reflects a first approximation to the psychological processes and an underlying assumption that computational and communicative processes will be subordinated to human problem-solving procedures. The placement of computational and communicative functions within each level reflects our current best estimate regarding the ability of humans, computers, and network communications systems to perform the functions alone or in some combination.

Borrowing from the Open Systems Interconnection model for computer networking, the DTDM environment may be viewed as an open system of decision-making and tactical-control nodes that are interconnected via physical and virtual protocols or as general procedures known and used by all DTDM peers. For example, the collection of standing orders issued by a commander to his watch officers constitutes a set of protocols. Similarly, the computational functions to monitor events associated with watch officer duties and the communications functions to support interactions among watch officers of different units constitute protocols at lower levels of abstraction.

Tactical decision functions of planning, monitoring, and performance of planned activities may be divided under this approach into protocols specified by the decision maker. Continuing the Open Systems Interconnection convention, such protocols would be a complete specification of procedures at one level of abstraction and would mask any interlevel interactions among protocols at other levels.

In order to specify decision functions within protocol levels, but with a greater range of action in an open system of decision-making nodes, we have adopted the use of "agents." The concept of an agent is an idealized combination of the computer science concept of agents interacting via messages in a distributed processing environment and the concept of a human operator of specified functionality. DTDM agents thus defined may function autonomously (and concurrently) to perform authorized actions involving objects identified as appropriate to them by senior agents or decision makers. To fully accommodate agent activities at the three levels of abstraction in our composite model, agents may be defined functionally as fully au-

Table 1—Illustration of DTDM representation requirements.

DTDM Protocol Levels	*Psychological (Rasmussen[4])*	*Computational (Year 2000 C^3I)*	*Communicative (Open Systems Interconnection)*
Human-directed activities (human and computer agents)	Goal-based interpretation and planning	Act and monitor	Application
		Decide	
		Plan	
			Presentation
Integrated man/machine procedures	Rule sets	Evaluate	
			Session management
		Classify	Message transport
			Network routing
Automatic	Skill-level processes	Process	
			Data link
		Sense	
			Physical

tomatic, semiautomatic (some functional combination of human and computer processes), or manual. The physical instantiation of an agent under this definition is an attribute assignment that may affect the performance level of the agent but does not affect its functional definition.

Using this concept of protocols and agents, the distributed decision-making process of any commander may be characterized as a collection of protocols composed of a combination of agents that perform local planning and monitoring functions through interactions with other agents at other nodes in an open systems communications architecture.

We hypothesize that knowledge representation and information flow requirements for DTDM may be determined in this approach by analyzing requirements for knowledge and information processing for a set of agents that are structurally and functionally defined in terms of internode activity. We are continuing to elaborate on this hypothesis and plan to test it.

Experimental Environment

This discussion of our experimental environment includes developing the interview system, interviewing experienced tactical decision makers, and defining and testing agents to carry out tactical plans.

Interview System Development. In order to model and test DTDM processes, we have developed a three-node computer-based interview and test system (refer to the block diagram in Fig. 4). With it, Navy DTDM conditions within validated scenarios may be simulated concurrently at each node (but with experimental control of information for each node). The nodes may represent any triad of decision-making peers, but our research objectives continue to focus on mission requirements defined for antiair, antisubmarine, and antisurface warfare area commanders (AAWC, ASWC, and ASUWC, respectively).

The environment consists of simulation and control programs operating on a VAX 11/780 computer and separate interactive mechanisms for the experimenter or test subjects to specify initial problem conditions, knowledge representation, and decision-making processes.

Using a rule-based system known as YAPS (Yet Another Production System), which is coded in Franz LISP and was developed at the University of Maryland, we have instantiated different knowledge bases as unique programming "objects" to model distributed decision-making protocols directly.

Interviews of Tactical Decision Makers. In coordination with other analysts, we have identified relevant and valid tactical scenarios to support our DTDM interview and test process. To achieve maximum benefit of the analysis and display capabilities of APL war-gaming facilities, we further refined the set of candidate DTDM scenarios to those also being used in the APL Warfare Analysis Laboratory, thus reducing the need for pretest DTDM scenario analysis and extending the utility of Warfare Analysis Laboratory displays (hard-copy plots and listings) and analysis products to the DTDM project. This association with the Warfare Analysis Laboratory also promotes greater efficiency in our experimentation because personnel involved in war-gaming projects that may also be DTDM subjects will already be familiar with specific test scenarios.

The scenario selected for initial DTDM interviews involves a Blue task group (without a carrier) in wartime opposition to a Red task group in the Indian Ocean. The scenario was recently used in the Warfare Analysis Laboratory to examine cruise missile engagements and was selected for the DTDM project because

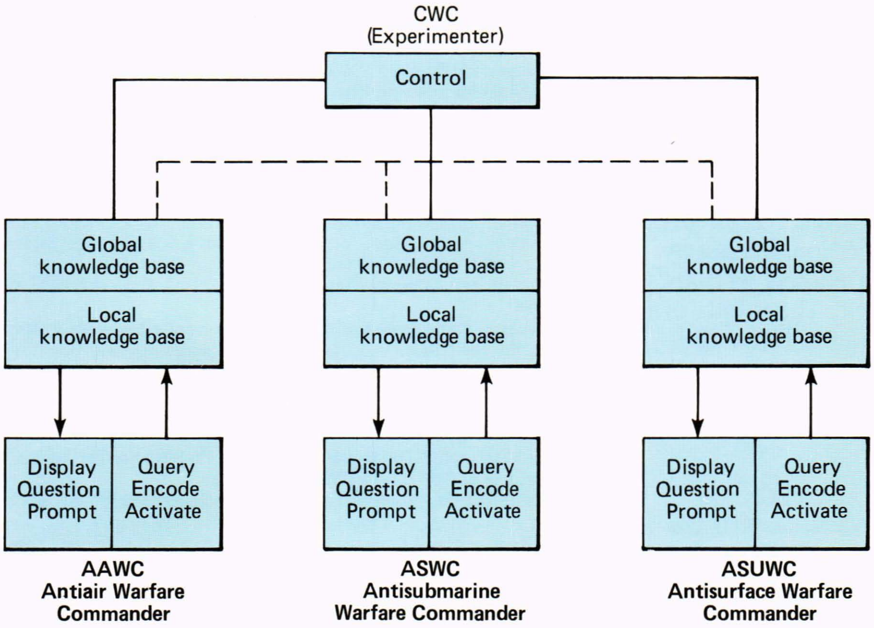

Figure 4—The DTDM interview/analysis system. Three (or more) distributed nodes, linked directly to a control node and indirectly via interruptible communications to each other (dashed lines), support scenario-based interviews with experienced tactical decision makers. Each node can serve a human decision maker as an interactive terminal with access to local and global databases through a structured man/system interface or it can function as a simulated decision maker operating on the basis of rules and knowledge structures obtained through interviews with human decision makers and represented in system software. The system thus supports both the interview process and the analysis and testing of interview protocols.

of the small number of units involved and the relative uniformity of mission requirements for the ASW, ASUW, and AAW areas. In addition, the special emphasis in the Warfare Analysis Laboratory on mission planning for this scenario is most opportune in that our initial interest in the DTDM effort is in planning processes and protocols for the actuation of plans.

Our analysis process begins with each subject being presented the necessary information from the Officer in Tactical Command for him to perform the duties of a warfare area commander. The information consists of fixed specifications of

- Intelligence estimate
- Mission of the force
- Officer in tactical command concept of operations
- Environmental conditions
- Resources of the force assigned to the subject decision maker

The subject is asked to prepare a plan for fulfillment of his responsibilities as a specified warfare area commander. Planning elements developed by the subject are examined in concert with the experimenters to identify protocols for the planning, monitoring, and actuation functions.

Agent Definition and Testing. As part of the development of his plan, each subject is asked to define the agents he requires to ensure appropriate and timely activation and observance of his plan. For example, the functions that an AAWC might authorize a staff watch officer to perform in his absence or in time-critical situations might define an agent at the highest level of abstraction of psychological processing.

The next step is for the subject's plan and agents to be instantiated in the interview and test system in the form of displays, rule sets, and algorithms as appropriate to the human-directed activities, integrated man/machine procedures, or automatic protocol levels. The agents defined by the subject will be instantiated insofar as possible in unique object-oriented production systems, with the activation event for each agent incorporated within an overall control structure. For example, a low-level agent defined as the mechanism that ensures that incoming Flash messages are immediately brought to the commander can be defined as an independent rule set that is activated every *n* seconds to examine incoming message traffic or is activated only on receipt of a Flash message.

Given the plan and agents specified by the subject, the subject's decision-making processes can then be stressed by exercising the plan and agents in controlled tactical scenarios that are representative of general tactical mission requirements. In order to focus our limited resources on issues most relevant to distributed decision processes, we constrain in-depth analysis of agent processes to the subset of agents clearly requiring interaction with agents at other nodes.

Some scenarios will present opportunities for synergistic cooperation among different decision makers' agents with respect to warfare-area requirements, while others will present conflicting mission requirements. The effectiveness of various agents under several conditions will be observed and, where possible, measured against criteria derived from our taxonomic framework, including skill-, rule-, and knowledge-based processes in the psychological, computational, and communicative aspects of tactical decision making.

Testing for conditions involving DTDM conflict or opportunities for synergy is further accommodated in the concurrent activation of all three nodes of the experimental environment; decision-making processes are activated at each node by different subject/experimenter combinations or by using agent rule sets at one or more nodes.

CONCLUSION

We have described an ongoing research effort to elucidate the fundamental psychological, computational, and communicative processes involved in the coordination of problem solving and decision making by multiple peer-level tactical decision makers who are spatially and electronically separated. The results of our investigation should provide useful guidance to decision-aiding system theorists and designers as well as to other researchers in distributed tactical decision making.

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