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Analysis and modeling of information flow and distributed expertise in space-related operations

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Abstract

Evolving space operations requirements and mission planning for long-duration expeditions require detailed examinations and evaluations of information flow dynamics, knowledge-sharing processes, and information technology use in distributed expert networks. This paper describes the work conducted with flight controllers in the Mission Control Center (MCC) of NASA's Johnson Space Center. This MCC work describes the behavior of experts in a distributed supervisory coordination framework, which extends supervisory control/command and control models of human task performance. Findings from this work are helping to develop analysis techniques, information architectures, and system simulation capabilities for knowledge sharing in an expert community. These findings are being applied to improve knowledge-sharing processes applied to a research program in advanced life support for long-duration space flight. Additional simulation work is being developed to create interoperating modules of information flow and novice/expert behavior patterns.

Keywords: Mission control; Group dynamics; Information technology; Supervisory control; Knowledge sharing; Task coordination

1. Introduction

Distributed sources of human expertise, equipment, and computer processing capability have become the hallmark criteria of a new era of collaborative project management, engineering system control, and scientific research. Physically distinct components, people, and support technologies linked by information and computing technology (ICT) systems are the most effective way to conduct large-scale and multidisciplinary research, where single sites simply cannot acquire the necessary data, and single investigators cannot be expert in all areas of a multidisciplinary project. The complexity of advanced engineering technologies often outstrips the capability of a single operator to monitor or control; current systems also have requirements beyond the capacity of artificial intelligence interventions across the range of operational conditions and emergency response modes.

However, significant challenges remain after the infrastructure of the ICT network and identification and individual training of human task performers

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have been established. Real-time task performance, information flow, and knowledge sharing require synchronization and integration of information at multiple time scales and levels of integration among individuals, teams, and larger organizations. Despite major advances in computing technology and network bandwidth, it remains an unrealistic goal to expect zero delay in any real-world distributed network consisting of multiple team members. In addition, dynamic limitations in network or bandwidth availability (on time scales ranging from seconds to hours) can provide acute and intermittent impacts on collaborative performance, even if overall information flow capabilities remain high.

This paper addresses the critical components of information flow and knowledge synchronization among human experts. The primary work described in this paper summarizes the author's experience in analyzing information flow at several time scales in the Mission Control Center (MCC) environment of space vehicle operations. Further applications of the work address information flow requirements for a multidisciplinary research center developing advanced life support technologies for long-duration space flight. The results of this work will help to define, inform, and expand information architecture requirements that will provide improved ICT support of MCC operations, with particular emphasis on information flow that is robust with respect to:

- *Delay*: knowledge of and response to the world cannot be exchanged instantaneously due to transmission delays, sensemaking tasks, and control lags;
- *Operational evolution vs. system design*: continuously operational systems deviate from original designs, requiring improved understanding of current local system state;
- *Distributed expertise*: local and remote experts must be able to exchange critical context information, and trade off timing, knowledge, control capability, and other resources and constraints.

Unavoidable delays in information availability become an inescapable element of the coordination effort, made more complex by the multiple sources of delays influencing the research team in distinct ways. Delays may be due to limitations in physical resources (lack of sensors at all appropriate sites, energy flow constraints), or transmission limits. In addition, logistic issues (time zone, travel, or other schedule constraints limiting immediate contact) may prevent immediate access to the appropriate source of expertise. Even once contacted, delays are associated with researcher awareness and "sensemaking" (time required to understand and interpret incoming data), and knowledge sharing (expertise of one researcher being communicated effectively to other researchers, especially when controversial or challenging interpretations are proposed).

2. Information flow, knowledge sharing, and distributed supervisory coordination

Individual-based human control of engineering systems has been a long-standing research in human factors and ergonomics. The information flow work in this paper represents an expansion of fundamental human–system interaction research in the area of manual control [1,2], as well as teleoperations and human supervisory control [3,4]. The concept of Distributed Supervisory Coordination (DSC) extends this research, both in terms of number and coordination requirements of human task performers, and the time scales and complexity of coordination activities.

Supervisory control models examine the role of human–systems interfaces (HSI) to provide effective human performance and task control in complex engineering systems. In traditional supervisory control models, the emphasis of the HSI design is to provide seamless manual control capabilities across a range of system dynamics, including gain, delay, and complex matching of sensor inputs and actuator outputs to human perceptual and sensorimotor capabilities [5,6]. A complex engineering design problem exists because the human supervisory controllers must be able to simultaneously manage their knowledge of the world-at-a-distance being controlled, as well as their knowledge of the HSI dynamics to perform required tasks (see Fig. 1).

The DSC concept extends this framework in two important ways. The HSI emphasis of human supervisory control assumes that the output of the human supervisory controller is directed to an engineering component, primarily a robotic or other automation component. In distributed human collaboration, the out-

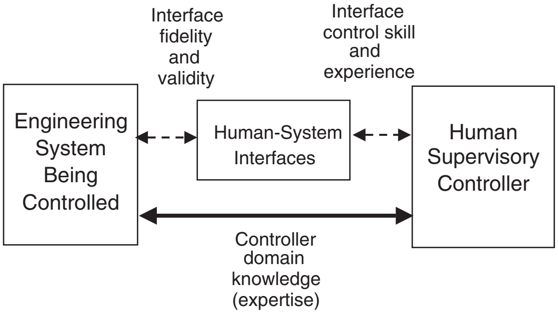

Fig. 1. Simplified model of human supervisory controller interactions and information flows.

put of any individual's interactions may be directed to another individual (human communication) as well as automation. Although network and coordination research [7–9] may refer to these forms of information flow interchangeably as actor–actor communication, it is clear that current generations of automation do not have the capabilities or limitations of cognitive processing which are expected in human–human communication. Therefore, human–automation interactions remain distinct in information flow dynamics, expectations, and coordination capabilities from human–human interactions.

The second extension attributable to DSC is that the focus of task performance is not simply manual control of physical components, or group-level decision making, but a range of strategic, operational and tactical performance tasks in both cognitive and physical domains of performance [10,11]. Therefore, communication between members of a DSC network share knowledge and understanding of the world based on varying levels of expertise, interactions with distinct or overlapping engineering components, and availability of shared as well as individual information, in addition to distinct "spans of control" or decomposed functional demands as described in human supervisory control paradigms [12–19]. See Fig. 2 for a graphic representation of the DSC problem.

3. Information flow issues in mission control

In the MCC environment, information flow occurs through a variety of communication paths based on a set of events that describe actions (changes in state of engineering system components, software processes, or human cognitive activities), or interactions (commands to distributed sensors/actuators, network data exchanges, conversations between experts, or human interactive controls of engineering components). MCC coordination is led by the Flight Director, who is responsible for the overall completion of mission objectives and effective coordination of the MCC team of flight controllers. Communication support for flight controllers involves exchange of time-sensitive engineering system domain expertise, maintenance of necessary communication paths, strategic coordination, and management of shared information and knowledge synchronization. This latter function, of network knowledge management and support for information sharing, is centered in the Ground Controller console in the flight control room of the MCC.

MCC communications take place using a proprietary ICT design known as the digital voice intercommunications system (DVIS), which allows a member of the flight control team (FCT) to listen to multiple communication channels (with their associated voice traffic) simultaneously, in order to support the DSC tasks of managing the spacecraft. These team collaborations and distributed ICT networks differ from traditional supervisory control (command and control) systems in two significant ways. First, it cannot be assumed that the locus of expertise and control remains fixed throughout the task. Second, the task constraints and performance demands do not permit strict control of all critical task parameters, requiring additional focus on adaptation and modification of plans based on emerging events and new knowledge.

From a purely technical perspective, astronauts and MCC-based flight controllers must coordinate activity to maintain the effective functioning of an extremely complex engineering system. Traditionally, between 18 and 24 primary (front room) controllers are supported by dozens of additional technical (back room) support personnel in the system management, control, troubleshooting, and performance enhancement of the space vehicle. During the early years of the NASA space program, almost all space vehicle functions had to be controlled from the ground, describing a more traditional supervisory control paradigm [3]. With the increasing complexity of the space vehicle, the expanding range of mission activities, and the enhancements in computing power and miniaturization,

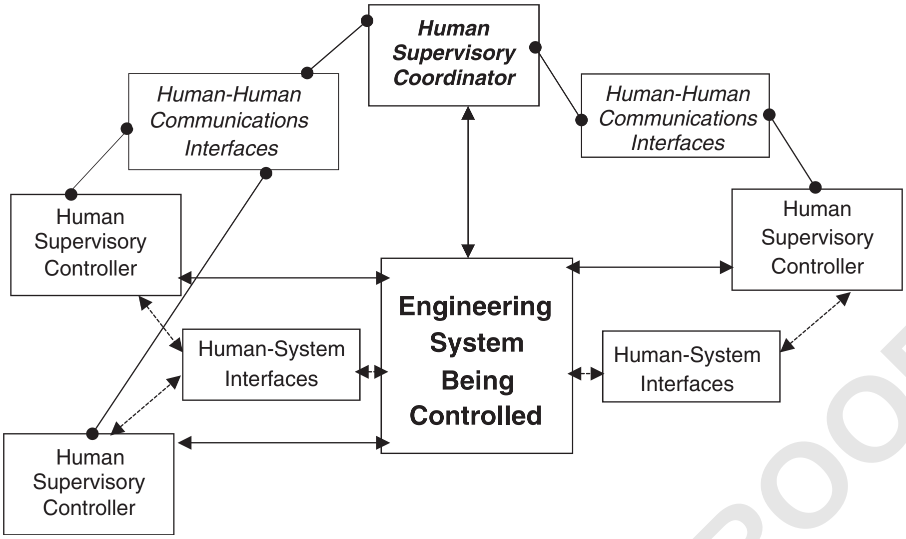

Fig. 2. Distributed supervisory coordination problem. Note the addition of communication interfaces and additional coordination roles of coordinator.

the roles and responsibilities of the MCC controllers have changed with respect to members of the astronaut crew.

The training and flight qualification process for a controller may, in some elements, rival that of the astronaut: between 2000 and 2002, it is estimated that only approximately 30% of those who begin the 3-year training process of moving to the “front room” will succeed in their efforts. Because of the professional status of astronauts, and the distribution of expertise and information among controllers, the concept of Supervisory Control is not strictly applicable to the MCC—crew setting. The Flight Director is responsible for coordinating, soliciting, and utilizing the expertise of the MCC controllers, who are in turn responsible for various technical domains and coordinating the activity of more specialized back room support personnel–all in real time.

A special member of the MCC-controller team is known as CAPCOM (Capsule Communicator, derived from original references to the Mercury astronaut orbital vehicles as “capsules”), and is responsible for communications with astronaut crew members on board the space vehicle. CAPCOM holds a unique place in several respects: the CAPCOM console position in the MCC is always next to that of the Flight Director, showing its critical importance to controller–crew coordination. CAPCOM is also always another astronaut, thus attempting to bridge the MCC–crew differences in group membership and task role, and providing unique indication that astronauts are a distinct and autonomous group rather than simply distant or subordinate members of the controller team [20]. During task performance, CAPCOM is the only member of the MCC authorized to speak directly with members of the crew—even the Flight Director coordinates with the crew via CAPCOM.

DVIS must support communications between the MCC and the astronaut crew, between front-room controllers and back-room support personnel, and between controllers with distinct technical domain areas of expertise. In addition, the MCC facility itself consists of a number of individual computer displays that each controller uses for their own specialty, as well as shared displays for coordinated MCC awareness of vehicle status and mission activity. Thus, the DVIS and other ICT systems to support information flow in the MCC and between the MCC and the vehicle represent a separate engineering system (focused on data exchange, information flow, knowledge sharing, and expertise coordination) that operates in parallel with, and in support of, the space flight engineering

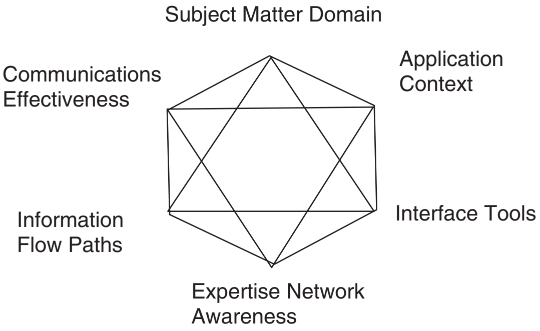

Fig. 3. Dimensions of expertise in distributed supervisory coordination network.

system of the vehicle.

Flight controllers must use these ICT systems to develop and enhance their understanding of vehicle activity, and to synchronize understanding and task performance with members of the on-board crew, resulting in a unique form of distributed supervisory coordination represented by combinations representing different critical dimensions of expertise (see Fig. 3). Please note that the different MCC domain expertise areas (e.g., electrical, propulsion, life support) are all represented in Fig. 3 as the "subject matter domain" dimension of expertise. The interface tools dimension represents the emphasis on human–system interfaces seen in Fig. 1. The communications and team synchronization skills required to move to a front-room position are described as "communications effectiveness" expertise.

4. Applications to research-based information flow

Tremendous advances in ICT tools and bandwidth capabilities have led to new opportunities for communities of researchers to collaborate to perform large-scale and/or complex analyses that exceed the capabilities of any one researcher or institution. These tools include multimegabit networks to support real-time video collaboration, high-speed transfers and distributed computing to process gigabyte-size and above analysis files, and integrated multisite relational and semantic database architectures. (By contrast, ICT capabilities between MCC controllers and astronaut crews remain limited to DVIS-style voice and modem-level data bandwidth levels.) The NASA life support science community is one environment where these trends are evident. Research teams and engineering and science students collaborate to develop "equivalent system mass" models to identify capabilities to support human habitation for up to 1000 days with no material resupply, to facilitate an expedition mission to Mars. An advanced life support (ALS) model consists of many-component systems with functional non-linearities, information uncertainties, and time-varying system parameters. ALS researchers, then, have an urgent need to utilize ICT networks to collaborate with each other and gain access to shared data and distributed physical facilities [21]. This need is specifically noted in a recent US government report of the President's Information Technology Advisory Committee [22]. Databases to support information flow and knowledge sharing between members of the ALS community (such as the Online Project Information System, OPIS: see <http://opis.arc.nasa.gov/>) are in active development and constant evolution.

The NASA Specialized Center of Research and Training for Advanced Life Support (NSCORT-ALS) is a complex supervisory coordination network to conduct advanced integrated development of ALS prototype technologies. The NSCORT-ALS effort requires the coordination of over 20 investigators, with a strong interdisciplinary mix of specialties, spread among three participating university campuses (Purdue, Howard University, Alabama A& M University). NSCORT-ALS represents an enterprise-level research colaboratory, requiring information flow and knowledge sharing at individual, group, and organizational units of aggregation, as well as resource coordination over multiple time scales and information integration requirements. (Even coordination of activity with respect to time has challenges. Howard and Alabama A& M are in the US Eastern and Central time zones; Purdue is located in a region which does not shift its clocks, and thus switches from Eastern time in the fall and winter to Central time in the spring and summer.)

The NSCORT-ALS program has included work to provide research coordination support for continuing cycles of knowledge development, capture, storage, and utilization. Individual researchers within a research colaboratory see this effort as facilitating their own work—defining information needs from other researchers, specifying formats for data exchange, and populating group collaboration and idea-sharing "virtual spaces" based on their own areas of expertise. In addition to the research documentation process, this shared information space provides an effective training ground for new generations of graduate students (D. Whitaker, personal communication, 26 February 2004). However, the development of a coordinated electronic environment to allow researchers to share these aspects of their work is a distinct technical discipline. Both the NSCORT shared resources and the OPIS database require dedicated IT professionals who are responsible for maintaining the information flow paths and knowledge-sharing process capabilities for the ALS research community participants. It is still an open question in the human factors, cognitive engineering, and user interaction design fields regarding how such dynamic repository functions should be supported, what types of user interfaces are best suited for those functions, and how operational experience is transformed into reference expertise and synchronized knowledge structures across multiple time scales.

Both NSCORT-ALS researchers and NASA program managers have expressed desires to define user information needs and data exchange requirements, describe information architecture structures for common data exchange capabilities, and evaluate current collaborative information and communication technology (ICT) implementations. These ongoing activities can be described in terms of a sociotechnical systems engineering analysis of information flow in dynamic environments. This analysis includes examinations of cognitive engineering, group and organizational dynamics of information sharing, and usability engineering of information and communication technology (ICT) systems. Note that the emphasis of this discussion is on the information exchange requirements to support task coordination for ALS systems integration, rather than the decision-making processes of option selection or risk assessment in technology evaluation.

One possible source of confusion for coordinating researchers and projects of this type is the interplay of different types of models operating at distinct levels of systems analysis. It is useful to distinguish *conceptual models* (representations of how systems are intended to interact), *functional models* (descriptions of physical interactions of critical flow variables, transformation processes, and input–output relations), and *analytical models* (mathematical calculations of how systems will behave over time). In addition, based on the MCC model, we distinguish the NSCORT-ALS into the *ALS Engineering System Simulations*, and the *Distributed Coordination Information Flow System*. The NSCORT-ALS effort is devoted to developing integrated ALS simulations, rather than creating an actual working prototype ALS. Thus, the focus of the NSCORT-ALS effort is devoted to the behavior of the Information Flow Network and Engineering System Simulation modules, as shown in Fig. 4.

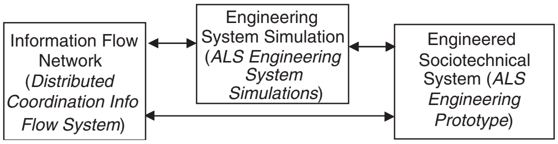

Fig. 4. Interaction of system descriptions and analysis emphases in multidisciplinary NSCORT-ALS research program.

Most models of information flow and coordinated action in "expert" networks emphasize coordination tasks between intelligent agents, and/or rational activity between human actors [23]. Relatively little attention has been paid to the description and modeling of information flow or behavior of knowledge sharing communities [24]. Thus, while significant (and legitimate) concern may be devoted to the effort of distributed *decision making* under task, information, and time constraints, this paper (and other author research as well as NSCORT-ALS task performance) examines the effort and demands to achieve effective distributed *resource coordination* (including knowledge exchange and information flow).

The NSCORT-ALS effort includes both research investigators conducting explorations of novel technology behaviors, and students engaged in design project-based learning activity. As of February 2004, a first-order engineering system simulation has been created, linking mass flows between human activities, plant and fish ecology, and proposed waste recycling technologies (operating in air, water, and solids flow pathways). Because the multiple research projects are at different stages of maturity, creative applications of prior knowledge from a variety of past studies are required to compensate for partial gaps in available data (J. Alleman, personal communication, 24 February 2004; D. Whitaker, personal communication, 26 February 2004).

Project teams in these contexts almost invariably consist of members with heterogeneous skill sets and disciplinary areas of focus ("distributed expertise") that must be integrated to achieve the highest quality project. Even colocated teams rely more heavily on ICT for sharing information, task products, and project plans. ICT use can overcome limitations of class and work schedules, particularly as project due dates arrive at term end. Distance education and multidisciplinary design course initiatives further complicate the team coordination and performance needs for engineering students and faculty. In these cases, distributed expertise and distributed availability of resources in team-based design projects become high-fidelity analogs to the research and production tasks of practicing scientists and engineers. As a result, the ability to effectively use ICT networks to support team coordination and project task performance becomes an essential skill to be developed in the context of engineering and science education.

5. Developing simulations of expertise networks

The author's work to describe a Distributed Supervisory Coordination model in an expertise sharing community is focusing on developing non-rational, non-normative (i.e. exploring the range of human behavior, rather than simply rational agent-based or economic-based performance) simulations of information flow. Currently, four simulation modules are envisioned, examining distinct aspects of expert community behavior, novice–expert transitions, and information flow processes. The modules represent the following types of information flow processes:

- *Asking*: novices bring queries to the community, which are then available to be answered by one or more experts, depending on complexity, comprehensibility, expert availability, and initial direction of the query (similar to "ask an expert" bulletin boards);
- *Learning*: novices become members of an expert community, and use existing experts and reference sources to develop expertise in a particular area while learning about the structure and processes of the community (exemplified in graduate school education);
- *Sharing*: a mixed group of novices and experts interact using shared ICT (such as a discussion list or chat room) to exchange information, perspectives, and social affiliation, rather than simply answer specific task-oriented questions;
- *Solving*: members of the expert community are responsible for monitoring and troubleshooting problems and are focused on effective task performance to maintain system functioning (such as in the MCC controller environment).

It is expected that component-based modules in each of these four areas can, when combined, produce robust simulation capabilities suitable for examining a very wide range of behaviors in a distributed supervisory coordination or expert community development setting. This set of capabilities to investigate information flow and task coordination processes at a variety of units of aggregation represents a significant advance in human performance modeling and analysis. The eventual capability to investigate information flow in analytical and predictive manners (what a group does, and what characteristics influence patterns of activity), rather than simply proscriptive ones (what a group should do, based on specific requirements and assumptions of actor behavior) addresses very high priority research needs identified in previous studies of organizational and human performance research [25].

Recent project activity has emphasized initial development of an Asking module, which has been coded in AutoMod 9.1, a manufacturing-based discrete event simulation package. Already, preliminary results indicate the influence of very basic assumptions (such as whether a novice knows whom within the expert community they should direct a query, the time lag between query initiation and expert response, or whether all queries go through a central source) on the overall behavior of the network over time. In our models, system activity examines numbers of satisfied and unsatisfied query requesters, patterns of non-responsive answers (the expert's response is not understood, or not relevant, to the novice's query), and in-process network patterns over time, rather than simply reporting summary outcome results.

Future efforts will require examination of both continuous and discrete model behavior, as well as the sensitivity of process flows to different distributions of information events, expert responses, and flow constraints. It has already been seen that the development of an expert information flow network description, and initial discussions of data exchange and knowledge-sharing information architectures, can significantly influence the coordination and task performance capabilities of the cooperative research endeavor. We expect that ongoing results will also indicate technology needs to support MCC system evolutions, and improved ICT capabilities to integrate human expertise, engineering system event analysis, and human–system interface enhancements to further improve expertise development and maintenance in the space operations environment.

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