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EXPLORING THE BOUNDARIES OF COMMAND AND CONTROL MODELS OF DISTRIBUTED TEAM PERFORMANCE IN AVIATION AND AEROSPACE OPERATIONS

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Traditional command and control (C2) models focus on a centralized command managing and directing one or more subordinate elements to perform required functions. However, in distributed C2 environments, a human commander has less ability to fully understand and control the behavior of "agents" (either human domain experts or autonomous automated systems) in real-time operations. In this paper, we explore the situational, information, and human performance issues that constrain the appropriateness of classical C2 system design, and highlight the need for distributed C2 information flow capabilities, in contemporary human-human and human-automation teams. We discuss these issues in the context of modern day aviation and aerospace operations.

Both organizational command and control (C2) structures and human supervisory control paradigms (including human-automation interaction architectures) are based on models of command information flow and agent behaviors in complex systems. C2 involves the functions of planning, directing, coordinating, and controlling operations to achieve organizational objectives (U. S. Department of Defense, 1994). Traditional C2 models focus on a centralized command managing and directing one or more subordinate elements to perform these functions. However, in distributed C2 environments, a human commander has less ability to fully understand and control the behavior of "agents" (either human domain experts conducting coordination tasks, or autonomous systems with increasing levels of on-board capabilities) in real-time operations. Thus, as modern systems continue to grow in complexity and scope, a greater need has emerged for C2 models that flexibly adapt to task and situational constraints. Accordingly, in this paper, we explore the situational, information, and human performance issues that constrain the appropriateness of classical C2 system design, and highlight the need for distributed C2 information flow capabilities, in contemporary human-human and human-automation teams. We discuss these issues in the context of modern day aviation and aerospace operations (e.g., unmanned aerial systems, long duration spaceflight missions).

Command and Control of Distributed Expertise

Distributed team members share knowledge and understanding of the world based on varying levels of expertise in a variety of specialized domains, interactions with distinct or overlapping system components, and availability of shared as well as individual information (Salas, Cannon-Bowers, & Johnston, 1997). These distinct capabilities can be thought of as multiple dimensions of expertise, and not simply different levels of expertise in a single subject matter area (Caldwell, 2005). However, distributed expertise may alter coordination within the C2 structure in that the 'commanded' agents may have a different understanding of the situation as well as unique capabilities for processing current information and integrating system status information. Such agents may be able to develop independent or superior awareness, execution parameters, or updated evaluations of task requirements that might make obsolete a commander's orders. This problem is exacerbated when dealing with large teams consisting of teams of teams, as often found in military network-centric operations (e.g., Gorman, Cooke, & Winner, 2006).

Of particular interest in such domains is *communication efficiency*. This concept reflects a process of determining when meanings are shared or not, and then being more explicit in a reference to a term with differing meanings across members of a functioning team. Unfortunately, in distributed teams, such unshared meanings may not be visible, as each team member may be clear on their own meaning, and unaware that others also have a clear understanding--but not of the same meaning (e.g., "positive feedback" has a negative connotation for a controls engineer, but a positive connotation for an industrial / organizational psychologist) (cf. Qureshi & Vogel, 1999). In aviation, dynamic, fluid teams benefit from a strong, shared, and generalized professional, operational, and cultural training process, and thus, this would be expected to facilitate communication efficiency. For example, flight crew can refer to the same shared training processes and patterns of implicit meanings from working at the same airline with the same organizational culture and training programs. However, in spaceflight operations, involving individuals with a broad and diverse range of training, specialization, experience, and cultural background, the challenge becomes how to enable a distributed team of experts to perform successfully as a distributed expert team (cf. Stagl et al., 2007).

As the complexity of both the operational scenario and the organizational architecture increase, the classical expectations of a commander capable of directing and anticipating the needs and instructional demands of each commanded agent become less viable. For instance, the structure of a spaceflight mission control team consists of multiple flight controllers, each with his or her own technical subsystem domain. This group of technical subsystem controllers is integrated by controllers with responsibilities for shared displays and computer systems (translating incoming data to synchronized information presentation) as well as Flight Directors responsible for coordinating the technical subsystems to achieve strategic goals (translating information to shared knowledge) (Caldwell, 2000; 2005). This model represents a coherent functional architecture that allows for coordination of multiple domains of expertise, any one of which may achieve greater detailed local awareness than the supervisory Flight Director. As will be discussed in the next section, C2 of distributed expertise is further complicated when the commanded agents are both human and non-human entities.

Information and Communication Technology in C2 Operations

The integration of information and communication technology (ICT) into C2, as evident in aviation, aerospace, and military network-centric operations, has resulted in the increased prevalence of human-automation teams, comprised of both human experts and expert automated systems. This creates unique challenges that must be overcome to ensure effective coordination among distributed members. A socio-cognitive perspective emphasizes that human operators' beliefs about and trust in automation dictate their subsequent reliance on automated systems (such as intelligent agents or decision support systems), ranging from the extremes of over-reliance and complacency to under-reliance and mistrust (Cuevas, Strater, Caldwell, Fiore, & 2007; Lee & See, 2004). Fortunately, this issue can be addressed through adequate training regarding the automation's functional capabilities (e.g., reliability) and limitations (e.g., effects of contextual factors) as well as through appropriate system display design (i.e., information presentation in terms of content and format) (Lee & See, 2004). Furthermore, true 'collaboration' in distributed human-automation teams is somewhat at odds with classical C2 models. In modern human-automation teams, the automated system (e.g., intelligent agent) can be viewed as a true partner collaborating with human experts and not simply a directed entity or useful collaboration tool (Cuevas, Fiore, Caldwell, & Strater, 2007). The integration of ICT in human-automation teams, therefore, is enabling a type of flattening or upward flow of information that would not be possible in traditional C2 architectures.

To illustrate, ICT, such as web-based C2 systems, supports military operations by allowing commanders to engage subordinate leaders and staffs in collaborative planning and decision making at all levels within units (Riley, Endsley, Bolstad, & Cuevas, 2006; U. S. Army, 2001). By supporting these critical processes, this technology enables commanders to reduce decision cycles within their organizations. Web-based C2 systems also facilitate the rapid dissemination of orders based on the commander's decisions to the lowest levels, thus maximizing time available for tactical units to prepare for, synchronize, and initiate decisive action. However, the limitations associated with the ICT used may significantly influence effective communication and coordination among distributed team members. For example, studies on computer supported collaborative work and groupware have highlighted both the benefits and potential drawbacks of introducing new ICT into distributed team interactions (e.g., Nunamaker, 1997; Olesen & Myers, 1999; Qureshi & Vogel, 1999). In particular, one perspective is to categorize human actors in terms of either users of ICT or those that structure the ICT for the users in the process of technology-use mediation (Orlikowski et al., as cited in Olesen & Myers, 1999). Structuring the ICT involves adapting the new technology within the context of use to facilitate integration into the organization as well as modifying the context, as appropriate, to accommodate the use of the new technology. Thus, changes in technology may force teams to restructure the patterns of information flow among members as well as the nature of their work (Mcgrath, Arrow, Gruenfeld, Hollingshead, & O'Connor, 1993).

In aviation and aerospace operations, the ICT available to distributed team members may also differentially influence team interactions and information flow. As an example, interest in using unmanned aerial systems (UAS) for a broad range of purposes is increasing at an unprecedented pace, making integration of UAS into the National Airspace System a priority for the Federal Aviation Administration. Modern day UAS include significant technological advances, blending automation with dynamic, decentralized control. In particular, UAS have fundamentally different aircraft control and communication architectures from manned aircraft due to the remote pilot location. Thus, a critical challenge facing the UAS community is to develop ICT that enables operators to interactively manage the flow of information from UAS with varying levels of autonomy while also facilitating collaboration with other UAS teams and support personnel. One area of particular interest is developing, testing, and fielding a C2 architecture for increasing multiple UAS control capability. Supporting this capability will require technology that facilitates seamless transitions between automation levels, situation assessment aids, and distributed teaming (Fern et al., 2011).

Within the context of spaceflight, given the task demands and system dynamics of NASA Mission Control Center operations, it is impossible for a unitary centralized C2 structure to effectively perform the required tasks to achieve mission success (Caldwell, 2000). Multiple ground personnel (e.g., mission control operators, research scientists, and other space mission support personnel) must communicate information and coordinate their efforts, not only among each other but with the astronaut crewmembers in space. Further, technological advances that have made possible longer duration manned missions, such as human exploration of Mars, have also brought about a concomitant push to reevaluate the concept of crew autonomy versus ground control (Kanas, 2005). For example, for long duration spaceflight requiring higher levels of crew autonomy, the role of the Mission Control Center may transition to that of Mission Support Center; Earth-bound ground personnel would take part in strategic and tactical mission planning and mission evaluation activities, and planetary explorers would be responsible for execution-level mission planning and mission execution (Grant et al 2006). In this domain, a more decentralized C2 architecture would be more practical and personnel require ICT that can enable these decentralized operations. Thus, ICT must effectively support the range of information flow processes and coordination activities (e.g., information exchange; coordination of distributed expertise) required by personnel, both on board the spacecraft and in the Mission Control Center, to perform their tasks safely and efficiently (Caldwell, 2006).

Conclusion

As organizations continue to evolve and integrate even more advanced ICT capabilities, traditional models of C2 must similarly mature in order to flexibly adapt to the challenges faced by distributed expert teams comprised of both human experts and expert automated systems. A critical challenge is ensuring that human operators have an accurate and complete understanding of the capabilities and limitations of supporting information technologies (Cuevas, Fiore et al., 2007; Strater et al., 2011; Strater et al., 2012). Equally important is recognizing how the integration of advanced ICT into C2 operations alters information flow and management. For example, web-based collaborative tools may actually circumvent the ability to conduct a strict C2 chain of information flow by making more paths of communication open with less control by centralized commanders. Additionally, the shift to new information flow capabilities may require a concurrent shift and re-prioritization of tasking to match operators' level of knowledge and experience with such systems (Caldwell & Cuevas, 2008; Caldwell, Palmer, & Cuevas, 2008). The continued evolution of C2 organizational architectures to include increasingly sophisticated information systems requires identifying and addressing the effects these changes will have on technology-mediated information flow and team coordination.

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