1.11 Cognitive Systems Modeling and Analysis of Command & Control Systems

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Abstract. Military operations, counter-terrorism operations and emergency response often oblige operators and commanders to operate within distributed organizations and systems for safe and effective mission accomplishment. Tactical commanders and operators frequently encounter violent threats and critical demands on cognitive capacity and reaction time. In the future they will make decisions in situations where operational and system characteristics are highly dynamic and non-linear, i.e. minor events, decisions or actions may have serious and irreversible consequences for the entire mission. Commanders and other decision makers must manage true real time properties at all levels; individual operators, stand-alone technical systems, higher-order integrated human-machine systems and joint operations forces alike. Coping with these conditions in performance assessment, system development and operational testing is a challenge for both practitioners and researchers. This paper reports on research from which the results led to a breakthrough: An integrated approach to information-centered systems analysis to support future command and control systems research development. This approach integrates several areas of research into a coherent framework, Action Control Theory (ACT). It comprises measurement techniques and methodological advances that facilitate a more accurate and deeper understanding of the operational environment, its agents, actors and effectors, generating new and updated models. This in turn generates theoretical advances. Some good examples of successful approaches are found in the research areas of cognitive systems engineering, systems theory, and psychophysiology, and in the fields of dynamic, distributed decision making and naturalistic decision making.

1.0 INTRODUCTION

According to Ref. [1], forces deployed in future expeditionary Crisis Management Operations (CMO) will need to rely on extraordinary capabilities to operate in austere and distant theatres of operations, on interaction and collaboration within and between different organizational cultures, between people with different backgrounds, education and experience, and on managing and maintaining technological and doctrinal effectiveness and interoperability.

CMO – be they military missions, counter-terrorism or emergency response – comprise complex, laborious and dangerous tasks, requiring resolute and determined teamwork under extreme conditions [2]. Deployed units must also be able to operate independently and with little support while still ensuring operational security and mission efficiency without risking excessive resource depletion.

CMO teams incorporate numerous human and artificial team members, widely scattered across the whole theatre of operations. They can operate autonomously for certain time periods and in specific areas, but they are mostly forced to coordinate their actions very accurately with one another.

New technology will offer extensive support to every phase of CMO. The enormous potential of prospective high-capacity information processing and real time interaction in distributed, dynamic mission environments is yet to be fully exploited.

Additionally, success in future military and emergency response missions requires highly capable understanding, defined as *the perception and interpretation of a particular situation in order to provide the context, insight and foresight required for effective decision-making* [3], enabling every commander and operator to develop a comprehensive appreciation of the situation and a detailed system insight, leading to safe and efficient mission accomplishment.

Finally, the turbulent environment in which these units operate stresses the need for Organizational Agility (OA), defined as *“the capacity to be infinitely adaptable without having to change…The goal is to keep internal operations at a level of fluidity and flexibility that matches the degree of turmoil* *in external environments, a principle known as requisite variety."* [4]. This requires adaptive and versatile principles and concepts for Command and Control (C2) along with agile high-performance organizational structures, with broad and deep support from strategic, operational and tactical doctrine.

2.0 AN INTEGRATED COGNITIVE SYSTEMS MODELING FRAMEWORK

Highly capable Command and Control (C2) support is needed for omnidirectional, continuous interaction and information exchange between the executive level and the team-on-site. However, as Rochlin [5] and others have observed, the specific skills and properties that systems, managers and operators have to possess in order to yield optimal mission performance in such critical and uncertain situations are not easily identified. Hence, they are difficult to improve. *Action Control Theory (ACT)* [6] is a conceptual framework specifically composed to facilitate modeling and analysis of complex dynamic tactical systems and processes and of their states and state transitions.

The different research areas of ACT have until now developed along separate paths of evolution. Flach & Kuperman [7] concluded that it is essential to develop a unified and proactive approach in research and systems design for future warfare environments. ACT is a composite theoretical structure designed to generate comprehensive and robust models of systems, tasks and missions, supported by advanced experimental and measurement methods, and data analysis techniques. It can support complex, multi-level human-machine systems design in the military, aviation and emergency response domains [8].

2.1 Cognitive Systems Engineering

The area of Cognitive Systems Engineering (CSE) has grown at an increasing pace since the first significant contributions were published in the 1980s by Rasmussen [9; 10], who introduced the concept of skill-based, rule-based and knowledge-based behavior for modeling different levels of human performance. Hollnagel & Woods [11] made a significant contribution to this field by their definition of a Cognitive System (CS) as a Man-Machine System (MMS) whose behavior is goal-oriented, based on symbol manipulation and uses heuristic knowledge of its surrounding environment for guidance. A CS operates using knowledge about itself and the environment to plan and modify its actions based on that knowledge. According to Hollnagel [12], the definition has been revised over the years in order to comprise new findings in human-machine systems research and to cover a more comprehensive and fundamental set of system properties: what the system achieves, what objectives it serves and what its intentions are. The current CS definition is *a system that can modify its pattern of behavior on the basis of past experience in order to achieve specific anti-entropic ends* [12]. Military forces are often analyzed and modeled as aggregates of Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, Facilities and Interoperability (DOTMLPFI), all of which are elements of the total operational capability. Viewing this capability together with its operational context as a CS facilitates modeling and analysis with significantly greater breadth and depth.

2.2 Complex Dynamic Adaptive Systems, Control Theory and Cybernetics

From the work of Ashby [13], Brehmer [14] and many others it is well known that most complex systems have real-time, dynamic properties; the system output at a given time is not only dependent of the input value at this specific time, but also on earlier input values, and that a good regulator of a system has to implement a model of the system that is to be controlled. Put otherwise, Ashby's law of requisite variety [13] states that the variety of a controller of a dynamic system has to be equal to or greater than the variety of the system itself. By the term *dynamic system* is meant an object, driven by external input signals *u(t)* for every *t* and as a response produces a set of output signals *y(t)* for every *t* [6].

CMO possess highly dynamic and nonlinear operational system characteristics, i.e. small actions or decisions may have serious and irreversible consequences for the mission as a whole [15]. Modern literature describes the broader aspects of defense systems and CMO in terms of Complex Adaptive Systems (CAS) [16; 17] in the sense that crisis management forces or emergency response organizations demonstrate CAS properties, and identifies adaptive mechanisms at the levels of adaptive systems, capability development and collective/society, which adjust through learning, evolutionary development and cultural change to fulfill an externally imposed purpose.

The concepts of control theory and CAS can be used as metaphors in research on decision making, especially in multiple-player, dynamic contexts. The mathematical stringency and powerful formalism of control theory makes it possible to describe and analyze systems as diverse as technical, organizational, economic and biological systems. Orhaug's [18] notion that decision making constitutes the regulatory function in command and control processes strongly supports the control theory approach. This notion also supports the fact that the hierarchical command structures of military and emergency response organizations are strongly coupled to both centralized and distributed decision making principles [19]. Annett [20] used control theory to investigate team skills. Four fundamental requirements must be met [21; 22;12] if control theory is to be used in analysis and synthesis of dynamic systems:

1. There must be a goal (the goal condition).

2. It must be possible to ascertain the state of the system (the observability condition).

3. It must be possible to affect the state of the system (the controllability condition).

4. There must be a model of the system (the model condition).

2.2.1 Controlling Joint Systems and Processes

The combined view of control theory in technical as well in behavioral domains is crucial for success in this research area.

To this could be added two widely used concepts, originally presented by Rasmussen [10] and adapted to the context of modeling and analysis of C2 systems:

Level of abstraction: At what level/s of organizational or functional abstraction are functional C2 requirements satisfied and C2 capabilities implemented?

Level of aggregation: At what level/s of organizational or functional aggregation are functional requirements satisfied and capabilities implemented?

When a function is A) *implemented* at one level of abstraction, B) *represented* at a second level of abstraction and C) *controlled* at a third level of abstraction the requirement for timely and complete information varies accordingly. On the other hand, it is not important whether a function or mission is carried out by an operator or by an automated system under higher-order supervision, the commander still need to be able to handle ill-structured problems and develop an accurate *appreciation* [23] – going beyond what is normally defined as developing *situation awareness* [24].

C2 in CMO is prone to *model error.* It is unavoidable in such dynamic and uncertain situations. The necessary adjustments and updates of the controller's internal system model can be made by constantly measuring the deviation of the system output from the reference value. The joint cognitive system is unstable without feedback, and thereby feedback will be needed to correct deviations and compensate for the incompleteness and inadequacy of the internal system model. Reason [25] emphasized the importance of balance between feedback (reactive) control and feedforward (proactive) control. This concept is crucial to achieve optimal C2 performance in a tactical mission.

2.3 Decision Making in Complex Systems Control and Mission Command

Brehmer [14] suggested the use of control theory as a framework for research in Distributed Dynamic Decision Making (DDDM). The conventional view of decision making, supported by normative theories, reduces decision making to selecting an appropriate action from a closed, pre-defined action set, and to resolution of conflicts of choice. As a consequence, the analysis of decision tasks focuses on the generation of alternatives and the evaluation of these alternatives as in Multi-Attribute Utility (MAU) analysis [26]. Research in dynamic decision making has instead been based on analysis of several applied scenarios, e.g. military decision making, operator tasks in industrial processes, emergency management, aviation and intensive care which Brehmer [14; 19] summarized as follows:

1. A series of decisions is required to reach the goal.

2. The decisions are mutually dependent.

3. The state of the decision problem changes over time.

4. The decisions have to be made in real time, requiring true dynamic and adaptive capabilities throughout the organization.

2.3.1 Naturalistic Approaches to Decision Making

Zachary & Ryder [27] reviewed decision making research during the last decades and elaborated on the recent major paradigm shift in decision theory. The shift is from analytic, normative decision making procedures described in Kleindorfer et al. [26] to Naturalistic Decision Making (NDM), developed and described by Klein [28; 29], Zsambok & Klein [30] as well as by Klein & Woods [31]. NDM applies to many dynamic and potentially dangerous areas of activity such as military missions, air traffic control, fire fighting, emergency response and medical care [32]. The essentials of this paradigm are condensed below:

1. Human decision making should be studied in its natural context.

2. The underlying task and situation of a problem is critical for successful framing.

3. Actions and decisions are highly interrelated.

4. Experts apply their experience and knowledge non-analytically by identifying and effecting the most appropriate action in an intuitive manner.

2.3.2 Tactical Team Decision Making

According to Cannon-Bowers et al. [33], tactical decision making teams in modern warfare or crisis management are faced with situations characterized by rapidly unfolding events, multiple plausible hypotheses, high information ambiguity, severe time pressure, and serious consequences for errors. There are also cases when geographical separation or other forms of distributed environments in which the teams operate impose additional difficulties. To be able to adapt to these situations, team members must co-ordinate their actions so that they can gather, process, integrate, and communicate information timely and effectively. This is particularly true in CMO where it is difficult to assess performance with a single correct answer or in situations where several individual decision makers must interact as a team.

Another important aspect is how the actual mission and the mission environment affect team performance. Serfaty & Entin [34] drew the following conclusions concerning the properties and abilities of teams successfully performing tactical, hazardous operations:

1. The team structure adapts to changes in the mission environment.

2. The team maintains open and flexible communication lines. This is important in situations where lower levels in a command hierarchy have access to critical information not available to the higher command levels.

3. Team members are extremely sensitive to the workload and performance of other members in high-tempo situations.

2.4 Psychophysiology

Within joint cognitive systems performing complex, high-risk military and emergency response missions there is a fundamental and profound connection between human operator physiological stress response and discrepancies between expectancies and experiences. Levine and Ursin [35] describe stress response as a warning of an occurring homeostatic imbalance.

This implies that the concept of model error from control theory once again can be applied. The stress response is also mobilizing physiological resources to improve performance, which is regarded as a positive and desirable warning response. The Cognitive Activation Theory of Stress (CATS) describes the phases of the stress response as an alarm occurring within a complex adaptive cognitive system with feedback, feedforward and control loops, no less but no more complicated than any other of the body's self-regulated systems [36]. The time dimension of stress responses must be accounted for very carefully.

2.5 Models of Action Control

The point of departure in our ACT-based systems modeling endeavor was the definition of a Tactical Joint Cognitive System (TJCS) [4] as the system

• To which a mission is assigned.

• To which the operational command of the mission is appointed.

• To which the responsibility for effecting the mission is handed.

• To which the resources needed for performing the mission are allocated.

A TJCS is an aggregate of one or several instances of four principal sub-system classes:

1. Technological Systems, for example vehicles, intelligence acquisition systems, communication systems, sensor systems, life support systems, including the system operators.

2. Command and Control Systems, consisting of an information exchange and command framework, built up by technological systems, rules, procedures and protocols, and directly involved decision makers.

3. Support Systems, comprising staff functions, logistic functions, decision support functions, organizational structures, doctrine, Tactics, Techniques and Procedures (TTPs) and various kinds of service support.

4. Tactical Teams, composed and defined according toSalas et al. [37] as: "Two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have been assigned specific roles or functions to perform, and who have a limited life-span of membership."

The TJCS forms the basis for the Tactical Action COntrol Model (TACOM). The principal components of the TACOM are the Mission Environment, the Tactical Joint Cognitive System, the Situation Assessment function, and the Cognitive Action Control function.

The next step is integration of these concepts into a Mission Execution and Control Model (MECOM). The MECOM consists of one or several TACOMs extended with control theoretic components, to handle system disturbances, model error, and to allow an adaptive and balanced mix of feedforward and feedback control.

The last step in the model formation process is combining and aggregating several MECOMs into unilevel and multilevel MECOMs.

2.6 Model Validation

In earlier publications [6; 38; 39; 40] we have reported on the progress of the Tactical Real-time Interaction in Distributed EnvironmeNTs (TRIDENT) project.

Numerous battle management and emergency response studies have been carried out in which we used every opportunity to test, refine and augment the modeling, measurement, data collection and analysis concepts of TRIDENT [41].

The TRIDENT concepts for analysis and evaluation on aggregated system levels have met high acceptance among the subjects; trained and skilled professionals performing their daily tasks in their accustomed work environment. This is consistent with studies by Rencrantz et al. [42] and Svensson et al. [43] of experience and performance in complex operational settings. However, from time to time it is claimed that reliability and validity of subjective workload ratings are insufficient. To address this critique we designed a study using hormonal response measures, inspired by the results of Svensson et al. [44], who studied workload and performance in military aviation, Zeier, [45] who studied workload and stress reactions in air traffic controllers, and Holmboe et al. [46], who studied military personnel performing exhausting battle training. The study is described by Norlander [47].

3.0 DISCUSSION

From the study results we could identify a number of particularly interesting causes of mission failure or poor performance. The predominant error modes were:

• Timing of movement and of tactical unit engagement.

• Speed of movement or maneuver, which is especially important in the initial phase of engagement.

• Selection of wrong object. In warfare or crisis response there is high risk for selecting wrong objects, in navigation, in engagements, or in visual contact.

After a retrospective cognitive reliability and error analysis [32] we found that mission failure or poor performance in every case could be attributed to:

• Slow or even collapsed organizational response.

• Ambiguous, missing or insufficiently disseminated, communicated and presented information.

• Equipment malfunction, e.g. power failure or projectile/missile impact.

• Personal factors: inexperience, lack of team training etc.

The results from the hormonal response study suggest three potentially significant mechanisms influencing how the team is able to execute mission control, which consequently also influences mission efficiency [47]:

1. Time-dependant filtering functions like defense and coping mechanisms according to the Cognitive Activation Theory of Stress (CATS).

2. Performance limiting factors due to specific mission and task situation factors and resource requirements.

3. Balance between feedforward and feedback in mission-critical action control.

4.0 CONCLUSIONS

Our theoretical advances and the experimental results validate that cognitive systems analysis of C2 in CMOs is a versatile and effective approach. Cognitive systems analysis facilitates:

1. Identification of limiting factors of a specific individual, unit, system, procedure or mission in CMO.

2. Assessment of the magnitude of influence of these factors on overall tactical performance.

3. Generation and implementation of solutions to improve insufficient capabilities and contribute to successful mission accomplishment.

4. Methodological support to analysis, development and evaluation of complex CMO.

5. Improving training programs for tactical decision making and resource management.

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