

Breaking the Barriers: Facilitating Efficient Command and Control in Multi-Service Emergency Management

Arne Worm

Swedish Defence Research Agency, Man-System Interaction Division

P.O. Box 1165, SE-581 11 Linköping, Sweden

arne.worm@foi.se

Keywords: Command and control, system design, modelling

Abstract

In military operations and emergency management, operators and commanders must rely on distributed 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 whose operational and system characteristics are highly dynamic and non-linear, i.e. small actions or decisions may have serious and irreversible consequences for the entire mission. This paper reports on research from which the results led to a breakthrough: An integrated approach to information-centred systems analysis to support future command and control systems research development.

Introduction

The nature of complex dynamic processes as military operations, emergency management and air traffic control are high-risk activities, where human and artificial team members together perform tasks requiring extreme mobility, efficiency, agility and endurance. These distributed systems incorporate numerous team players, widely distributed across the whole theatre of operations. They can operate autonomously for certain time periods and in specific areas, but primarily they are forced to co-ordinate their actions very accurately with one another. Adequate performance in complex, high-risk, tactical operations requires support by highly capable management. Commanders and other decision-makers must manage true real time properties at all levels: individual operators, stand-alone technical systems, higher-order integrated socio-technical systems and forces for joint operations alike. Highly qualified information management resources are vital to facilitate omnidirectional, continuous information and distribution support from the chief executive level to the team-on-site levels. Sometimes individual operators and sensor systems must without delay be allowed to affect decisions and actions of a senior commander.

The Action Control Theory Framework

The underlying principle was integration of well-established scientific disciplines into a pioneering research direction, *Action Control Theory*, a framework specifically composed to facilitate empirically based conceptual modelling of dynamic, complex tactical systems and processes and of their states and state transitions. The research areas constituting ACT have until now developed along separate paths of evolution. However, now it is time to investigate what they might offer when implemented in an integrated, cohesive and co-ordinated manner. Flach & Kuperman (1998) concluded that it is essential to develop a unified, proactive, CSE-based approach in research and systems design for future warfare environments. We agree, and hold a strong belief in the power of integrative research approaches that are built on solid classical and innovative theoretical work, using comprehensive yet simple and robust conceptual and specific models of systems, tasks and missions, supported by advanced experimental and measurement methods and data analysis techniques.

The resulting models will be used for complex, multi-level human-machine systems design in the military, aviation and emergency response domains. Action Control Theory (ACT) is a composite theoretical structure, derived from advances in

- I. Cognitive Systems Engineering (CSE).
- II. Systems Theory, Control Theory and Cybernetics.
- III. Decision Making in Complex Systems Control and Mission Command.
- IV. Psychophysiology.

Theoretical Constituent I: 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 (1983; 1986), who introduced the concept of skill-based, rule-based and knowledge-based behaviour for modelling different levels of human performance. Hollnagel & Woods (1983) made a significant contribution to this field by their definition of a *Cognitive System* (CS) as a Man-Machine System (MMS) whose behaviour 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 (1999), 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 definition describes a CS as a system that can modify its pattern of behaviour on the basis of past experience in order to achieve specific anti-entropic ends. For example, in Command and Control (C²) tasks in military missions a multitude of sensor systems, communication systems, training programs, personnel and procedures are all elements of the total operational system. Viewing this system as a CS permits the integration of all existing control resources; operators, commanders, technological facilities, doctrine, tactics, techniques and procedures, organisation and training into a co-ordinated system that safely and efficiently achieves its mission.

Theoretical Constituent II: Dynamic Systems Theory, Control Theory and Cybernetics

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 . From the work of Ashby (1956), Conant & Ashby (1970), 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.

According to Worm, (2000), the combined view of control theory in technical as well in behavioural domains is crucial for success in this research area. When a function is implemented at one level of abstraction, represented at a second level of abstraction and 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 an automated system under higher-order supervision or a highly qualified operator carries out a function or mission, the operators and the supervisory controllers still need to maintain an adequate situation understanding. In most situations the active agents in a dynamic system, such as soldiers/operators and their closest commander or squad leader, operate in a time scale of seconds to minutes. Their commanders and their command and control systems operate in time scales of hours to days. The key issue is to implement a system theory-based framework to cope with such dynamic properties, and of the environments such systems operate in.

The mathematical stringency and powerful formalism of systems theory makes it possible to describe and treat systems as diverse as technical, organisational, economic and biological dynamic systems in basically the same manner: as processes, or clusters of processes, with a built-in adherent or assigned control system. According to Conant & Ashby, (1970), Glad & Ljung, (1989) and Brehmer, (1992), four fundamental requirements must be met, if control theory should be used successfully 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*).

Theoretical Constituent III: Decision Making in Complex Systems Control and Mission Command

The conventional and classic *Analytical Decision Making* approach, 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. Hence, the analysis of decision tasks concentrates on the generation of alternatives and the evaluation of these alternatives according to some criterion, usually expected value. According to Lehto (1997), Cohen et al. (1998), Wickens (1992) and Kleindorfer et al. (1993), the most familiar classical framework for decision making contains two main parts: *Bayesian probability theory* for drawing inferences about the situation at hand, and *Multiattribute Utility Theory* for selecting an optimal action. There is a lot to be said about analytical, mono-theoretical approaches, especially when investigators and researchers claim they have a stringent and formal theory which "takes care of it all"

regarding the host of requirements in need of fulfilment for the theory to hold in a real-world decision situation.

Brehmer (1992) suggested the use of control theory as a framework for research in *Distributed, Dynamic Decision Making*. Brehmer's research was based on analysis of several applied scenarios, e.g. military decision making, operator tasks in industrial processes, emergency management and intensive care (Brehmer, 1988; 1992). The following results were clarified in these analyses:

- The decision making was never the primary task. It was always directed towards some goal.
- A series of decisions is required to reach the goal.
- The decisions are mutually dependent.
- The state of the decision problem changes, both autonomously and as a consequence of the decision-maker's actions.
- The situational dynamics require decisions to be made in real time.

Theoretical Constituent IV: Psychophysiology

Traditionally, stress research has been oriented toward studies involving the body's reaction to stressors (a physiological perspective) and the cognitive processes that appraise the event or situation as a stressor (a cognitive perspective). However, current social perspectives of the stress response have noted that different people experiencing similar life conditions are not necessarily affected in the same manner. There is a growing interest in the epidemiology of diseases thought to result from stress. It has been noted that the incidence of hypertension, cardiovascular ailments, and depression varies with such factors as race, sex, marital status, and income. This kind of socioeconomic variation of disease indicates that the stressors that presumably dispose people toward these illnesses are somehow linked to the conditions that people confront through their history of varying occupational and social position and status in the society. The stress response is a warning of a homeostatic imbalance occurring (Levine and Ursin, 1991). This implies that the concept of *model error* from control theory once again can be applied. The stress response is also mobilising 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 cognitive system with feedback, feedforward and control loops, no less but no more complicated than any other of the body's self-regulated systems (Eriksen et al., 1999). 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. Decision-makers are not free to make decisions when they feel ready to do so. Instead, the environment requires decisions and the decision-maker, ready or not, have to make these decisions on demand. According to Brehmer (1991) this causes stress in dynamic decision making tasks. In order to cope with this stress, decision-makers have to develop strategies for control of the assigned dynamic tasks and for keeping their own workload at an acceptable level. Coping strategies of individuals are primarily social in nature. The manner in which people attempt to avoid or resolve stressful situations, the cognitive strategies that they use to reduce threat, and the techniques for managing tensions are largely learned from the groups to which they belong. Although the coping strategies

used by individuals are often distinct, coping dispositions are to a large extent acquired from the social environment.

Methods: The TRIDENT project

In earlier publications (Worm, 1998b; 1999b; 1999c) we have reported on the progress of what would later be known as the *Tactical Real-time Interaction in Distributed EnvironmentS* (TRIDENT) project. The primary objective of TRIDENT is to develop a coherent and straightforward package of theoretically sound and empirically validated methods and techniques for human-machine systems analysis in the setting of tactical mission scenarios. The components of TRIDENT are described in Worm (2000) and are summarised below:

- Using the Action Control Theory (ACT) Framework for conceptual modelling of dynamic, complex tactical systems and processes, of their states and state transitions.
- Identification of mission and unit state variables, and of action control and decision making mechanisms for process regulation (Worm, 1998a; 1998b).
- Mission Efficiency Analysis (Worm et al., 1998; Worm, 1999a) of fully manned and equipped units executing full-scale tactical missions in an authentic environment.
- Measuring information distribution and communication effectiveness (Worm, 1998b).
- Measuring workload by means of the NASA Task Load Index (Hart & Staveland, 1988).
- Assessing team member psychosocial mood by means of the Mood Adjective CheckList (MACL, Sjöberg et al., 1979).
- Assessing situation awareness (Endsley, 1995) as a function of mission-critical information complexity (Svensson et al., 1993)
- Measuring level and mode of cognitive, context-dependant control of the team members, and identifying what decision strategies were utilised by the team and team members.
- Applying reliability and error analysis methods for investigating failure causes both in retrospect and for prediction (Hollnagel, 1998).
- Validating identified constructs and measuring their influence using advanced data analytic procedures.

Studies

Numerous battle management and emergency response studies have been carried out in which every opportunity was used to test, refine and augment the modelling, measurement, data collection and analysis concepts of TRIDENT. Implementing these ideas for tactical mission analysis in potentially dangerous, stressful and cognitively complex environments showed to be very effective.

Using the TRIDENT concepts for analysis and evaluation on aggregated system levels has so far been very rewarding, with high acceptance among the subjects; trained and skilled professionals performing their daily tasks in their accustomed work environment. However, We have also experienced some critique. It is occasionally claimed that reliability and validity of subjective workload ratings are insufficient. For that reason we considered incorporating a measure of workload and stress which is commonly

accepted in the scientific community. Hormonal response measures were considered, inspired by the results of Svensson et al. (1993), who studied workload and performance in military aviation, Zeier, (1994) who studied workload and stress reactions in air traffic controllers, and Holmboe et al. (1975), who studied military personnel performing exhausting battle training.

We designed a study in order to elucidate to what extent hormonal physiological stress indications are linked to the rating, observation and data collection methods normally used in TRIDENT to assess workload and tactical performance. The details of the study are described in Worm (2000).

Results

From the studies 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 manoeuvre, which is especially important in the initial phase of engagement.
- Selection of wrong object. The environments of ground warfare or emergencies offer many opportunities for choosing wrong objects, in navigation, in engagements, or in visual contact.

After a retrospective cognitive reliability and error analysis (Hollnagel, 1998) It was found that mission failure or poor performance in every case could be attributed to:

- Slow or even collapsed organisational 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.

Empirical results through the four-year project life suggest three potentially significant mechanisms influencing how the team is able to execute mission control, which consequently also influences mission efficiency:

- Time-dependant filtering functions like defence and coping mechanisms according to the cognitive Activation Theory of Stress (Eriksen et al.; 1999, Levine & Ursin, 1991).
- Performance limiting factors due to specific mission and task situation factors and resource requirements (Reason, 1997; Hollnagel, 1998; Worm, 1998c; 2000).
- Balance between feedforward and feedback in mission-critical action control (Reason, 1997; Worm, 2000).

Applications

We have for a number of years struggled towards building a foundation for analysis and evaluation of high-stake, life-threatening tactical missions in various work contexts. Although earlier results indicate that we have reached a workable, reliable and valid result, the question is still if the findings are generally applicable. The theoretical achievements were a complicated and arduous venture, in that we have constantly striven for empirical evidence. Nevertheless it is obvious that a scientific breakthrough has been achieved. We argue that the ACT / TRIDENT approach can be used as an advanced systems engineering support and will facilitate:

1. Identification of limiting factors of a specific individual, unit, system, procedure or mission.
2. Assessment of the magnitude of influence of these factors on overall tactical performance.
3. Generation and implementation of measures to assist, control and improve insufficient capabilities and contribute to successful accomplishment of future missions.
4. Methodological support in future integrated C³I systems.
5. Improving training programs for tactical decision making and resource management.

References

- Ashby, W. R. (1956). *An Introduction to Cybernetics*. London: Chapman & Hall.
- Brehmer, B. (1988). Organization of decision making in complex systems. In L. P. Goodstein, H. B. Andersen, & S. E. Olesen (Eds.), *Tasks, Errors, and Mental Models*. London: Taylor & Francis.
- Brehmer, B. (1991). Time scales, distributed decision making, and modern information technology. In J. Rasmussen, B. Brehmer, & J. Leplat (Eds.), *Distributed Decision Making: Cognitive Models for Cooperative Work*. Chichester: Wiley.
- Brehmer, B. (1992). Dynamic decision making: Human control of complex systems. *Acta Psychologica*, 81, pp. 211-241.
- Cohen, M. S., Freeman, J. T., & Thompson, B. (1998). Critical Thinking Skills in Tactical Decision Making: A Model and a Training Strategy. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making Decisions Under Stress: Implications for Individual and Team Training*, pp. 155-189. Washington, DC: American Psychological Association.
- Conant, R. C., & Ashby, W. R. (1970). Every good regulator of a system must be a model of that system. *International journal of System Science*, 1, pp. 89-97.
- Endsley, M. R. (1995) Towards a theory for situation awareness in dynamic systems. *Human Factors*, 37, pp. 32-64.
- Eriksen, H. R., Olf, M., Murison, R., & Ursin, H. (1999). The time dimension in stress responses: relevance for survival and health. *Psychiatry Research*, 85, pp. 39-50.
- Flach, J. M. & Kuperman, G. (1998). *Victory by Design: War, Information, and Cognitive Systems Engineering*. (Report No. AFRL-HE-WP-TR-1998-0074). Wright-Patterson AFB, OH: Air Force Research Laboratory, Cre System Interface Division.
- Glad, T. Ljung, L. (1989). *Reglerteknik. Grundläggande teori*. [Automatic Control. Basic Theory.] Lund: Studentlitteratur.
- Hart, S. G., & Staveland, L. E. (1988). Development of a multi-dimensional workload rating scale: Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human Mental Workload*. Amsterdam, The Netherlands: Elsevier Science B.V.
- Hollnagel, E. (1998). *Cognitive Reliability and Error Analysis Method (CREAM)*. Amsterdam, The Netherlands: Elsevier Science B.V.

- Hollnagel, E. (1999). Modelling the controller of a process. *Trans Inst MC*, Vol. 21, No 4/5, pp. 163 – 170.
- Hollnagel, E., & Woods, D. D., (1983). Cognitive Systems Engineering: New Wine in New Bottles. *International Journal of Man-Machine Studies*, 18, pp. 583-600.
- Holmboe, J., Bell, H., & Norman, N. (1975). Urinary Excretion of Catecholamines and Steroids in Military Cadets Exposed to Prolonged Stress. *Försvarsmedicin*, 11, p. 183.
- Kleindorfer, P. R., Kunhreuther, H. C. & Schoemaker, P. J (1993). *Decision sciences. An integrative perspective*. Cambridge: Cambridge University Press.
- Lehto, M. R. (1997). Decision Making. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics*, 2nd Ed., pp. 1201-1248. New York, NY: Wiley.
- Levine, S., & Ursin, H. (1991). What is stress? In M. R. Brown, G- F. Koob, & C. Rivier (Eds.), *Stress – Neurobiology and Neuroendocrinology*. Marcel Dekker, New York, pp. 3-21.
- Rasmussen, J. (1983). Skills, rules, and knowledge: Signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-13, pp. 257-266.
- Rasmussen, J. (1986). *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*. New York: North-Holland.
- Reason, J. (1997). *Managing the Risks of Organizational Accidents*. Ashgate.
- Sjöberg, L., Svensson, E., & Persson, L.-O. (1979). The measurement of mood. *Scandinavian Journal of Psychology*, 20, pp. 1-18.
- Svensson, E., Angelborg-Thandertz, M., & Sjöberg, L. (1993). Mission Challenge, Mental Workload and Performance in Military Aviation. *Aviation, Space and Environmental Medicine*, Nov., pp. 985-991.
- Wickens, C. D. (1992). *Engineering Psychology and Human Performance*. (2nd ed.) New York: HarperCollins.
- Worm, A. (1998a). Tactical Joint Cognitive Systems Performance in Dynamic, Distributed, Time-Critical Operations. In *Proceedings of The 4th International Symposium on Command and Control Research and Technology*, Stockholm, Sweden.
- Worm, A. (1998b). Joint Tactical Cognitive Systems: Modeling, Analysis, and Performance Assessment. In *Proceedings of The Human Factors and Ergonomics Society 42nd Annual Meeting*, Santa Monica, CA: The Human Factors Society.
- Worm, A. (1998c). *Command and Control Science: Theory and Tactical Applications*. Linköping Studies in Science and Technology, Thesis No. 714, Linköping University, Linköping, Sweden.
- Worm, A. (1999a). Mission Efficiency Analysis of Tactical Joint Cognitive Systems. In *Proceedings of The NATO International Symposium on Modelling and Analysis of Command and Control*, Paris, France.

- Worm, A. (1999b). Evaluating Tactical Real-time Interaction in Multi-agent, Dynamic, Hazardous, High-stake Operations. In Proceedings of The Human Factors and Ergonomics Society 43rd Annual Meeting, The Human Factors Society, Santa Monica, CA., USA.
- Worm, A. (1999c). Performance of Joint Cognitive Systems In Dynamic, Time-Critical, Hazardous Distributed Operations. In Proceedings of The 8th International Conference on Human-Computer Interaction, IRB-Verlag, Stuttgart, Germany.
- Worm, A. (2000). On control and Interaction in Complex Distributed Systems and Environments. Linköping Studies in Science and Technology, Dissertation No. 664, Linköping University, Linköping, Sweden. ISBN 91-7219-899-0.
- Worm, A., Jenvald, J., and Morin, M. (1998). Mission Efficiency Analysis: Evaluating and Improving Tactical Mission Performance in High-Risk, Time-Critical Operations. *Safety Science*, 30, pp.79-98. Elsevier Science B.V., The Netherlands.
- Zeier, H. (1994). Workload and psychophysiological stress reactions in air traffic controllers. *Ergonomics*, 37, pp.525-539.

Biography

Dr. Arne Worm is an officer in the Swedish Armed Forces, currently assigned to a senior researcher position at the Swedish Defence Research Agency. Dr. Worm holds a Master's degree in Mechanical Engineering and Automation, and a Ph.D. in Systems Engineering and Human-Machine Interaction from the National Graduate School for Human-Machine Interaction at Linköping Institute of Technology and Stockholm Royal Institute of Technology, supported by the National Foundation for Strategic Research. Dr. Worm's main research interest is tactical real time interaction in distributed environments, which includes command, control, communications and intelligence support of military operations, air traffic control and emergency management. His core research areas are computerised automation, human-machine interaction, control theory, mathematical modelling, cybernetics, cognitive systems engineering, distributed team decision making, and team training. Dr. Worm received the IBC International Order of Merit in December 2000 for his outstanding research in the Human Factors and Systems Engineering domains.