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Hybrid Cognitive Capabilities in EDGE Operations

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ABSTRACT

Contemporary and future defense and security operations are increasingly time-critical, resource-critical and safety-critical, requiring vigilance, awareness and determination. Commanders and operators frequently encounter uncertainty, risk, time-criticality and resource shortages while mastering the challenges of distributed, complex systems, strong functional coupling and interdependencies. Operational characteristics are highly dynamic and non-linear; Minor events, decisions and actions may have serious and irreversible consequences for the entire mission. This requires adaptive and versatile principles and concepts for Emergent, Dynamic, Global and Evolutionary operations (EDGE) operations, along with high-performance human and technological (i.e., hybrid) cognitive capabilities. Additionally, operating in a hazardous operational environment requires comprehensive operational awareness - shaped, supported and utilized by human and machine agents, in joint capabilities. Joint human-machine agents constitute hybrid capability components, able to accurately and rapidly sense, perceive and interpret relevant events and circumstances in order to sustain and improve decision-making and action, enabling every commander and operator to develop a wide-ranging appreciation of the situation.

Keywords: Autonomy, Adaptation, Cognition, Command, Emergence, Sociotechnical, Systems

INTRODUCTION

Operating in a contested mission environment requires comprehensive operational awareness, with the ability to accurately and rapidly perceive and interpret relevant events and circumstances. In order to provide the context, insight and foresight is required for effective decision-making. EDGE Operations are of particular concern; while some operational tasks necessarily would employ a human component, other tasks can only be accomplished through non-human intelligent entities, acting autonomously within the socio-technical enterprise.

At the conceptual level, EDGE Operations can be described as the coordination of kinetic and non-kinetic means of power in the physical, information, and cognitive domains, to asymmetrically exploit the opponent's vulnerabilities, and defeat or render irrelevant his abilities, will, structures and systems.

EDGE Operations execute at a level of fluidity and flexibility that matches the degree of variation in the external environment, a principle known as requisite variety (Ashby, 1956), proven in a broad spectrum of safety-critical systems, missions, and operating environments.

EDGE CAPABILITIES AND CHARACTERISTICS

EDGE Operations are conducted by Edge Capabilities, with the following overarching characteristics:

1. **Emergent:** In EDGE Operations, distributed, interdependent complex adaptive systems create emergent effects – effects that are greater than the sum of the individual effects of the input systems and that cannot be unambiguously attributed to individual observed properties.
2. **Dynamic:** EDGE Operations are complex, laborious and dangerous endeavours, requiring resolute and determined action under extreme conditions. EDGE Capabilities accomplish missions successfully under exposure to uncertainty, risk, time-criticalities and resource shortages.
3. **Global:** Actions by Hybrid Cognitive Systems in multiple operational domains, integrated in planning, synchronized in execution, with the speed, reach and scale needed to gain advantage and accomplish their mission.
4. **Evolutionary:** Heterogeneous, self-learning and adaptive behavior, originating in qualitative, structural change within and between complex system components. EDGE capabilities display three main evolutionary characteristics:

   a. ***Adaptive*** – Ability to perceive, understand and deal with change under time-, risk- and resource-critical conditions.
   b. ***Exaptive*** – Radical re-purposing under conditions of stress, driving an evolving, emergent system characterised by qualitative, structural change.
   c. ***Learning*** – Experience from ongoing and completed campaigns are translated into action, reducing the time from discovery to implementation.

Complexity, Autonomy and Interaction

A complex system is any system in which the parts of the system and their interactions together represent a specific behavior, such that an analysis of all its constituent parts cannot explain the behavior. In such systems, the cause and effect cannot necessarily be related, and relationships are non-linear - a small change could have a disproportionate impact. In other words, as Aristotle said: ‘the whole is greater than the sum of its parts’. This requires adaptive and versatile principles and concepts for complex Multi-Domain Operations along with high-performance human, technological and organizational architectures Norlander (2019). Operational success is strongly linked to effective interaction and collaboration within and between the physical, information and cognitive dimensions. Autonomous systems, different organizational cultures, people with different backgrounds, education and experience rely heavily on collectively managing and maintaining operational availability, versatility and efficiency. In many situations the desired effects cannot be linearly planned and reliably predicted, but must be anticipated to emerge from shaping the Operational Environment (OE) and influencing the agents operating in the OE.

There are several issues concerning the use of mission-specific and contextual information and knowledge for judgment, decision, and choice, as well as the information-coupled activities leading to supervisory control of a complex, partly or completely automated process, and the more obvious control of the involved technological systems. This also concerns the degree of automation needed to achieve flexible task and resource allocation, and relates to all kinds of Human-Machine interaction concerns and management tasks at every organisational level. A monitoring or feedback portion of the efforts is required to execute supervisory control. There is also a need for functions enabling learning and adapting over time, but also for a feedforward part that is crucial to ensure rapid and reliable, autonomous response in routine decision situations. According to the U.S. Congressional Research Service (2021), DARPA's Mosaic Warfare concept is an ambitious endeavour into Human-Machine capabilities in extensively, sometimes entirely, autonomous operations.

AUTONOMY CONCEPTS MUST CAPTURE COGNITION AND COLLABORATION

Human-Autonomy Systems and Cognitive Systems: Learning From Experience and Adapting to Circumstances

Autonomous systems are systems capable of making decisions independently and function without human intervention. One example is a Cyber-Physical System (CPS), in which, according to Derler et al. (2013), computing and physical processes are intricately woven together, with data from the environment and actuators being managed by the computer.

Physical and computational systems communicate through networks, and computation devices communicate with physical system processes affecting each other via feedback and feed forward control loops. Human-Autonomy Systems (HAS) are individual agents, each characterized by being goal-oriented and self-directed. Thus, the physical actions of the HAS affect the computations and vice versa autonomously. A HAS can function autonomously in the environment by interacting with other objects and systems, handling tasks that may appear opaque, inaccessible or otherwise inexplainable.

> *Definition 1: A Human-Autonomy System (HAS) is a system comprised of at least one human operator and at least one adaptive artificial entity.*

Both agent classes are able to autonomously engage with its environment in direct interaction, involvement and/or interdependency with humans and other artificial entities in order to meet a certain mission objective.

> *Corollary 1: A HAS must be able to create, sustain and evolve a Comprehensive Operational Awareness.*

Besides deciding and acting on an individual basis, both the human operator and the artificial entity complement each other's decision-making processes and actions and jointly solve problems. In order to do so, they must be able to understand complex, conceptual constructs and ideas (relative to the activity) to adapt effectively to the environment and to combine task related with social and team related skills that enable effective and efficient collaboration.

The HAS definition mirrors the definition of a cognitive system by Rasmussen et al. (1994), "operating by using knowledge about itself and its environment to plan and modify its actions based on that knowledge". In Hollnagel (1999) a cognitive system is defined as a system that "can modify its pattern of behavior on the basis of past experience in order to achieve specific anti-entropic ends". This definition fits any organism or system that is to prevail in a dynamic environment.

The conclusion from this is that a HAS must possess three fundamental capabilities to act as a Cognitive System (CS), defined by Norlander (2011) as cornerstones of modern complex cognitive systems science:

- A cognitive system is capable of adaptation to the varying conditions of the surrounding environment;
- A cognitive system is capable of prediction of how the surrounding environment evolves over time;
- A cognitive system is capable of regulation in order to reach an equilibrium that matches the current conditions of the surrounding environment.

If we view the role of human-autonomy systems in the context of Multi-Domain Operations (NATO, 2022), the agents must be able to apply these capabilities in relation to a multitude of organizational entities, human/artificial operators, sensor systems, communication systems, doctrine and networks are all elements of the total operational system. Analogous to the groundbreaking findings by Conant and Ashby (1970), the conclusion of this is that an artificial cognitive system has to be capable to adapt, predict and regulate to a level at least in line with human decision-making process and action to be able to complement each other.

The adaptive capability can be understood in the light of the CS definition provided above. Additionally, recent work in the realm of Superminds by Malone (2018) suggest that human and artificial entities can jointly utilize Artificial Intelligence and Hyperconnectivity to form learning loops, constituting strategic planning and decision-making capabilities of business corporations, government agencies and global organizations. The conceptual structures of Cognitive Systems, Cyber-Physical Systems, Autonomy and Superminds all support the characterization of human-autonomy systems, enabling the foundation of a principal concept of Cognitive Command, based on the supporting concepts below, as Autonomous Adaptive Agents (AAAs).

AUTONOMY AND CONTROL ARE RELATED, BUT DISTINCT CONCEPTS

Previous research on autonomy has largely focused on understanding how different "levels" of automation changes the working conditions for human operators Sheridan and Verplank, (1978); Parasuraman, 2000). This view largely prevails today, as can be seen in the development of self-driving cars.

Future applications of robotics and autonomous capabilities suggest a world were different robotic or software entities are integrated in society, fulfilling many tasks and even taking on responsibility for different managerial tasks. As described later in this paper, this calls for technologies that are able to autonomously engage within the operational context and environment, without continuous human supervision. In terms of perspectives that can provide theoretical foundations for this advanced approach, this can be seen as a case of a socio-technical system. However, while socio-technical aspects of human-autonomy constellations are of importance, we need also to focus understanding towards the cognitive aspects of both autonomous agents and human operators and commanders in order to better grasp the possibilities and limitations of hybrid human-autonomy systems in terms of performance and the types of tasks that can be supported.

A FUNCTIONAL PERSPECTIVE ON INTELLIGENT, AUTONOMOUS COLLABORATION

In the case of Multi-Domain Command in the operational and cognitive dimensions, we need to understand how a unit consisting of both humans and autonomous agents can reach their goals and how control, rather than functions, is allocated in the human-machine system. Further, both humans and autonomous agents are bounded in their rationality, although by different characteristics, deciding how control should be allocated between humans and autonomous agents depending on context and current goals.

The discussion benefits from this as it takes place in a hypothetical zone where the exact technical components cannot be described, as they do not yet exist. However, we can describe what a Human-Autonomy Team (HAT) is/should be in terms of what it can do, i.e., its functional properties (NASEM (2022), which is in line with the Cognitive Systems Engineering (CSE) perspective of Rasmussen et al. (1994).

A Human-Autonomy System can be seen as a cognitive system in its own right, and the CSE approach can be used to better understand the human-autonomy system in different situations and contexts. The concept of a human-autonomy system is integrated with the central premise of the human operator and decision maker as a capability component, operating symbiotically with technological artefacts (Norlander, (2014). Human operators are constantly collecting and building knowledge about themselves, other agents and the operational environment. They apply skills, rules and heuristics to plan and modify their actions based on that knowledge. Every commander and every human and artificial agent must develop a capability for sensemaking to enable a comprehensive detailed system insight, leading to safe and efficient mission accomplishment (Weick et al., 2005).

Command and Execution in High-Risk Missions With Cyber-Physical Systems as Autonomous Adaptive Agents in High-Reliability Organizations

In most day-to-day operations, operational reliability, availability and high technical performance at the lowest possible cost are enduring overarching objectives, and risk awareness in the organization is often limited. However, fundamental work by, among others, Vincent and Amalberti (2016); Cook and Rasmussen (2005); and Rasmussen, (1997) have firmly established that more specialized operational domains, i.e., aviation, space, maritime, intensive care, nuclear power and military systems, require extraordinary approaches to risk awareness and risk management. These cases can be classified as complex dynamic endeavors, and the costs of incidents, accidents, breakdowns, and deliberate attacks are valued not only in economic terms but also in human lives.

When two or more threats manifest simultaneously, the emergent, systemic impact can be much greater than the sum of its parts. This is known as Compound Risk. Short-term and intense system shocks are likely to interact with more persistent threats and reinforce each other, exacerbating their impact on operational effect.

To understand compound risk we need to consider dimensions that are not usually the primary focus of experts in Human Factors: The dynamic system characteristics and emerging effects of compound risk. Vincent and Amalberti (2016) describe this concept for compound risk management by shifting risk approaches; Operations transition from ultra-safe, i.e., to avoid risk by prioritizing preventive strategies, via high reliability, i.e., to manage risk, by prioritizing procedures and adaptation strategies, to ultra-adaptive, i.e., to apply more extreme adaptation, resilience and recovery strategies.

Additionally, the concept of risk and uncertainty is indivisibly unified with trust. Besides constituting an autonomous intelligent entity, an AAA is also designed as a collaborator, meaning it is able when executing its tasks to complement the human decision-making process and task execution. Because of this AAAs will, when integrated in human-based teams, be more perceived as team members than a collection of tools. Employing capabilities containing HAS in the form of human operators and AAAs must rely on an organization and doctrine that aims to achieve error-free performance and safety in every mission, every time — all while operating in complex, high-risk or hazardous environments.

Such organizations have been studied extensively and defined by Weick and Sutcliffe (2015) as High-Reliability Organizations (HRO), operational units that are comprised by predictable and repeatable capabilities and systems that support consistent operations while identifying and preventing potentially catastrophic incidents before they happen.

RECOMMENDATIONS: TOWARDS AN ESSENCE OF COMMAND FOR HUMAN-AUTONOMY SYSTEMS

A conflict situation within or with operational reach into the information and cognitive dimensions can rapidly escalate or change character in fractions of a second, and this requires adequate response times. This is beyond the ability of humans, hence requiring the use of high-performance, automated cognitive capabilities comprised of multiple, distributed human-autonomy systems. Furthermore, without the appropriate distribution of information, and the necessary decision rights to the CPS that match their required level of autonomy, the decisions and actions needed for success in EDGE Operations will not be achieved in a timely manner. Reduction of response times enables losses of command capability to be minimized, or restored more quickly if degraded. This would indicate that command approaches that can respond more rapidly to changes in circumstances (e.g., a loss of communications capability or an unforeseen cross-domain system shock) would be more appropriate for operating in a contested operational environment (NATO 2022).

In addition to the ability to act in a timely manner to exploit or manage rapidly changing circumstances, the requirement to interact and collaborate in EDGE Operations calls for command approaches, originally formulated by Alberts and Hayes (2006), that:

- Utilize multiple paths for information dissemination;
- Adapt its interactions to changing circumstances; and
- Dynamically delegate decision rights between autonomous and human agents.

Norlander (2022; 2023) proposes formulating a future-oriented essence of Multi-Domain Cognitive Command, with equal relevance and applicability on human and autonomous agents in a HAS. This Essence of Command comprises three overarching conceptual mainstays:

1. *Make uncertainty and awareness your allies;*
2. *Stagnation equals defeat;*
3. *Multi-Domain Command is Agile Hybrid Cognitive Systems Command.*

In this context we need to use a model that describes Command, Operational Environment, Missions and Emergent Effects at different echelons. This model is based on work by Norlander (2019) and Josefsson et al. (2019), and represent different aspects of emergent crisis dynamics in the cognitive command function, i.e., the commander and supporting functions temporarily losing their ability to think ahead and anticipate the forthcoming course of events, disabling command and succumbing to uncertainty and excessive risk.

CONCLUSION

Operating in a contested mission environment requires comprehensive situational awareness, enabling and reinforcing accurate and rapid perception and interpretation of mission-relevant events and circumstances, and facilitating the provision of context, insight and foresight required for effective decision-making and action. Complex EDGE Operations are of particular concern; while some operations, missions and tasks necessarily must employ a human component, others can only be accomplished through non-human intelligent entities, acting autonomously within the socio-technical enterprise. The Cognitive Systems body of research was utilized to overcome the duality of traditional human-machine research, focusing on better understanding what people actually do with technology rather than what functions belong to the machine and what functions belong to the human. The Human-Autonomy Systems (HAS) research domain contributed with characteristics of self-learning, emergence, and evolution among the entities of the complex system, demonstrating heterogeneous and adaptive behaviour.

According to the theory and concepts for Autonomous Adaptive Agents (AAAs), an agent is also viewed as a team member, meaning it is able to autonomously complement human decision-making when executing its tasks. Building cognitive systems and capabilities requires a mental shift – striving towards an Agility mindset that permeates security and defence policy, legal and financial frameworks, science and technology agendas, strategy and operations. Employing the Cognitive Systems, HAS and AAA paradigms for EDGE Operations permits the integration of all capability elements into an adaptive distributed system that can achieve a mission safely and efficiently. Based on these studies and with the support from other fields of study, we devised a number of strategy elements as part of an essence of Cognitive Command and Complex Decision-making.

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