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Distributed Situation Awareness in Nuclear, Chemical, and Maritime Domains

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The increase in size, automation and complexity of modern sociotechnical systems changed the dynamics of work environments and calls for new methodologies and metaphors towards safety of complex systems. Chemical, nuclear, and transportation (i.e. road, maritime, and aviation) industries are composed of various nested sub-systems where smooth coordination and communication are essential features to achieve continuous and safe operations. Even though such sub-systems exist since the industrial revolution, fewer studies have been conducted in these domains: to understand the work as it is done (rather than it is imagined), which is the only way to shed light about the variability in work performance and how these sub-systems can combine to generate dangerous and unexpected outcomes. The theoretical framework of Distributed Situation Awareness provides a firm background to investigate the sub-systems that constitute the chemical, nuclear, and maritime industries/domains. This paper unfolds the key sub-systems (*e.g.*, operators, human-computer interfaces, communication tools, and distant/different locations) that play a critical role in normal and abnormal situations in these industries. The complex interconnections among various artifacts are explained and their significance is assessed.

1. Introduction

In systems with multiple adaptive agents, task-relevant awareness and knowledge must be distributed among the involved agents . When the awareness of task-relevant information is distributed among multiple agents this is called Distributed Situation Awareness (DSA) and has been defined as "…activated knowledge for a specific task, at a specific time within a system" (Salmon et al., 2006), p. 1291). In addition, DSA is seen as being an emergent property of the joint cognitive system. In other words, it is not reducible to any specific actor in the system. This can be seen in correspondence with a systems approach, which is aptly described in the following quote: "Complex systems cannot be understood by studying parts in isolation. The very essence of the system lies in the interaction between parts and the overall behavior that emerges from the interactions. The system must be analyzed as a whole." (Ottino, 2003), p. 293). However, describing the psychological or systemic construct of DSA is not only of academic interest, but also of particular practical interest for the identification of how DSA is related to the capability of remaining in control of a dynamic process. Situation Awareness is – as we will debate – intimately related to being in control. In order to ensure safe and efficient operation one must focus on the interactions and coordination among the control units (Petersen, 2004) . DSA is thus a system construct that according to proponents resides in the whole system (Stanton et al., 2006). The system can be understood by considering the whole instead of parts, as each part has multilevel

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connections and dependencies to other parts. When the control system involves humans that are able to perceive and understand the meaning of elements in the world around them, the system model must also encompass the characteristics of humans. Several industrial accidents evolved on account of lack of understanding of the interconnections of subsystems (let us not forget human is an important subsystem constituting the whole system) (De Carvalho, 2011). Indeed, the collaborative compatibility among the subsystems enables the whole system to work in an efficient (Nazir et al., 2015), effective (Vidal et al., 2009), and importantly safer way (Nazir and Manca, 2014). In sociotechnical systems the governance of the system relies on multiple adaptive actors – both humans and technical. Automatons are (like humans) adaptive agents as they can react to changes in the controlled process and by themselves bring about system state changes (Hollnagel and Woods, 1999). This is commonly seen in any automated system, from the simple homeostatic controller to a complicated multidimensional control as in Dynamic Positioning systems used aboard vessels in the maritime domain (Stanton *et al.*, 2014). Likewise, the chemical industry is saturated with complex interdependencies, dynamic interactions among various agents , and multi-level control loops and nuclear power plants, which are composed of several sub-systems *e.g.*, hardware, human operators and control systems (Junior et al., 2012, Carvalho et al., 2007). Thus, like humans, automated systems perceive the world (often through sensor inputs) and adapt to this input by effectuating some type of output or action that can bring about system state changes (Petersen, 2004). From a control theoretical viewpoint, enabling control maintenance in sociotechnical systems requires the awareness of assessing the necessary changes that must be made in order to achieve some goal (*e.g.*, control requirements) and the possible ways on how an operator can produce these changes (*e.g.*, control possibilities) (Petersen, 2004). Hence, an adaptive agent must be aware of what is needed to be done to achieve a goal, and the agent must know how the necessary actions can be done. In a reduced manner, we can say that DSA is awareness of the current and near future control requirements as well as the current and near future control possibilities.

The article describes communalities among three domains (namely nuclear, chemical, and maritime) of sociotechnical systems (Nazir et al., 2014) and connects the hierarchical means-ends approach (Moray et al., 1994) to point out the necessary parts that should be the content of DSA. For instance, the content of DSA should be related to the parts of the sociotechnical system's means-end hierarchy and how sub-systems are able to cause changes in system states that enable goal achievement in a controlled manner. By defining the subsystems and their interrelationships as described by control requirements and control possibilities, we define the areas where the content of DSA is similar among different domains. Hence, if two or more systems have similar interrelationships among sub-systems or within the nested sub-systems with regard to control situations, then these similarities will allow the research to be transferable among research domains. The following sections highlight briefly the subsystems of the three industries under focus.

2. Process systems in Chemical and Nuclear domains

A process industry is the combination of hardware (equipment, process units like distillation columns, heat exchanger, furnaces, boilers, vessel, pumps, compressors, valves), software (soft sensors (Ahmed et al., 2009), feedback and feed-forward controllers, model based techniques, real time optimization), automation, utilities, and human operators. All these components (or adaptive agents) complement each other, and any their failure may result in devastating accidents. Communication among various agents (as per the definition of DSA) is of vital importance for the continuous operations and production, the significance of which increases manifold once abnormalities or uncertainties are introduced in the system.

In an early study on nuclear power plant operations, Carvalho and Vidal (2007) indicated that safety and availability of nuclear operations still rely on humans, both through human reliability and human ability to handle adequately unexpected events. Ergonomic field studies of nuclear power plant control room operator activities(Mrugalska, 2014) and more specifically on the analysis of communications within control room crews show how operators use verbal exchanges to produce continuous, redundant, and diverse interactions to successfully construct and maintain individual and mutual awareness, which is of paramount importance to achieve system stability and safety. Such continuous interactions enable the operators to prevent, detect, and reverse system errors or flaws by anticipation or regulation.

The first effort to use the DSA in improving process safety was conducted by Nazir et al. (2014). They explain how the ultimate consequences of abnormal situations depend on the shared understanding, compatibility, and effective communication among operators (Nazir et al., 2012). They also highlight the importance of both shared mental model and joint cognition to facilitate communication and the subsequently necessary actions. The adaptability of the control systems defines the resilience of the system *i.e.* the higher the adaptability the higher the ability of the system to absorb the uncertainties and operate (or return) within the safe operating conditions (Rankin et al., 2014). The categorization of operators in chemical/nuclear industry is broadly split into two *i.e.* control room operators and field operators. The former are responsible to work in a control room,

which involves architectures, mechanisms, and algorithms for monitoring and controlling the plant. The latter work in the field, where the operations are generally performed physically (if and when required) and continuous communication with the control room is also expected.
Figure 1 shows, in a very simplistic manner, the distributed nature of both chemical and nuclear industries, the agents involved, and the possible control situations. The descriptive analysis of each subsystem is out of scope of this paper.

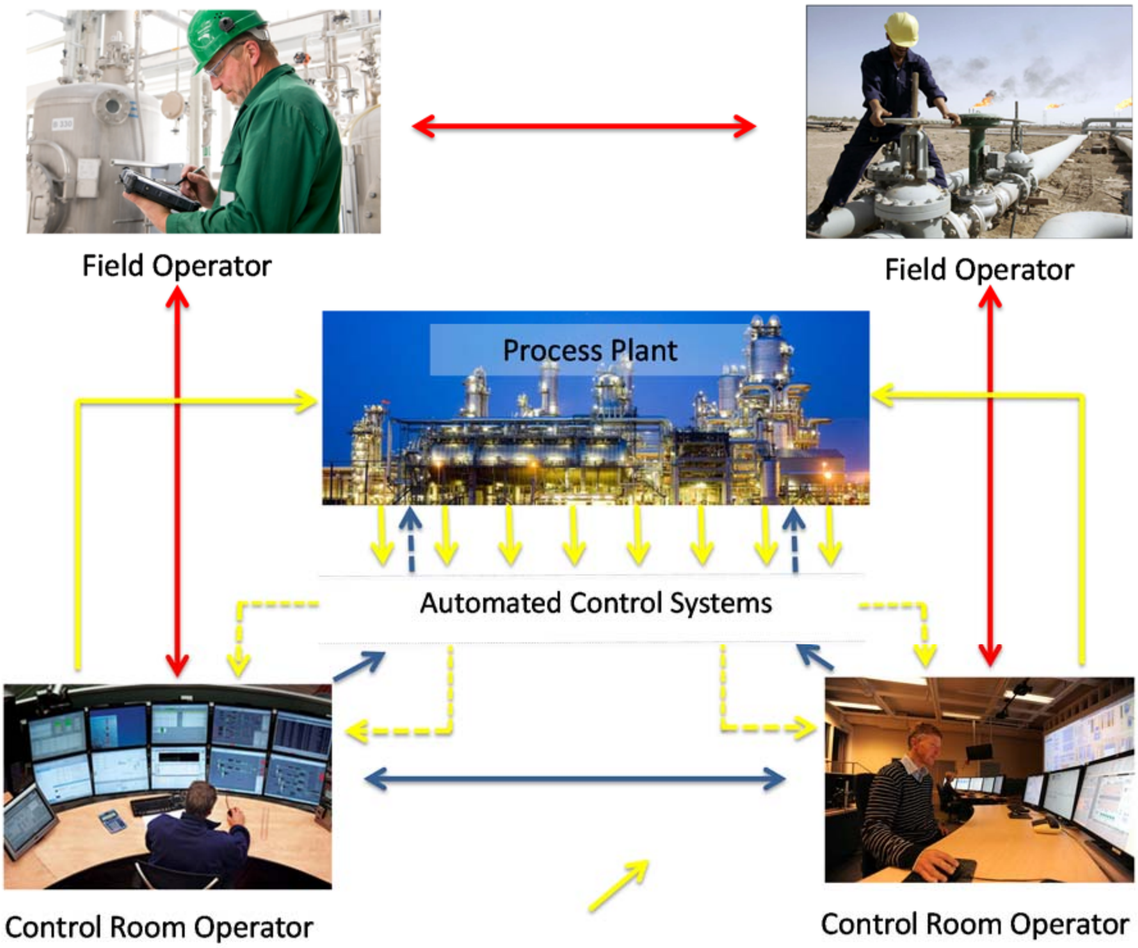

Figure 1: The control situations and their interconnections among various agents that constitute DSA in chemical and nuclear industries. The Red Arrows show communication, Blue Arrows show Control Action Input, Dashed Arrows indicate information modified by Control Systems, and Yellow Arrows show feedback to the (sub)system

3. Subsystems in maritime domain

The main activity in the maritime domain is to navigate vessels between ports. Maritime Navigation is composed of hardware in the form of vessels (e.g., hull, machinery), of control system hardware (e.g., input devices, screens, dials) and of software in the form of control systems (e.g., dynamic positioning systems; Sørensen, 2011) and finally of the operative environment – which is continuously changing and that requires constant adaptation. The maritime domain is also characterized by a number of factors that greatly increase complexity of operations such as the lack of standardization of interfaces and technology, complex and variable team compositions, changing constituents of work teams, cross-disciplinary teams, and the geographical distributions of workers and teams. Figure 2 shows the schematic overview of the main components/teams aboard a vessel and their interconnections.
As mentioned above, the crew aboard vessels can vary greatly, but there are two major teams (navigators and machine engineers) that are always aboard large vessels. Navigators are responsible for safely and efficiently manoeuvre and navigate the ship and to show timely and correct adaptive manoeuvres when the vessel

encounters environmental challenges (e.g., weather) or other vessels/obstacles. For manoeuvring, the navigators will utilize control actions on the vessel's bridge control systems which are transduced and transformed by the automatic control systems to the effector system (e.g., propellers and rudders) that will have their effect on the water surrounding the ship's hull. The navigator's job is to adjust the vessel to disturbances from the outside world. On the other side, the machine engineers' main responsibility is to maintain and supervise the vessel's power plants to ensure that the ship has sufficient power to enable the necessary work tasks. Their work domain is restricted to the power plants itself, hence they do not adapt to external disturbances as the Navigators are doing.

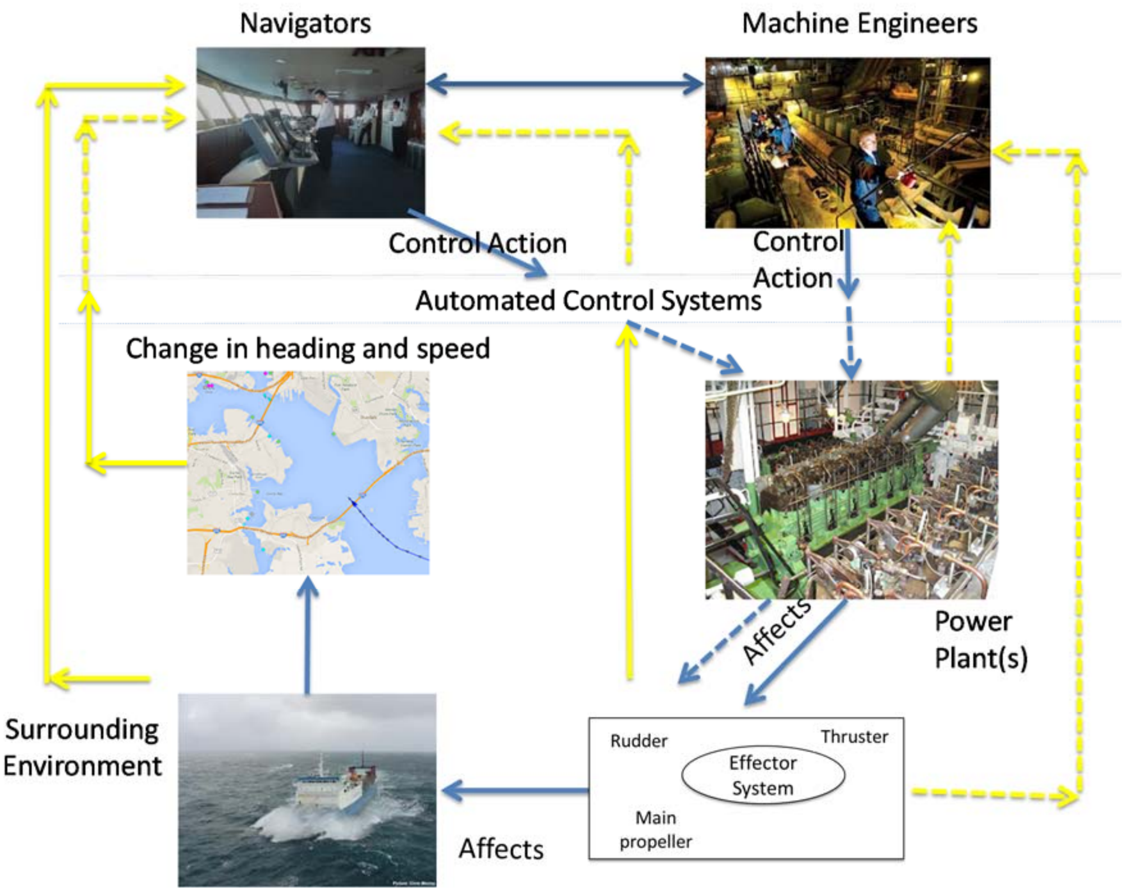

Figure 2: The control situations and their interconnections among various agents that constitute DSA in maritime industry. The Red Arrow shows communication, Blue Arrows show Control Action Input, Dashed Arrows indicate that information modified by Control System and Yellow Arrows show feedback to the (sub)system

4. Comparison of domains

The differences among nuclear, chemical, and maritime domains are evident in terms of the final product i.e. transportation in case maritime, desired product (e.g., polymer, fertilizer, commodities, fuel, pharmaceuticals) in case of chemical industry, and energy in case of nuclear power plants. However, in terms of complexity, socio-technical and control/functionality, similarities are present. Within the concept of control theory, as explained earlier, the functional similarities among various agents/sub-systems in these domains are summarized in Table 1.

The three columns of Table 1 show the common features among the various agents, independent of the terms and acronyms used. The main challenges, as categorised in the first column under the heading of functionality, are faced in each industry and a clear relevance exists. Even though, the operations and technical details have differences among these industries, the cognitive resources required by the relevant operator to successfully handle and execut the tasks are broadly similar.

Table 1: Similarities among Nuclear, Chemical, and Maritime domains/industries in the light of DSA and control situations

Functionality	Nuclear Industry	Chemical Industry	Maritime Industry
Automated control system	New plants: Real time optimization, model predictive control, dynamic predictive controllers, soft sensors, emergency shutdown system. Old plants: no digital controllers, hardwired automation, safety related functions automated	Real time optimization, model predictive control, dynamic predictive controllers, soft sensors, emergency shutdown system, etc.	DP, Machine controllers, Automatic identification systems, sensors in power plants, emergency shutdown system etc.
Presence of sub-systems	Hardware (unit operations), control systems, human operators	Hardware (unit operations), control systems, human operators	Bridge, control systems, human-machine interfaces, Human operators, external environment
Uncertainties in systems	Abnormalities in operating conditions, leakages, human error (slips, lapses, rule violations), lack of appropriate procedure, etc.	Abnormalities in operating conditions, leakages, human error (slips, lapses, rule violations), lack of appropriate procedure, lack of appropriate procedure, etc.	Unexpected events (behaviour of other vessels and weather), blackout, engine malfunction, malfunction on effector/control systems, knowledge of water depths (for coastal/shallow waters)
Human –Human Interaction	Continuous interaction among control room operators, maintenance operators, field operator, non-technical staff	Continuous interaction among control room operators, maintenance operators, field operator, non-technical staff	Continuous verbal communication within bridge and within machine room. Radio communication between bridge and machine room.
Human-Machine Interface	New plants: Distributed control screens, supervisory control and data acquisition, Process and Instrumentation displays Old plants: Analogue control rooms, hardwired synoptic panels, knobs and dials	Distributed control screens, supervisory control and data acquisition, Process and Instrumentation displays	On bridge: Radar, ECDIS, Radio communication, User interfaces for control of effector systems.
Control loops	Spread throughout the plant, interconnections at multilevel with dependencies and inter-dependencies among various agents (See Figure 1).	Spread throughout the plant, interconnections at multilevel with dependencies and inter-dependencies among various agents. (See Figure 1).	See Figure 2
Distributed nature	Subsystems and adaptive agents are geographically distant, e.g., control room operators, production facilities, and field operators	Subsystems and adaptive agents are geographically distant as well, e.g., control room operators, production facilities and field operators	Subsystems and adaptive agents are geographically distributed inside one vessel (e.g., bridge and machine room) and large operations often include multiple vessels.

5. Conclusions

This paper showed that in spite of differences in complex systems, the application of human factors constructs (DSA, in this case) allows researchers across various disciplines to work together to improve the safety among those sectors. Thus, the tools and methods developed for one domain can be deployed for another. In addition, we highlighted the necessity and importance of investigating the sub-systems in nuclear, chemical, and maritime domains. This work can be considered as a starting point to explore the similarities in terms of adaptive agents and sub-systems involved in complex socio technical systems.

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