Sensor C2 in a future operational environment - A suggestion for an experimental study[☆]

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Abstract

In a future and data-intensive operating environment, threats can be assumed to vary considerably. One example of such threats is missiles that can achieve speeds of Mach 5 and above. To handle this type of threat alone, it implies at least two things. First, that a suitable operational picture is provided that take account for future long distance threats. Second, it is likely that it will be even more important to be able to collect, filter, process and understand relevant data to make priorities and make proper decisions under short time conditions. Third, when considering threats by cyberwarfare, these threats can be considered as conducted in the speed of light. This, in summary, will probably suppose an efficient and dynamic command and control (C2) of available and different types of sensors, from directly controlled to sensors guided by artificial intelligence (AI), on a future battlefield. In this paper, we propose an experimental study to investigate from which levels of sensor C2 that can be centralised, decentralised, or a combination thereof, and which seems to be sufficient to be able to in time respond to threats in a geographically and by information enlarged operating environment.

Keywords: Command and control, Decision support, Future operating environment, Sensors, Situational understanding

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1. Introduction

Command and control (C2) as a term is in many respects a dichotomy that points to two contradictory aspects of the task of running an organisation. Firstly, it points to the creative process of exercising command. Secondly, it points to the very structures, rules, and relationships that both constrain and enable command. For a commander to be efficient, he or she needs not only to be able to cope with the problem at hand, he/she must also understand, and sometimes overcome, the control structures which are the basis of the organisation he/she is set to direct. Independent of how the control structure is designed and implemented, there are fundamental C2 functions that need to be in place in order for a military organisation to work. Several thinkers in the military domain have suggested how these functions could be modelled, such as illustrated in Boyd's observe–orient–decide–act loop, also known as the "OODA-loop" [1, 2], Brehmer's dynamic–observe–decide–act loop, also referred to as the "DOODA loop" [3, 4, 5], Lawson's model for command and control [6], etc. Almost all of these models comprise the following C2 functions: monitoring, sensemaking (here equivalent with Brehmer's late definition of orientation), decision-making/planning, and executing/acting. Of these functions, the orientation and decision-making functions have been the subject of numerous studies [e.g., see 3, 4, 7].

The function for gathering intelligence, henceforth referred to as "monitoring," has traditionally been handled by specialist staff members that aggregate information from various sources and present it to planners and decision-makers. Today, the capacity and speed of some weapon systems challenge this approach. Not only in terms of keeping situational pictures up to date in near real time, it also challenges the C2 process of directing and allocating sensors.

For our continued discussion, we are using Brehmer's theoretical framework of C2, which often is depicted in the form of the DOODA-loop [e.g., see 3, 4]. Its name; the dynamic OODA-loop, is a homage to colonel Boyd's well known OODA-loop [1]. Originally, Brehmer defined four requisite functions in his DOODA-concept [7]; (1) Data collection (2) Sense making, which later was relabelled to Orientation [see, 5] (3) Planning and (4) Military activity.

An adapted version of the original DOODA-loop was presented by Spak and Carlerby [8]. Here, the C2 system was considered as system of interest (SOI) in a system environment bounded by a mission respondent system (Figure 1). When examining the C2 system, it is basically formed by the functions and processes as suggested by Brehmer [e.g., see 3, 4, 5], but with some adjustments in labelling and with additional elements. However, considering the elements forming the mission respondent system, viz., the C2 system and the execution system and its interrelated parts, can all be considered as systems in their own right.

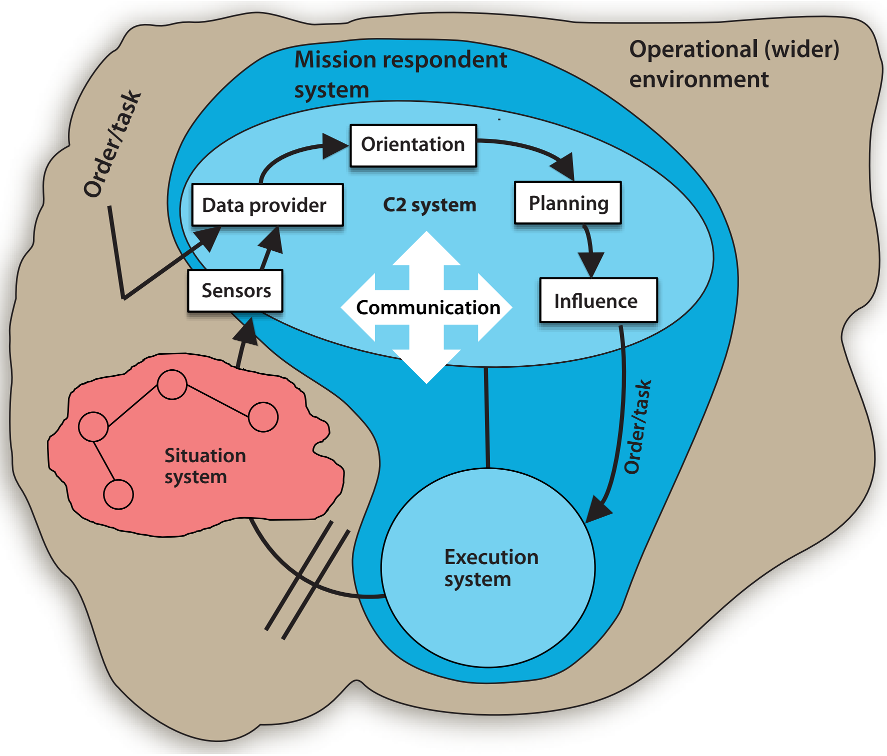

Figure 1: An adapted DOODA-loop in a systemic context.

1.1. The C2 system - its subsystems and functions

A C2 system that is formed by its subsystems can be related to Brehmer's discussion about the logic of design [7, pp. 212]. From that, Brehmer argue that the design of a C2 system basically is a top down process that start with the purpose *why* the system should be designed at the first place. The next step is to describe *what* the system should accomplish, viz., the different functions that are necessary for the system to fulfil its purpose. Finally, Brehmer put forward that the final step of the design is to describe the form of a system by considering *how* its functions are fulfilled. Brehmer also stress that the scheme can be utilised bottom-up for *understanding how* an existing system operates [5] (Figure 2).

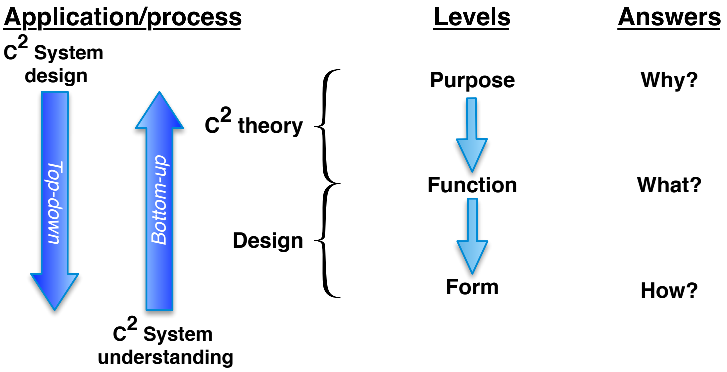

Figure 2: The basic logical design scheme [5, p. 67].

Although Brehmer relate his proposed design logic to Rasmussen's abstraction hierarchy [9], he also in his latest publication [5, p. 66] refer to Ackoff and Emery [10]. The latter authors do, however; use the term "structure" instead of "form." The two terms can generally be considered as equivalent. In this paper though, we prefer to use "structure" in the meaning of "[the] arrangement of and relations between the parts or elements of something complex" [cf., 11]. In addition, we comply with Ackoff and Emery who writes [10, p. 16]:

> "The meaning of *purpose* depends on the meaning of *function* and function is used […] in contrast with structure. Structure is a very general concept that includes geometric, kinematic, mechanical, physical, and morphological concepts." Furthermore [p. 26], "[*f*]*unction* is a generic concept as *structure* is. It is not in any sense opposed to structure but is […] completely compatible with it."

This is also in line with the argument put forward by Johansson [12] that suggests that structures both constrain and enable how and where C2 functions can be realised. Accordingly, since we consider a C2 system created by interrelated subsystems with certain purposes and functions, the structure of the C2 system and its subsystems is of interest.

Clearly, the term "system" is central in this article and thus how we define its meaning. As pointed out in Spak and Carlerby [8], the meaning of the term system is so diversified, that it is beneficial to agree upon a basic definition. Since our interest is the design of *purposeful* C2 systems, we here have adapted the definition of a system provided by Wasson [13, p. 3]:

> “An integrated set of interoperable elements or entities, each with specified and bounded capabilities, configured in various combinations that enable specific behaviors to emerge for Command & Control, C2 by Users to achieve performance-based mission outcomes in a prescribed operating environment with a probability of success.”

This definition is also compatible with the rules for identifying systems discussed by Flood and Carson [14, pp. 71]. Here, we primarily advert to the rule of defining a system that implies that the system as such, or its components can exert control over the functioning or activity of a potential component. Therefore, *if any aspect of the system as it stands can control its potential elements, then it is included as a part of the system.* If not, and it can only be influenced, or only contribute inputs to the system (or receives outputs), then it is only part of a defined system’s environment. This statement is important and also crucial when defining a system’s border.

1.2. The functions and subsystems of a C2 system

From viewing the different functions in Figure 1 as systems in their own right, any support for such a viewpoint cannot be found in Brehmer [e.g., cf. 4, 7, 5]. Thus, Brehmer do not provide any support for which purposeful subsystems that might be necessary for a superordinate mission or C2 system. Certainly, Brehmer have considered, in line with the reasoning of Simon [15], that every system [function] needs to be decomposed until an appropriate level is reached where a certain system’s structure can be found. For example, when designing subsystems that produces appropriate products. In summary, Brehmer give some examples of subfunctions [5, pp. 89]; however, since Brehmer primarily consider the DOODA-loop as a process model [5], guidelines are missing regarding the transformation from function, to structure, and to how purposeful and goal directed (teleological) subsystems can be achieved by design.

Our first objective here is to present a framework based on cybernetics and systems science that can be utilised when analysing, designing, and measure a C2 system’s different subsystems efficiency and effectiveness. From that, we will propose guidelines for an experimental study to investigate from which level of sensor C2 (centralised, decentralised, or a combination thereof) seems sufficient to be able to in time respond to threats in a future operational environment.

2. Systems, subsystems, and the necessity of recursive control

A simple C2 system requires at least two interrelated systems. One system that can exercise command and control and one system that are commanded and/or controlled. Yet, when considering C2 systems that contain some degree of complexity; e.g., by interrelated subsystems, they usually have some general properties. One example of this, which easily can be related to design, is given in Lawson [16] and is illustrated below (Figure 3).

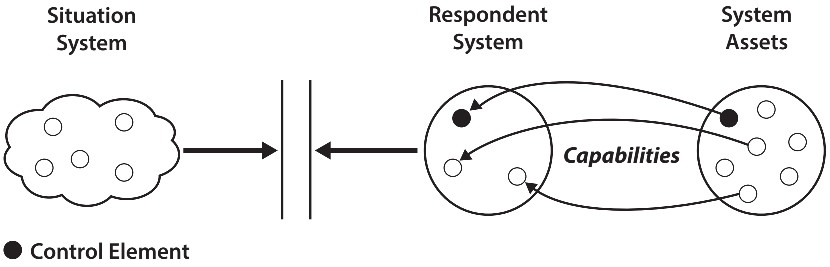

Figure 3: The system coupling diagram. *Adapted from* [16, p. 23]

In Lawson [16], the system coupling diagram can exemplify the design of a respondent system based upon system assets. These assets can be regarded as provided by a superordinate system to handle a situation, or a “situation system.” The two lines between the situation system and the respondent system illustrate the two systems’ interface. Here, the situation system provides both input to the respondent system and is the recipient of outputs from the respondent system’s actions.

Furthermore, with support of the system-coupling diagram concrete principles are provided that establish thirteen system rules defined by Lawson [16, pp. 37]. One of these rules is that one of the elements of a respondent system *must* provide control of its own assets. Both the control element with the respondent system’s all available assets can however, be viewed as functions or subsystems of the responent system itself. Based on this reasoning, we can make a premise that designed subsystems must include a control element, which also highlights the recursive nature of decomposing system parts in included subsystems.

3. Appropriate functions and structures in C2 systems

While further exploring Brehmer's DOODA-loop (Figure 1), the C2 system can be viewed as part of a superordinate system, viz., a mission respondent system. The mission respondent system can be viewed as a respondent system designed to influence a situation, or a situation system, viewed as a system in its own right in terms of Lawson [16]. Accordingly, following both Lawson [16] and Flood and Carson [14] reasoning above, we can use a viewpoint where the boundary of our SOI either surround the C2 system and its elements, or extended to also surround the designed mission respondent system where the C2 system and its subsystems are included. From this, it follows that a mission respondent system's structure consists of interrelated subsystems that provide vital functions to operate as intended. As indicated above, the DOODA-loop, depicted in Figure 1 however lack the properties to explore a C2 system's structures and functions in a wider context.

We have found that two well known system theories are supportive where the phenomena of, in one hand, structures and, in the second hand functions, are applicable. The first theory is Stafford Beer's viable systems theory (VSM) [17, 18]. In his theory, Beer focus on the necessary content that has to be dealt with to control an organisation operating in a dynamic environment. Beer provides a basic structure connecting five interacting systems; however, he shows only each system as a black box without details.

The second theory we consider here is Miller's general living systems theory (LST) [19]. Miller, on his side, did not develop a structure for living systems. However, Miller pointed out the hierarchical relationship between subsystems and so called suprasystems, and the fact that while systems are manifested in the form of matter and energy, they are governed by information. Clearly, the two theories have different focuses and aim at different details, which also imply some problems.

A comprehensive work combining the two theories of Beer and Miller is made by Nechansky [e.g., see 20, 21, 22, 23, 24, 25, 26] with an aim to overcome the dilemma of the two theories focus of different details. Nechansky propose translating Beer's data-processing structures into a functional and structural approach to goal-oriented systems according to Miller's LST [23].

Adopting Nechansky's suggestion of how to combine the two theories, it is also possible to derive a respondent system's necessary input, components, their function, relations, and a system's output (cf. Figure 3). In addition, Nechansky also explore social systems goal values and where they are heading, which can be expressed as follows [26]:

$$\begin{aligned}&if\{[(external\ sensor\ data\ S1)\ (relation)\ (goal\text{-}value\ G1)]\}\ \text{AND}\\&\ \{[(internal\ sensor\ data\ S2)\ (relation)\ (goal\text{-}value\ G2)]\},\ then\\&\{trigger\ for\ a\ goal\text{-}orientated\ action\}\end{aligned}$$

By this expression, both sensors, that collect data from an operational (external) environment and sensors that provide data about fulfilment of internal goal(s) values can be accounted for. Nechansky provides a combined model that includes both Beer's system 1 to 5 and Miller's living systems. Hence, Nechansky [26] suggest that Miller's subsystems of processing *matter-energy* correspond to Beer's system 1 (operations) (see Figure 4). However, when discussing the validity and limits of his proposed approach, Nechansky make some interesting remarks that might affect sensor C2 [24, p. 106]:

> "[S]tructural considerations may loose unequivocally, because Beer's hierarchical issues and the related hierarchical decisions do not necessarily need the hierarchical structure shown in [Figure 4] and developed to match Beer's (1979) schemes. Any complex system with sufficient data processing capacity could handle the logical hierarchy of all these issues in a sequence, using just two levels. Then the upper level has to control which issues of systems 1–5 are currently processed and to make sure that the right data and goal-values are used for decisions at the lower level. This is the principle how a computer could process these issues. This would translate the processing of Beer's issues of system 1–5 into only two structural levels instead of four as shown in [Figure 4]."

The above described systemic approach to C2 provide different perspectives on the same fundamental problem; namely, how various structural arrangements can realise a set of fundamental functions. This has been applied in C2 agility theory which suggests that different structural arrangements for realising C2 are more or less appropriate for coping with different types of problems, or situation systems, using Lawson's terminology [16].

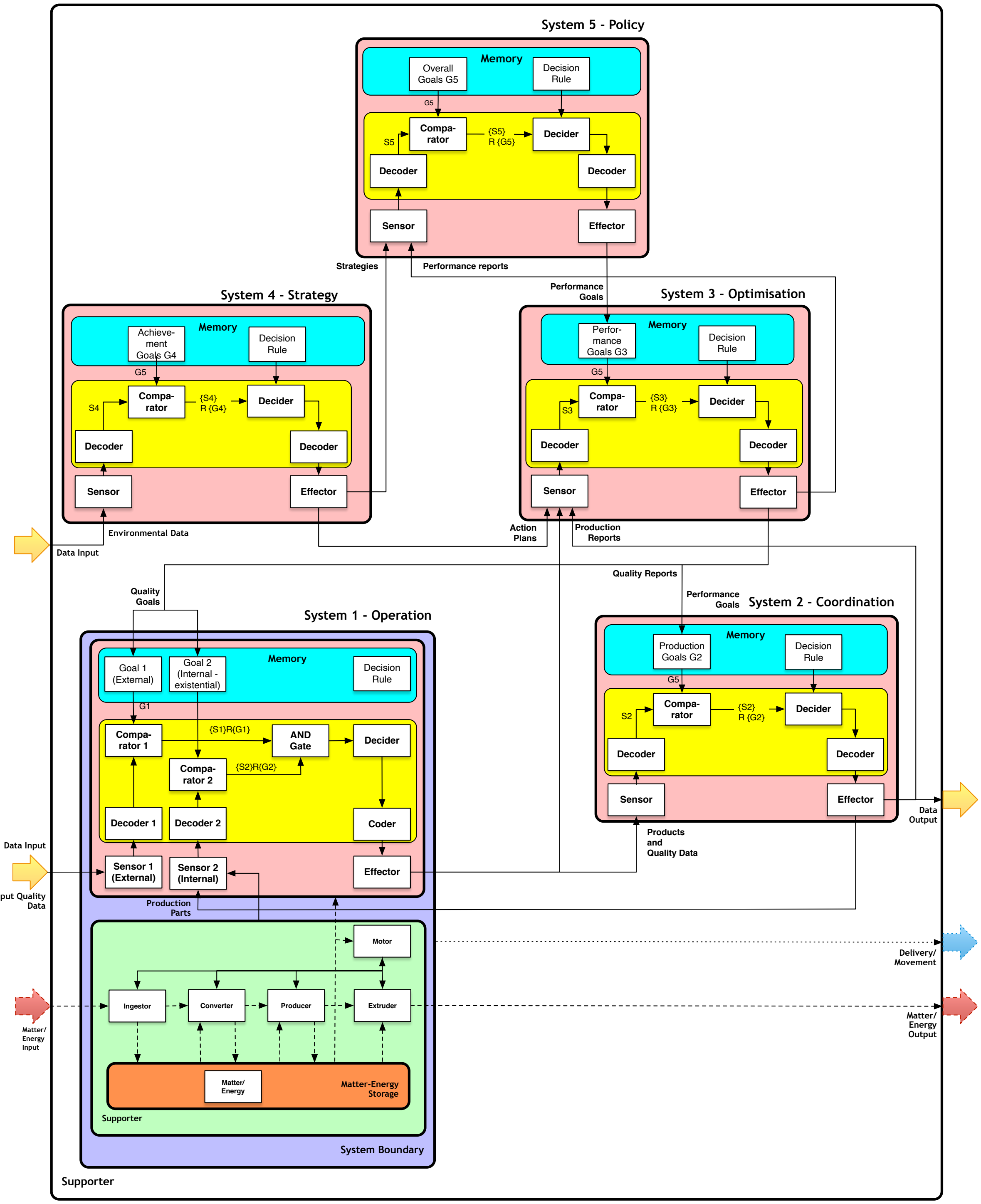

Figure 4: The structure for a viable system according to Beer with a structure for a living system according to Miller (lower left), with an enlarged feed-back system to control any production system. *Adapted from* [26].

C2 agility suggests that C2 can be described along three basic dimensions that frame the approach to realising how C2 is conducted: allocation of decision rights (which describe how control is distributed in the system and who actually has the mandate to allocate resources that interact with the situation systems, distribution of information that describes how information is disseminated within the system, and who actually has access to critical information about the situation system and own assets), and interactions (who can actually interact with whom – usually corresponding to organisation of the system).

As mentioned above, the fundamental argument of C2 agility theory is that different structural configurations will realise fundamental C2 functions in different ways that are more or less appropriate for different situations. This becomes evident already on the level of data collection (sensing) and data processing (from a human point of view "sensemaking" or "orientation"). Depending on the structural configuration of a system, available data will be gathered and transmitted to certain parts of the system, where it will be processed and turned into some type of information. This information will in turn be handled and used for decision making by certain individuals, depending on how information dissemination is arranged and how decision rights are allocated within the system.

As in any control task, information must flow at such a pace that the controller can utilise assets in a timely manner to express the requisite variety for maintaining control of the target process, or the situation system. C2 has by tradition and necessity due to limitations in communication technology (or lack thereof) been organised as hierarchies, both in terms of information flows, interactions, and allocation of decision rights. This has been a viable approach for a very long time, due to the fact that war has been an activity conducted by human beings.

The technical development during the twentieth and twenty-first century has challenged this fundamentally because technology has allowed for an increased speed of warfare, as well as geographical distribution of long-range weapons and logistics allowing for quick transportation of soldiers and weapons systems. Hierarchies, as structures for military C2, have been questioned repeatedly [27, 28, 29] but remain unchallenged as the main way of organising/structuring military continue to prevail. As pointed out in the beginning of this paper, the speed of some kinetic weapons, like ballistic missiles, has turned even the sense part of data collection into a major topic. Also non-kinetic capabilities; e.g., cyberwarfare, is a contributing issue for development of novel sensors to allow quick and effective countermeasures against an aggressor.

The ability to focus the right sensor in the right place at the right time is increasingly challenging. In a traditional and hierarchical, organisation, the structure of information channels and the allocation of decision rights usually is cumbersome in the sense that the individuals directing sensors rarely the ones that have the authority to decide where to direct them. Nor are they the ones interpreting the data produced by the sensor. All functions are divided into subtasks performed by a multitude of individuals coordinated by a few with the power to control the others. This creates “knowledge bubbles” within the system that simultaneously are burdened with control tasks.

Technology, in the form of highly coupled systems, and often automated, are used to overcome this by aggregating data from multiple sensors and performing computerised analysis of the data. Objects are detected, classified as targets, assigned identities (IDs), and tracked without involving any human activities. However, the structure realising other functions, such as orientation and decision making, is still manifested in the form of a hierarchy. For some weapons system there is local work-arounds such as allocating decision rights for critical systems to the individuals operating the same system, as in the case of some surface-to-air missile systems. Such systems are usually highly automated, and the only decision left to human operators concerns if a target should be engaged or not. The placement of such a system, and the way sensors are directed, is however, still a high-level decision performed by staff functions in the military organisation.

4. Summary and discussion for future work

The C2 of sensors is a field that is in need of further investigation. As the discussion of C2 and control models above suggests, the sensing ability of a system is a crucial factor for utilising system assets in a good way. Hence, our starting point is linked to our interest in designing purposeful C2 systems with suitable functions and structures. In addition, one objective in this paper was to present a framework based on cybernetics and systems science that can be utilised when analysing, designing, and measure a C2 system’s different subsystems efficiency and effectiveness. However, the structures realising these functions can be allocated in a potentially infinite number of ways. The hierarchical structures common to military organisations has sprung from a need to exercise control over other human beings. This is no longer the case. Today’s systems are truly socio-technical in the sense that they consist of a mix of capable technical system with advanced sensing capabilities existing side-by-side with human operators.

Previous research suggests that even if there is a large body of research on decision making under time-pressure, such as “dynamic decision making,” largely has focused on regulating tasks instead of high-level decision making [cf. 30, 31]. Simulation studies using microworlds, or so called scaled worlds, was a major breakthrough in such studies as it allowed for controlled experimentation in an interactive environment [32]. This allowed for studies of abstracted real-world tasks such as forest fire-fighting and chemical processes. In practice, these problems demanded continuous regulation of involved processes. In contrast, other researchers applied microworlds to study complex problems solving, such as acting as a major of a large city or the manager of a third world aid project [30]. None of these examples really reflect the problem described above which, for the human part, mainly is a problem of forecasting from which direction a threat may occur. To investigate this issue, a microworld approach may still be valid. Gonzales, Vanyukov and Martin [33] provide a detailed list of the most commonly used microworlds, which are informative for anyone seeking a broad perspective on the types of problems and simulations that have been developed. The purpose of a microworld is thus to present a recognisable problem to the subjects taking part in a study. However, the microworld must still be complex enough so that the subjects experience a dynamic situation presenting a certain degree of uncertainty. Johansson, Persson (a.k.a. Carlerby), Granlund and Mattsson [34] suggested that microworlds could be used to study C2, and provided examples of how this had been done using the C3Fire system.

4.1. Future work

Many tasks previously performed by humans are now entirely conducted by technical systems, which in turn operates at such speed that even more technology is needed to supervise them. Human decision making increasingly concern decisions on the level of policy or goal setting, while technical systems execute complex chains of tasks in the form of automated responses verging to what we call automation. For example, the Patriot system MIM-104 identifies IDs and presents potential targets to human operators whose main task is to verify whether the targets are hostile or not, and whether they should be engaged. All other aspects of the system are automated. The human component in the system thus perform only a part of sense making, or orientation in terms of Brehmer, and decision making. However, this assumes that someone already has decided where and for what sensors should sense for potential targets. This is a plausible task for humans, if it is possible to determine from what direction a threat may come, and if the threat moves at such speed that the human operator has enough time to verify the target as hostile and decide upon engagement.

On the other hand, in a future operational environment this may mean that the task of the human increasingly becomes to decide the location and direction of sensors instead of executing the orientation–action part of the C2 cycle as the latter will demand much swifter execution than is humanly possible. This can also be related to the quotation of Nechansky above and the model depicted in Figure 4. Thus, implementation of both present and envisioned technologies in the operational environment also might imply a forced "technology compression" of C2 where the orientation–action part of the C2 cycle can be handled by technology alone. For example, where artificial intelligence (AI), implemented as System 2, command and control instances of System 1 and for some time can override input from system 3, 4, and 5 (cf. Figure 4). Accordingly, the C2 of sensors is already a crucial part of the C2 cycle and will be so even more in the near future. How should then the problem of understanding sensor C2 be handled?

To study how a socio-technical system comprising both humans agents and technical systems with orientation and decision-making capabilities coping with the task of placing and directing sensors to cope with high-speed threats requires a simulation system that reflects these aspects. It must present a problem similar to the real world system, although not necessarily with a high degree of realism. It is unnecessary to simulate each step of the sensor-to-shooter chain. Instead, it must only reflect the fundamental problem of placing and directing the sensors, and then provide a sufficiently realistic evaluation of the outcome of the placement of the sensors and their direction in relation to a meaningful goal. The simulation should further be able to perform simulation runs to evaluate the consequences depending on from where an attack would be launched and with how many munitions. Such a simulation could thus be a "one shot game" for each specific configuration of sensors, albeit the outcome could be simulated from several different plausible actions from an antagonist.

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