Integrating Cognitive Sensors in the Intelligence Cycle

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ABSTRACT

This paper discusses the emergence of cognitive sensing in a NATO environment, with special attention for 'mission-cognition'. Mission-level cognition will require a novel approach in how these systems are integrated into the intelligence cycle. The optimisation of remote sensing capacities at mission level will allow for currently unseen advantages but also introduces new risks which have to be managed properly. The structure of this paper is to introduce mission-cognition as a concept, followed by a brief description of the current NATO Intelligence cycle. Finally, a number of contextual developments is referenced which may facilitate the adoption process of especially 'mission-driven' cognitive sensors.

1.0 INTRODUCTION

As often repeated in military literature, Sun Tzu already identified one of the key enablers for victory in battle: "Military intelligence is the key to war: without it, you cannot win". NATO has adopted this lesson via the AJP-2.7 "Allied doctrine for Joint Intelligence, Surveillance and Reconnaissance (JISR)" [NAT20]. This doctrine defines the Joint ISR process as the cornerstone of intelligence support to NATO. This process synchronizes and integrates the planning and operations of all collection capabilities with the processing, exploitation and dissemination of the resulting information to support operations.

In their final report, the NATO SET-227 Panel on Cognitive Radar captures the 'state of art' of modern sensors. Reference A summarises this report and describes how sensors are increasingly becoming aware of and adapting to their mission by means of cognition. The key concept in a cognitive system is the 'perception-action cycle' (PAC), a feedback mechanism allowing the sensor to observe its environment, where 'lessons learned' will be used to adjust the sensor to the environment or the ongoing mission.

Similar to the process of human cognition, future radars may optimise their detection performance through an increasing range of technologies like adaptive beam forming, dedicated wave forms, advanced clutter suppression methods and intelligent scheduling techniques. Cognition allows sensors or networks of sensors to reason about ongoing scenarios, with the aim of optimising its behaviour accordingly. Such networks need to be managed or controlled from a mission perspective, with operational measures of performance as leading principles.

The current JISR process entails a continuous loop of tasking, collection, processing, exploitation and dissemination (TCPED) of data, while the planning and tasking process ensures an optimal use of available collection platforms. However, cognitive sensors require degrees of freedom to optimise their behaviour and the existing JISR planning process may not be able to deal with this higher degree of autonomy from sensors.

A future JISR process needs to be able to handle highly autonomous sensors, both in how and where these sensors collect their data. As with Artificial Intelligent (AI) systems, cognitive sensors may be limited in explaining how particular conclusion have been reached, leading to challenges for JISR analysts to incorporate these results in the overall intelligence cycle.

This paper describes a number of selected topics related to the introduction of cognitive sensors in the NATO JISR processes, as an initial preparation for the proliferation of cognitive sensors in NATO. These topics will support NATO in monitoring the emergence of cognitive sensors and will prepare the Command Structure for a revision of the JISR process to embrace the benefits of such sensors in the future. The NATO CI Agency / JISR Centre supports the Allied Command Transformation (ACT) Science and Technology program with ongoing research on the emerging cognitive sensing and the subsequent introduction of this next generation remote sensing in NATO.

2.0 COGNITIVE SENSING

2.1 Emerging cognitive behaviour

In December 2019 S.Z Gurbuz and a team of co-authors published a paper on the past, present and future of cognitive radar [GUR19]. This paper reflects the final report of SET-227 on Cognitive Radar and presents a comprehensive overview of what cognitive radar entails and how the emergence of this newest generation of sensors and sensor networks may shape our future.

Detection of targets by means of transmitting signals and analysing the returns of these signals has been in use since World War II. Since then, the use of radar has evolved, leveraging the advantages of developments in radio frequency technology, signal processing, antenna design and software capabilities. Radars have become intelligent: they are able to adjust their settings to particular targets or circumstances through the use of adaptive waveforms, smart antenna beam forming techniques and processing algorithms like adaptive clutter suppression, resulting in increased detection performance, tracking capabilities at lower power emissions and lower probability of intercept signals.

Secure, high throughput networking options opened up opportunities for radar networks where distributed processing and multi-static detection further increased the overall surveillance capability. With many modern radars developed around a core of Software Defined Radios (SDRs), future sensor networks may look more like the ‘internet of things’, where any available sensor becomes part of a network rather than the highly expensive and costly dedicated radar systems of today.

The introduction of AI and more specifically machine learning (ML) has unlocked the next level of performance, referred to as ‘cognitive radar’. Although there is some confusion or even disagreement within the scientific world of the exact definitions, this paper follows the classification as provided in [GUR19], expanded with alternative definitions or descriptions obtained from an additional literature search:

Sensor classification	*Behavioral aspects*	*Potential alternatives*
Smart	Ability to adapt to the environment	uses advanced signal processing techniques to improve its performance, such as target detection, tracking, and identification
(Distributed) Intelligent	Often used interchangeable with ‘smart’	incorporates artificial intelligence (AI) algorithms to make decisions and adapt its operation based on the environment

Adaptive	Able to change processing of received signals as function of the environment	system that can adjust its parameters in real-time based on the changing environment
Fully adaptive	As 'adaptive' but with ability to change transmitted signal as function of target or environment as well	system that can adjust all of its parameters, including waveform, beamforming and processing, based on the changing environment
Cognitive	Mostly used synonymously with 'fully adaptive', 'intelligent' or 'smart'	mimics the cognitive processes of human perception, such as learning and decision making, in order to improve its performance

Table 2-1: Sensor behavioral classification [GUR19]

In 2006 S. Haykin published a paper which coined the term 'cognitive radar'. In his view, such a cognitive sensor requires three distinct features: "intelligent signal processing, which builds on learning through interactions of the radar with the surrounding environment; feedback from the receiver to the transmitter, which is a facilitator of intelligence; and preservation of the information content of radar returns" [HAY06].

Effectively, Haykin describes a feedback loop with the ability to learn from previous experience and retain this knowledge for future application in a dynamic environment. The concept of cognition originates from the field of neurobiology, where J. Fuster defined 'cognizance' in a human or system by the presence of a number of features [FUS03]. One of the prime features is the so-called 'perception-action' cycle (PAC). In [BRU18], Brüggenwirth et al present a three-layer cognitive radar architecture which clearly centralizes around the notion of the original PAC as described by Fuster:

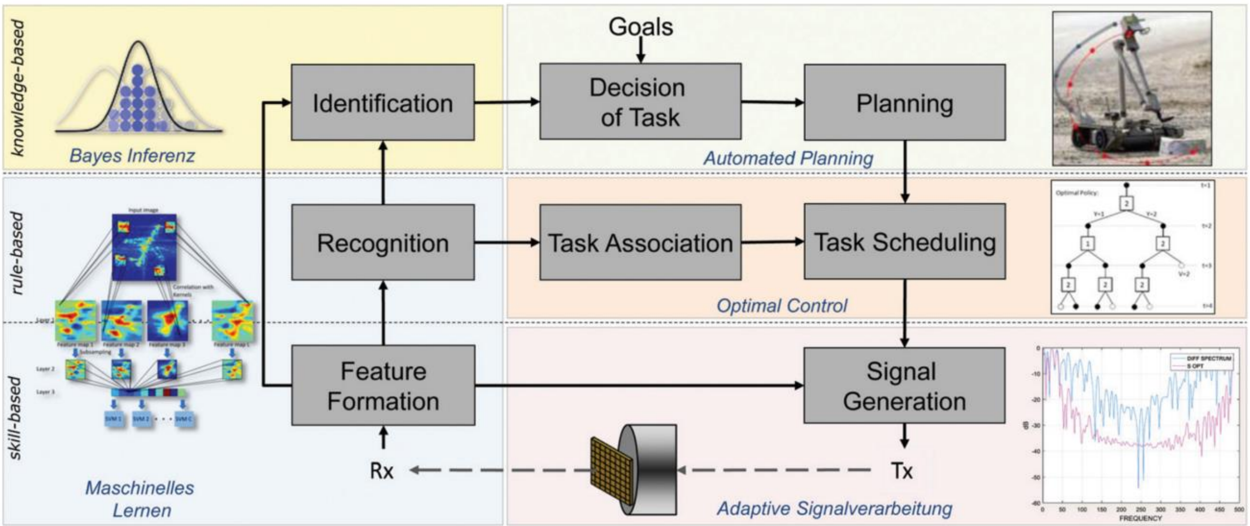

Figure 2-1: Three-layer cognitive radar architecture [BRU18, fig. 4]

2.2 Cognition in remote sensing

Many definitions concerning cognizance in sensor systems aim at the detection and tracking performance as a function of the *environment*.. These techniques improve the 'what' function of the radar rather than the 'why'. What refers to the identification and tracking of objects in the coverage area, where 'why' looks for reasons behind the observations.

Target trackers are mostly based on probability density considerations through models like Multiple Hypothesis Filterering (MHF), various members of the Kalman Filter (KF) family, Particle Filters (PF), Joint

Probability Density Association (JPDA) and so on. Such models are used to estimate the target's future position in order to optimise the detection performance. These approaches do not allow the extraction of meaning from how the track develops but only support the track maintenance function. The time horizon is limited to a milli-seconds to seconds timeframe, where the radar estimates the most reliable forecast of the target's position for the next update. Forecasting into the future for longer time periods will quickly reduce the reliability of the estimate, especially in case of highly manoeuvrable targets.

For decision makers using the sensor output, like air traffic controllers managing aircraft or for targeteers conducting a military operation, there is another dimension which becomes increasingly more important. It is not so much *what* is happening at a certain moment in time, but why it is happening. Long-term observation of the same airspace may reveal 'patterns of life' and detection of deviations from these patterns may be a pointer for the decision maker that her or his attention is required. Extracting patterns of life from a series of observations requires the Perception-Action cycle from Fig. 2-1 and therefore implies cognitive abilities in the sensor.

In [HAY06], Haykin does not reference cognitive abilities at the mission level but describes how sensors employ cognition to optimize the sensor performance. Learning abilities from a 'Haykin-cognitive' system focus on the interaction of the radar with the environment. This allows the introduction of a 'mission-cognitive' system, which optimizes its behavior as function of the *scenario* rather than the environment. Extending Haykin's approach to Bolderheij's concept of 'mission driven sensor management' [BOL07] now presents a two-level cognitive sensing approach as represented in the following table:

Cognition Level	Objective	Focus of the PAC	Time Horizon
Operational / Mission	'*Why'* do we see this ?	Mission, scenario	Minutes - Hours
Tactical / Technical	'*What'* do we see?	Environment, weather, clutter	Millisec - Sec

Table 2-2: Levels of cognitive sensing

In addition to the separation into 'tactical/technical' and 'operational/mission' cognition, there is another division, which is useful for the introduction of cognitive systems in the military command and control environment. Reasoning about the mission can be simply based on the sensor's own measurements, for instance in the case of an air surveillance system which needs to monitor air traffic. If no external information is used, such a system is called '*endogenous cognitive'*. Likewise, for systems, which use external sources of information to support learning or to improve the reasoning process, the term '*exogenous cognition*' is used. External sources of information can be any other type of data relevant for the scenario at hand, including other similar or non-similar sensors.

2.3 Performance Measures for cognitive systems.

By nature, a cognitive systems contains a knowledge base and an inference module, analoguous to a 'formal system' as described by Gödel [GÖD13]. Generally, a *formal system* is a system of axioms and rules of inference, where the application of these rules may generate new axioms. Knowledge can be described formally in terms of a data model, where the data elements have a strong similarity to the axioms. Reasoning in a cognitive systems comprises the process of recursively applying the rules of inference on the axioms, which could produce new and logically consistent axioms (the system is 'learning').

Consistency requires that there exists no statement such that the statement itself and its negation are both derivable in the formal system. For practical applications like cognitive radar, this means that there should not be any contradictions in the reasoning process, whereby the same axioms but with different rules would lead to a particular conclusion and at the same time the negative of the same conclusion. Proving consistency and completeness for a cognitive system or any other form of AI will be governed by both of Gödel's Incompleteness Theorems [GÖD13], a topic for future research.

Besides incompleteness and consistency, there are other features of cognitive systems which need to be better understood. Especially in the domain of cognitive sensing, knowledge representation within the sensor network, the approach towards building knowledge, timeliness of the output and the ultimate explainability of the sensor's decisions are aspects which bear significance on the way such systems can be introduced in the military environment.

3.0 CREATING 'UNDERSTANDING': THE INTELLIGENCE CYCLE

3.1 Introduction

Military decision making is characterised by significant levels of incompleteness, uncertainty and sometimes even unreliable or conflicting information as hostile forces may actively attempt to inject false information into the decision cycle. These challenges influence the initial understanding of a situation, the potential solutions that may be found and the estimated outcomes of each of these solutions. Consequently, the quality of the decision making process depends directly on how well uncertainty can be managed. The process to create an optimal understanding of the situation and the options available to Commanders is called 'intelligence', allowing these commanders to take informed decisions in terms of timeliness, accuracy and relevance.

Decision making under uncertainty has been studied for a long time by now. In his Chapter in the Handbook of Military Sciences [RIE21], Rietjes describes the shift from the traditional Jominian school of thought towards the more modern Clausewitzian approach. Both strands consider uncertainty as undesired but take different approaches towards reducing the impact on the decision cycle. Where the Jominians assume that uncertainty can be removed completely by breaking a problem down in solvable sub-components, the Clausewitzians acknowledge that uncertainty is unavoidable and can only be dealt with through reduction instead of full elimination.

Contemporary conflicts are characterized by significant complexity and inherent unpredictability, similar to the way Clausewitz described war. The actions from opposing forces are difficult to predict and do not only have a military component, but also need to be viewed in terms of the socio-economic, legal and ehtical contexts. The battlespace is in constant state of flux and is heavily influenced by new technologies, such as drones, cyber warfare, and AI, which can create new vulnerabilities and opportunities for both sides. Where in the past the enemy tried to obfuscate its presence and intentions, the challenge now seems to swing to the other side, where understanding and meaning needs to be distilled from a large surplus of potentially unreliable data, the so-called 'big data' problem. A problem for which the use of traditional analytical tools seems insufficient and for which Artificial Intelligence may be the answer.[1]

3.2 Structuring 'understanding' in the military domain

In NATO and many of the NATO Nations, the Intelligence Cycle (IC) is the cyclic process by which available information is collected, processed, and disseminated to decision-makers according to their direction, in order to inform their actions. The JISR process sits within the intelligence cycle and is used to task the collection, processing, exploitation and dissemination of single source intelligenct to address an intelligence gap identified during the intelligence cycle. The JISR process can use a wide range of platforms to gather information and a variety of analytical techniques to process and extract meaning of that information.

[1] Big Data in the Military – Preparing for AI | Emerj Artificial Intelligence Research (https://emerj.com/ai-sector-overviews/big-data-military/)

Should the required information not be available, an intelligence gap is identified. This triggers additional collection through the JISR process as highlighted in Fig 3-1, whereby a collection request is received, an asset is tasked, collection takes place through the most appropriate means, the information is processed then exploited by an intelligence analyst before being disseminated to the requestor.

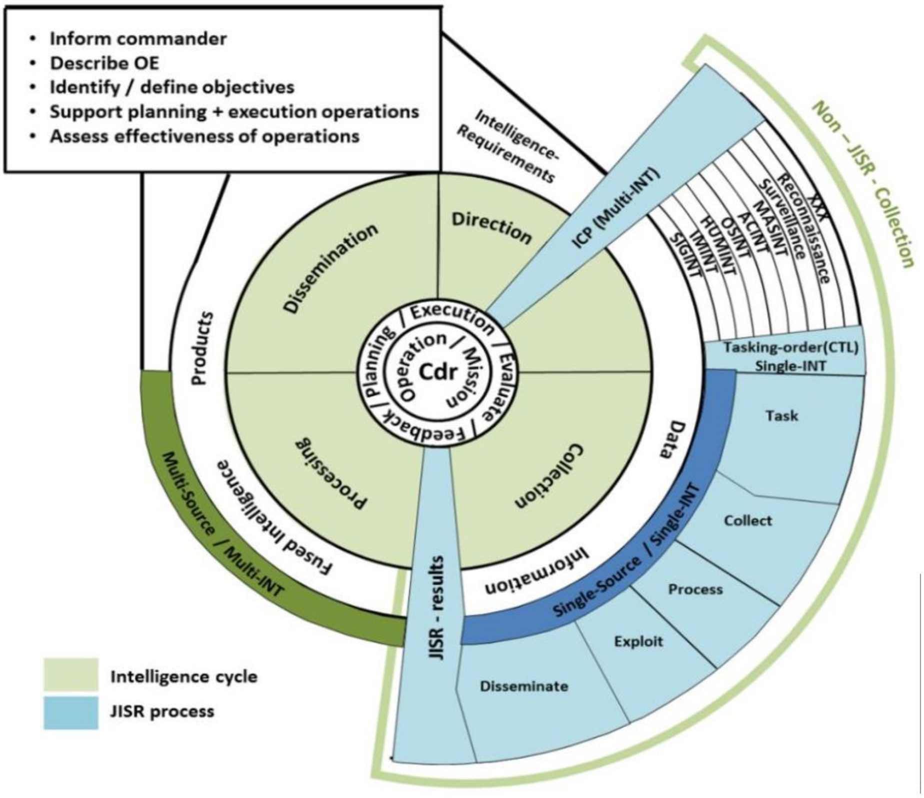

Figure 3-1: The NATO Intelligence Cycle and the JISR process

By using the intelligence cycle, the operational commander is better able to understand the battlefield and potential threats, and can make more informed decisions about how to respond. Additionally, the intelligence cycle helps military leadership to better understand the context and the environment in which they are operating, which can make operations more efficient and effective.

3.3 From sparse to big data sets

The proliferation of relatively cheap and mobile computing devices like mobile phones and tablets, have turned any individual into a possible sensor. Even the most basic mobile phones are equipped with a range of sensors, like GPS, attitude, wireless network interfaces, cameras etc. This trend doesn't stop with mobile phones but also extends to other equipment like household appliances, cars and even humans in the form of 'wearable devices'. The push for global connectivity is dubbed the 'Internet of Things' (IoT), with an estimated daily data production by 2025 of an impressive 463 EB or exabytes, where a single exabyte is $1{,}000^6$ bytes.[2]

On the military side, similar patterns can be seen. Individual weapon systems, like vehicles, aircraft etc, are equipped with a multitude of on-board sensors, including data links to allow sharing of relevant mission data. Despite on-board processing prior to dissemination, the timeliness and volume of the collected data sets

[2] Infographic: How Much Data is Generated Each Day? (https://www.visualcapitalist.com/how-much-data-is-generated-each-day/)

exceeds the human capacity to digest and process quick enough to extract meaningful mission data. As such, the modern mission environment can be considerd a 'big data' problem 'avant la lettre', requiring dedicated tools like smart storage / filtering, distributed processing and machine learning to extract meaning from the data.

Advanced machine learning may allow commanders to benefit from real time data analysis, have increased situational awareness, may support automated decision making and may include predictive features to simulate the effects of decisions in the form of 'what if' analyses. It is important for NATO and NATO Nations to ensure a seamless transition in the intelligence process, from the classic sparse data sets into the big data world that the military environment has become. Such transition needs to ensure that the military domain gets access to all benefits while reducing any disadvantages as much as possible.

4.0 CONTEXT FOR COGNITIVE SENSING

4.1 Introduction

Chapters 2 and 3 introduce the concepts of cognitive sensing as an emerging technology and the existing Intelligence Cycle as NATO's current method to structure the collection and processing of information, leading to a better understanding of our operational environment and actions. Both sections underline the importance of a seamless introduction of general AI concepts and especially cognitive sensing in particular. Although subject to future research, section 4.2 postulates that cognitive sensors map differently to the Intelligence cycle when compared to classic sensors.

While technology progresses, the same holds for the ideas and concepts developed by modern military strategic thinkers. Two relevant developments in particular deserve further attention, being the Multi-Domain Operation (MDO) doctrine and the '*problem-centric thinking*' which succeeds the more traditional 'target centric thinking'. Both MDO and 'problem-centric thinking' are briefly introduced in section 4.3 resp. Section 4.4, including a first approach on how each of these relates to cognitive sensors.

4.2 Mapping cognitive sensing to the Intelligence Cycle

Fig. 3-1 shows how sensor management sits within the blue JISR process as part of the overal green Intelligence Cycle. Cognition at the technical level is therefore considered as the next generation sensor optimisation for especially the JISR process. Mission-based cognition will eventually behave more like an autonomous intelligence analyst and as such, may act more on within the 'green' intelligence cycle. This is not a significant improvement of sensing quality but a paradigm shift which will require a different mindset from an intelligence doctrinal perspective.

Optimising sensor performance with regard to the mission, requires the sensor logic to be able to step through similar steps as the Intelligence cycle so: task, collect, process, exploit and disseminate. As the acronym 'TCPED' is mostly assuming a centralised intelligence process, the steps in this cycle have been loosely translated into 'direct', 'collect', 'process' and 'disseminate'. Fig. 4-1 shows a rudimentary mapping of the elementary steps in a misson-cognitive perception-action cycle may coincide with the intelligence planning process.

Society is now slowly becoming exposed to AI tools where these tools are able to engage in conversation or can do relatively complex tasks like generating coherent texts or computer code, nearly indiscernable from human authors. ChatGPT is currently the best known example of such an online AI. Although ChatGPT has achieved remarkable and impressive results in certain areas, the darker side also shows elementary flaws like biases in responses and sometimes even complete incorrect, fabricated or irrelevant answers to particular questions. As these answers are still presented in a very coherent way, a human reader may not be aware of the reliability of the response anymore.

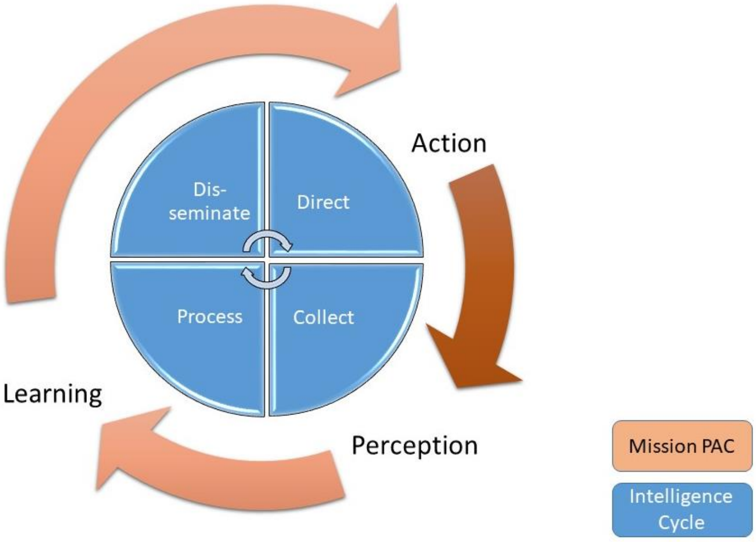

Figure 4-1: Mapping of a Mission-cognition PAC on the stages of the Intelligence Cycle

With the introduction of AI-based technology like mission-cognitive sensing, a number of new challenges will have to be addressed as part of the adoptation process. Several have been mentioned earlier in this paper, like the way to interface with these systems, the learning process, the reliability and maintainability of the knowledge base, the levels of integration of cognitive systems with other systems acting on the battle field etc.

The NATO CI Agency together with the Allied Command Transformation in Norfolk, have started a science and technology project in early 2023 to specifically investigate the challenges and potential solutions for the integration of cognitive sensing into the NATO intelligence cycle, to ensure a seamless transition at the moment that 'mission-cognitive' sensors will become operational reality.

4.3 Multi-Domain Operations (MDO)

NATO recognises the need for Joint operations as the response to a continuously changing battlefield with ever increasing complexity. The term 'joint' refers to an integrated concept including the traditional warfare domains of land, maritime and air warfare, with cyber and space as the two newest adoptions.

In the executive summary of the draft Initial Alliance Concept for Multi-Domain Operations [NAT22], the authors of NATO's Allied Command Transformation identify the current challenge as follows: "Military commanders face an increasingly complex battlespace that has indistinct geographical boundaries and where adversaries can project power and influence across all domains". Through the concept of Multi-Domain operations, NATO now recognises the need to include non-military or non-chain of command effectors in the decision cycle. To reach this effect, much more emphasis will be put on collaboration, coordination and synchronisation across areas extending the usual land, air, maritime, cyber and space domains.

The MDO concept acknowledges the need for a more holistic approach towards creating 'understanding', where understanding must be seen in a much wider context than just the military environment. Politics, economics, legal structures, cultures, geographics, history etcetera all contribute to the situational awareness which drives effective military operations. Military sensing, strictly limited to detecting objects on the battlefield, will have to follow along similar lines of development. Cognitive sensing, especially cognition at the mission level, may be the next generation sensing capability as needed from an MDO perspective.

4.4 From 'Target Centric' to 'Problem Centric'

Besides the holistic approach via multi-domain operations, there's another development which will affect the integration of sensors into the battle space. Partially inspired by MDO, operational military commanders slowly adopt a more problem-centric rather than a target-centric approach in their decision making.

The difference between *target-centric* and *problem-centric* is illustrated through an example from air traffic management. Besides handling the flow of air traffic, Air Traffic Controllers (ATCo's) also need to separate aircraft under Instrument Flying Rules (IFR). Target-centric surveillance would aim at providing ATCo's with a complete and reliable overview of aircraft positions, speeds and other relevant parameters. Air surveillance radars will therfore optimise their detection performance, even including a level of 'technical' or 'tactical' cognition.

A problem-centric approach would be for the air surveillance system to monitor the air picture and identify those situations which could lead to conflicts. Such interpretation of radar data can and is currently handled by more traditional algorithms, but seems very applicable to 'mission-level' cognition, where the radar's cognitive abilities learn what normal traffic patterns constitute and which particular pre-cursors to future air-collisions can be used to forecast such event.

At the moment of finalizing this paper, the UK MOD released the Joint Doctrine Note 1-23 on Intelligence, Surveillance and Reconnaissance [UKM23]. In this Note, the concepts of not only problem-centric based intelligence, but also 'activity-based intelligence' are introduced as contextual elements for the emergence of AI in general and cognitive sensing in particular. As such, like in this paper, the UK MOD Note illustrates the importance of proper integration of this next generation sensing into the military environment.

5.0 CONCLUSIONS

In this paper, the concept of *cognitive sensing* has been introduced, which is expected to affect military sensing at multiple levels. On a technical or tactical level, cognitive sensors will optimise behaviour with regards to the environment. Operational cognition implies that sensors or sensor networks employ cognition to optimise their behaviour as function of the developing mission.

Currently, NATO orchestrates the process of creating understanding through the Intelligence Cycle, within which the JISR process governs the collection of data via sensors. The Intelligence Cycle is an iterative process where the need for information is determined, collection assets are tasked, data is collected, processed and disseminated, after which the cycle repeats. Cognition in sensors may affect this cycle as the steps of the Intelligence Cycle may now run within the cognitive part of the sensors.

It is not yet clear how cognitive sensing will affect the Intelligence Cycle, nor how this next generation of sensing capability will be integrated into the NATO command and control environment. The introduction of Multi-Domain Operations aims at a more holistic approach to increase military effectiveness besides just the military domain. Such environment provides a natural home for mission-cognitive sensors within the Alliance.

The Electronic Warfare and Surveillance Branch of the NATO CI Agency cooperates with the Allied Command Transformation in Norfolk in investigating the challenges and opportunities of introducing cognitive sensing into the military domain. This research will focus mostly on 'misson-cognition' and the methods of how such next generation sensors can be incorporated into the Intelligence cycle.

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