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Threat evaluation and weapon assignment decision support: A review of the state of the art

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Abstract

In a military environment an operator is typically required to evaluate the tactical situation in real-time and protect defended assets against enemy threats by assigning available weapon systems to engage enemy craft. This environment requires rapid operational planning and decision making under severe stress conditions, and the associated responsibilities are usually divided between a number of operators and computerized decision support systems that aid these operators during the decision making processes. The aim in this paper is to review the state of the art of this kind of threat evaluation and weapon assignment decision support process as it stands within the context of a *ground based air defence system* (GBADS) at the turn of the twenty first century. However, much of the contents of the paper may be generalized to military environments other than a GBADS one.

Key words: Threat evaluation, weapon assignment, decision support.

1 Introduction

This paper contains a survey of literature on and recent developments in the state of the art of (semi)automated Threat Evaluation (TE)[1] and Weapon Assignment (WA) decision support within the military. We start with a description of the processes of TE and WA (§2), whereafter the complexity, relationships and contextual orientation of the Threat Evaluation and Weapon Assignment (TEWA) process with regards to Command and Control (C2), Data Fusion (DF), Situation Awareness (SA), Decision Support (DS) and Network Centric Warfare (NCW) are reviewed in §§3–7 respectively. A process diagram, exemplifying the processes discussed throughout the paper and their relationships within the context of a typical tactical Ground Based Air Defence System (GBADS) is presented in §8. Some conclusions with regard to the design of a TEWA DS system follow in §9.

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[1] The meanings of all military acronyms used in this paper are summarized in an appendix following directly on the bibliography at the end of the paper.

2 What is TEWA?

The majority of literature on TE and assignment problems (*e.g.* WA) typically include documentation describing business applications (*e.g.* risk management [94]), applications in the medical sciences [26, 106] as well as applications in the military domain, which is the focus of this paper.

2.1 The TE process

One implementation of the TE process is as part of the Intelligence Preparation of the Battlefield (IPB) process. IPB is an integrated approach towards analyzing the effects of terrain on friendly forces' ability to achieve their mission [108]. According to Glinton [40], the goal of IPB is to guide the collection, organization and use of intelligence information during the pre-deployment stages of a mission. IPB is typically split into four stages: battle area evaluation, TE, threat integration and production of a DS overlay [41]. TE, in this context, is a pre-deployment process by which a commander and his/her staff draw on their encyclopedic knowledge of the enemy, including its doctrine, tactics and capabilities, to deduce the nature of the threat they face [35]. The products of this stage of IPB are typically threat models, consisting of doctrinal templates[2], descriptions of enemy tactics and the identification of high value Defended Assets (DAs).

However, TE as part of a GBADS TEWA system is a poorly defined process, because of the difficulties related to the reproduction of operator thought in real-time [61]. It forms part of the cognitive domain of NCW and since its sub-domains (individual minds) are unique, attributes may be extremely difficult to measure or define. According to Borum *et al.* [9] "threat assessment consists of all the investigative and operational activities designed to identify, assess, and manage anything which might pose a threat to identifiable targets." According to Paradis *et al.* [81] TE refers to "the part of threat analysis concerned with the ongoing process of determining if an entity intends to inflict evil [*sic*], injury, or damage to the defending forces and its interests, along with the ranking of such entities according to the level of threat they pose."

Consequently, the evaluation of targets as *threats*[3] relies heavily on the use of the established situational picture[4] (comprising a set of target state estimates) and the available contextual information which may range from the locations of the DAs, attributes of platform types and attack techniques, Weapon Systems (WSs) and surveillance systems, doctrine, intelligence reports, features of the terrain and the tactical environment, through to knowledge of the OPFOR's structure and the recent history of its behaviour within the tactical environment [15, 46, 75, 77, 79, 80, 81].

Threats are typically assessed according to two criteria: *capability* and *intent* [75, 78, 88, 113]. The first criterion, capability, refers to the ability of the target to inflict injury or

[2]Doctrinal templates are graphical representations of the deployment patterns and dispositions preferred by an Opposing Force (OPFOR) while conducting standard operations (*e.g.* assembly, defence, movement to contact) under various circumstances [41].

[3]Threats, for the purposes of this paper, are aircraft classified as hostile, near hostile or unknown by another system responsible for track management. This process is later discussed in more detail.

[4]The relationships between TE and SA are discussed later in this paper.

damage to the DAs. Factors considered in assessing target capability include the composition and size of any group (formation) of targets to which it belongs, its proximity to the related DA, and attributes of its WSs and surveillance systems with relation to various attack techniques [81, 91]. The other criterion, intent, refers to the will or determination of the target to inflict injury or damage. Unlike capability (which is rather straight forward to assess), intent is generally more difficult to assess, since deciding whether a target is exhibiting intent is often very subjective (residing in the cognitive domain) [81]. However, factors that may be considered when assessing the intent of a target include its velocity, heading (course and bearing) and altitude with respect to the DA, the detection of emissions from its Fire Control (FC) radar, the estimation of its possible courses of action (attack techniques) based on its pattern of movement and the events and activities in which it has participated, as well as recognition of its use of deception or tactics to evade being detected or tracked [75, 78, 81, 91, 88].

The difficulties facing TE Decision Support System (DSS) developers are evident from the paragraphs above. According to [100], these difficulties may largely be attributed to the following three factors:

1. *Weak spatio-temporal constraints on relevant evidence.* Evidence relevant to estimation problems, such as target recognition or tracking, may be assumed to be contained within a small spatio-temporal volume, generally limited by kinematic or thermodynamic constraints. In contrast, many TE problems may involve evidence that is wide-spread in space and time, with no easily defined constraints.

2. *Weak ontological constraints on relevant evidence.* Evidence relevant to TE may be very diverse and may contribute to inferences in unexpected ways. This is why intelligence or cognitive analysis, like detective work, is opportunistic, *ad hoc* and difficult to codify in a systematic methodology [100].

3. *Weakly-modelled causality.* TE (for the purposes of this paper) involves inference of human intent and behaviour. Such inference is essential not only for predicting future events, but also for understanding present and past activities. Models are extremely difficult to formulate, since sub-domains (individual minds) are unique and attributes may be very difficult to measure or even define.

2.2 The WA process

In contrast with TE, WA is well documented and possible solutions have been investigated for a number of years (see, for example, [1, 47, 48]). Also known as Weapon Target Assignment (WTA) or Weapon Allocation, the WA problem[5] is a fundamental problem arising in defence-related applications of Operations Research (OR).

According to Paradis *et al.* [81], WA refers to the reactive assignment of WSs to engage or counter identified threats. The process requires decision making in real-time that is consistent with the related own force mission objectives and compliant with the Rules Of

[5]The WA problem may be formulated as a nonlinear integer programming problem and has been shown to be NP-complete by Lloyd and Witsenhausen [63].

Engagement (ROE), WS characteristics and environmental constraints. The WA problem may be considered from a number of different perspectives [81]. When investigating which WSs to assign, one of the following two perspectives is usually adopted:

1. The *single platform* perspective, which refers to a single platform protecting itself from threats, where assignment relates to selecting the most suitable WS to counter a threat.

2. The *force coordination* perspective, which refers to a C2 platform providing TE against third party DAs, where assessment relates to the identification of the most suitable armed platform to engage or counter a threat.

Furthermore, when investigating the approach by which these WSs are assigned, two perspectives are prevalent:

1. The *threat-by-threat* perspective, which refers to the assignment of WSs sequentially, in such a way that the best WS is essentially assigned to each threat in turn (from the highest priority to the lowest priority).

2. The *multi-threat* perspective, which refers to the assignment of WSs to the current set of threats concurrently, so that the assignment is best in some overall sense.

Technically, both the above mentioned approaches employ some form of optimization. What distinguishes them (according to [81]) is that threat-by-threat assignment is usually based on some type of greedy algorithm, whereas the multi-threat assignment typically involves the optimization of a given objective function subject to certain constraints. Examples of criteria and approaches that may be used for WA may be found in [23, 28, 65, 68, 70].

2.3 Combining the TE and WA processes

At the turn of the twenty first century, combination of the TE and WA processes became fairly common, with the majority of TEWA systems used on naval craft, where only one DA (namely the craft itself) is evaluated by the TE sub-system [3, 4]. In this case, the TEWA system is applied in a *point-defence* role. In contrast with the TE sub-system, the WA sub-system may also be used to assign weapons for the protection of other craft (DAs), if the host craft itself need not be protected [3]. That is, assignments may be made from a single platform or force coordination perspective. Within this naval context, these systems are often used as fully automated systems where stand-off weapons are seen as the primary threat to the DA(s).

In a GBADS context, where there are a number of prioritized DAs to protect (situated far from each other), a TEWA system is applied in an *area-defence* role. A TEWA system is thus at the core of a GBADS, providing customizable DS to the FC Operator (FCO) when prioritizing threats and assigning weapons in a rapidly changing, high risk and highly stressful [81] operational environment.

As is evident from the preceding sections, a typical tactical situation in a GBADS environment exhibits all the hallmarks of a complex system [19]. Any model of the situation necessarily comprises a large number of formative elements (such as enemy aircraft, DAs, WSs and sensor systems), and there is continual, dynamic, typically nonlinear interaction between these elements (looping and feedback of information and effects are common). Furthermore, any formative element typically influences, and is influenced by, a significant number of other elements — these interactions may be over large spatial and temporal scales, even though the formative elements themselves typically rely on local information, ignorant of the behaviour of the system as a whole. Finally, the system is open (even in the case of a large threat environment), far from equilibrium (in fact, often on the edge of chaos) and has history (*i.e.* the direction of time is important) [89].

Furthermore, because of the high cost and extensive research required to develop a complex TEWA system, related information is very scarce and the inner workings of such a system are typically kept secret. As a result, not much research has been published on GBADS specific TEWA systems, especially in South Africa [91].

3 TEWA and command & control

C2 in early warfare (prior to the 19th century) tended to be exercised by a single commander, who carried out all planning, direction and monitoring functions, with assistance from a few aides and messengers only [118]. However, during the 20th century, this approach evolved to the concept of a C2 *system*[6]. According to [55], a C2 system is defined as "the facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations." Note that this definition emphasizes the synergy required between human, doctrinal and Information Technology (IT) elements to ensure effective C2. According to [64] "a military C2 system should provide the commander with a clear understanding of the developing operation so that forces can be directed in a manner to meet a specified objective." Such a system surveys the operational environment, assesses what actions to take (*i.e.* aiding the TE process), and uses available resources to implement those actions (*i.e.* aiding the WA process).

Some forms of C2 are primarily procedural or technical in nature, such as the control of air traffic and air space (typically dictated by the applicable Air Space Control Means (ASCM)), the coordination of supporting arms, or the FC of a WS. Others deal with the overall conduct of military actions and involve formulating concepts, deploying forces, allocating resources and supervising troops. Evidently, the scope of operation of a TEWA system spans the scope set by both these forms of C2, and therefore a thorough understanding of the applicable operational processes of C2 is required before an efficient TEWA system may be designed.

Taking one step back from the complex C2 processes described in the preceding paragraphs, the C2 decision cycle may be described by the most basic, well known and widely accepted model of C2, namely Boyd's[7] Observe-Orient-Decide-Act (OODA) loop. In [56],

[6] *Command* may by defined as an "authoritative act of making decisions and ordering action," and *control* as an "act of monitoring and influencing this action" [6].

[7] Colonel John (Richard) Boyd (1927–1997) was a United States Air Force fighter pilot and military

the OODA loop is recognized as a model of a decision cycle that is applicable to all C2 systems — friendly and adversary. Note that several other recognized decision process models exist, but that the functional elements of these models are the same. These models include: Lawson's C2 process model [76] (sense-process-compare-decide-act), the Monitor-Assess-Plan-Execute (MAPE) model [42], the input-process-output model [96] and the find-fix track-target-execute model [107].

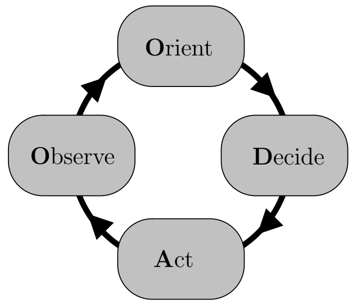

Figure 1: *The OODA loop.*

The OODA loop model, represented graphically as a circular connection of the four phases of the decision cycle, is depicted in Figure 1. During the *observation* phase information is gathered, pertinent to the decision at hand. Information may be collected from either internal sources (typically a feedback loop within the decision-making entity) or from external sources (typically sensors or information sources outside the decision-making entity).

Boyd [10] emphasized that most of the cognitive effort during the decision process resides in the *orient* phase, which consists of two sub-phases: *destruction* and *creation*. A decision making entity will attempt to *destruct* or decompose a problem until the sub-problems are close to situations for which the decision-maker has a plan. Familiarity with these sub-problems is gained though education, training, experience and instructions, and solutions may be seen as a compilation of doctrine based contingency plans. The decision-maker simply matches the current situation to one he/she has experienced, thought about, or has been instructed on, and applies the planned solution to the sub-problem. Problems are thus matched with their respective contingency plans, which are then combined or *created* into an overall plan of action.

If a decision-maker creates a single feasible plan (during the orientation phase), the *decision* phase is simply whether or not to execute. Of course, if there is more than one overall plan (or combination of contingency plans), one must be chosen as a course of action. This decision often involves weighing the risk or cost of a plan against its potential benefit [107]. A single superior choice usually results in a quick and confident decision, while many good feasible plans to choose from may take longer. Similarly, with many poor choices, the decision may take longer as the emphasis shifts from choosing the plan with the highest probability of success to choosing the plan with the lowest risk or failure.

The *action* node in Figure 1 represents the execution of a chosen course of action or plan.

strategist of the late 20$^{\text{th}}$ century whose theories have been highly influential in the military and in business. He was known as "Forty-Second Boyd" for his ability to defeat any opposing pilot in aerial combat in less than forty seconds [116].

These actions may include a physical attack or movement, the issuance of an order, or a focus of effort on the sensors for a better observation during the next cycle of the process.

According to [107], a common misconception of the OODA loop (as shown in Figure 1) is that the OODA decision cycle processes a single series of sequential events. Instead, the OODA loop process is described as continuous in [56]. That is, an entity simultaneously has multiple concurrent OODA processes with all phases underway at any given time. Of course, the nodes in Figure 1 may also be *destructed* or decomposed into more OODA loops, describing the C2 processes. An example is shown in Figure 2. Note that these OODA loops run in parallel and that more OODA loops may be formed on higher levels of cognition. Evidently, the outcomes at the various nodes in Figure 2 determine the decision loops followed.

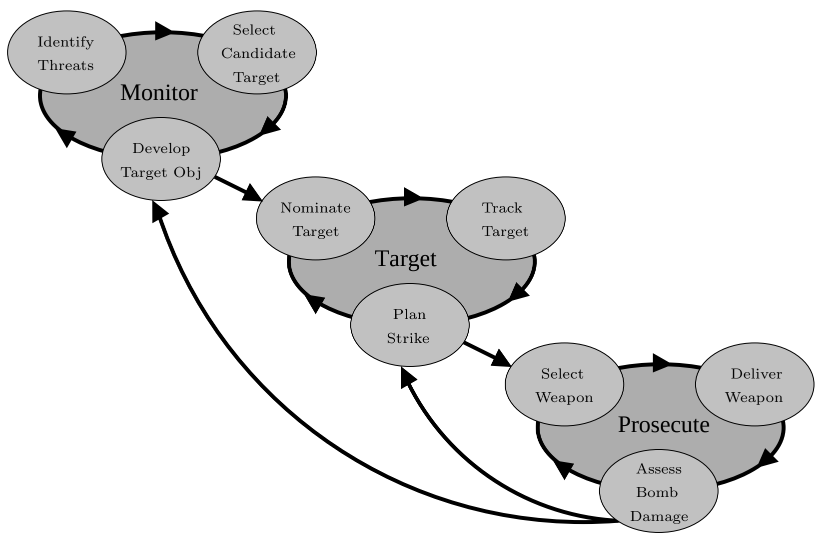

Figure 2: *A number of OODA loops in parallel [22].*

For example, consider the *Assess Bomb Damage* node in Figure 2. If the damage assessment process indicates that the target was not *killed*, another WS may be selected (starting the *Prosecute* OODA loop again) if it is indicated in the current strike plan. If not, the decision process in the *Plan Strike* node of the *Target* OODA loop is initiated — commencing the planning of another strike. Alternatively, if the damage assessment process indicates that the target was *killed*, the *Develop Target Obj* node of the *Monitor* OODA loop may be initiated to identify, select and develop (evaluate) another target.

The question arises as to how the OODA loop may be utilized to defeat one's enemy. Firstly, it is important to note that the OODA loop reflects how C2 is a continuous, cyclical process. In any conflict, the antagonist who can consistently and effectively cycle through the OODA loop faster (*i.e.* who can maintain a higher Operational Tempo (OPTEMPO) of actions) gains an ever-increasing advantage with each cycle. With each reaction, the slower antagonist falls farther and farther behind and becomes increasingly unable to cope with the deteriorating situation. With each cycle, the slower antagonist's actions become less relevant to the true situation — C2 itself deteriorates [66]. It is thus vitally important to generate OPTEMPO in C2 (imagine the loop in Figure 1 spinning faster and faster as the OPTEMPO increases). Speed is thus an essential element of effective C2, which implies shortening the time required to make decisions, plan, coordinate, and communicate. This may, of course, be achieved by providing germane DS with regards to the TE and WA processes.

Since war is competitive, it is not absolute speed that matters, but speed relative to the enemy; the aim is to be faster than one's enemy, which means interfering with the enemy's C2 as well as streamlining one's own C2 [66]. The speed differential does not necessarily have to be a large one; a small advantage exploited repeatedly can quickly lead to decisive results. Nevertheless, the ability and desire to generate a higher OPTEMPO does not negate the willingness to bide time when the situation calls for patience. The aim is not merely rapid action, but also meaningful action.

Secondly, a faster OPTEMPO causes confusion and disorder within the OPFOR. According to Boyd [11], the goal of the warfighter should be to "collapse [the] adversary's system into confusion and disorder by causing him to over and under react to activity that appears simultaneously menacing as well as ambiguous, chaotic, or misleading[8]." Furthermore, Vincent [110] states that the defining problem of C2 (that overwhelms all others) is the need to deal with uncertainty[9]. Were it not for uncertainty, C2 would be a simple matter of managing resources. In the words of Von Clausewitz [111], "war is the realm of uncertainty; three quarters of the factors on which action in war is based are wrapped in a fog of greater or lesser uncertainty. A sensitive and discriminating judgment is called for; a skilled intelligence to scent out the truth." The purpose of a TEWA system (in combination with other systems) should thus be to aid in the achievement of this "skilled intelligence," improving SA and reducing operator uncertainty, resulting in increased OPTEMPO.

4 TEWA and data fusion

The problem of deriving inferences from multiple items of data pervades all biological cognitive activity and virtually every automated approach to the use of information [101]. Consequently, the universality of DF has engendered a profusion of overlapping Research and Development (R&D) in many applications.

Special consideration should be devoted to the works performed by the Joint Directors of Laboratories (JDL)[10] in 1987, who developed a functional model that illustrates primary functions, relevant information and databases, and interconnectivity to perform DF. The goal of this JDL DF model is to facilitate understanding and communication among ac-

[8]Of course, these ideas are not entirely new. Tzu [109] (a heavy influence on Boyd), counselled that "all warfare is based on deception. Therefore, when capable, feign incapacity; when active, inactivity. When near, make it appear that you are far away; when far away, that you are near ... anger his general and confuse him."

[9]This is confirmed by the following statement by Paradis [81]: "Practitioners regard the key enabler for C2 as information superiority."

[10]More specifically, this work was done for the US DoD by the DF Subpanel of the Technology Panel for Command, Control and Communications (C3) of the JDL. This group is now re-chartered as the Data and Information Group within the Deputy Director for Research and Engineering's Information System Technology Panel of the US DoD [103].

quisition managers, theoreticians, designers, evaluators and users of DF systems so as to permit cost-effective system design, development and operation [115]. During the course of this work in 1987, the initial JDL DF lexicon [114] was compiled, defining DF as "a process dealing with the association, correlation, and combination of data and information from single or multiple sources to achieve refined position and identity estimates, and complete and timely assessments of situations and threats, and their significance. The process is characterized by continuous refinements of its estimates and assessments, and the evaluation of the need for additional sources, or modification of the process itself, to achieve improved results." According to Steinberg *et al.* [103] the initial JDL definition was too restrictive, considering the very wide range of similar DF problems encountered in engineering, analysis and cognitive situations (in the military and civil[11] domains). Consequently, the following concise definition was proposed [103]: "DF is the process of combining data to refine state estimates and predictions."

The JDL model's differentiation of functions into fusion *levels* provides a useful distinction between DF processes that relate to the refinement of *objects*, *situations*, *threats* and *processes* [115]. A number of revisions of the JDL model and its levels exist [62, 101, 103, 102]. Reasons for revisions include goals such as "to clarify some of the concepts that guided the original model," "to refine the categorization representing different levels of fusion problems to better reflect different classes of DF problems" and "to broaden the definitions of fusion concepts and functions to apply across as wide a range of problems as possible, beyond the initial focus on military and intelligence problems" [102]. We describe a 2004 revision of the JDL DF model (including the various levels of fusion) here with reference to older revisions — depending on relevance to the context of this paper. A visual representation of this model is provided in Figure 3.

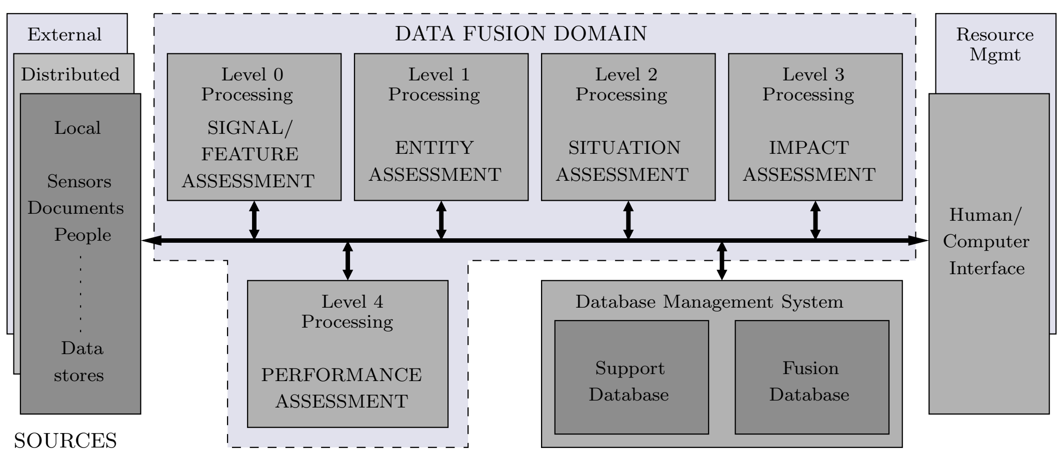

Figure 3: *The revised JDL DF Model (2004) [102].*

On *Level 0* signal/feature assessment encompasses various uses of multiple measurements in signal and feature processing [103]. In general, these problems concern the discovery of information in some region of space and time. On *Level 1* entity assessment (object assess-

[11]Civil uses of methods in DF are found in robotics, medical diagnosis, earthquake prediction, satellite resource mappings and traffic surveillance [97].

ment) is concerned with the estimation of the identity, classification, attributes, location, and the dynamic and potential states of entities. For example, in an AD application, observations from various sensor sources may be associated with a specific track or target within the system. On *Level 2* situation assessment concerns inferences regarding relationships among entities and contextual implications concerning entities and relations [102]. For example, tracks (or hypothesized entities) may be associated into aggregations. Furthermore, the state of the aggregate may be represented as a network of relations among the aggregation elements [103]. On *Level 3* impact assessment deals with the estimation and prediction of the *utility* or *cost* of an estimated world state (*i.e.* situation) to a user objective (*e.g.* a specific mission). According to [103], this level of fusion involves the "estimation and prediction of effects on situations of planned or estimated/predicted actions by the participants (*e.g.* assessing susceptibility and vulnerabilities to estimated/predicted threat actions, given one's own planned actions)." The *impact* of an assessed situation (resulting from DF level 2) is estimated. During performance assessment on *Level 4*, DF functions combine information to estimate a system's Measures Of Performance (MOPs) and Measures Of Effectiveness (MOEs) based upon a given desired set of system states and/or responses [102].

The TE and WA processes relating to the levels of DF mentioned above are placed into context according to Table 1, taken from [102], in which a comparison between and contrasting of the five DF levels are presented.

DF Levels	**Association**	**Estimation**	**Product**
Level 0 Signal/Feature Assessment	Observation-to-Signal or Feature*	Feature Extraction	Estimated Signal/Feature States & Confidences
Level 1 Entity Assessment	Signal/Feature-to-Entity or Sensor Entity State Report-to-Entity*	Attribute Entity State Estimation	Estimation Entity State & Confidences
Level 2 Situation Assessment	Entity*-to-Entity*, Entity*-to-Relationship* or Relationship*-to-Relationship*	Relational State Estimation	Estimated Relationships, Situation (set of Relationships) & Confidences
Level 3 Impact Assessment	Situation*-to-System Courses of Action	Cost/Benefit Analysis	Estimated/Predicted Entity & Situation Utilities & Confidences
Level 4 Performance Assessment	System States*-to-Goals	Performance Analysis	Estimated MOPs and MOEs & Confidences

Table 1: *Characteristics of the revised JDL DF levels [102]. Note that where indicated by an asterisk, association is made with features, signals, entities, relations and situations that are* postulated *by the system.*

According to [102] the benefit of this scheme of partitioning fusion functions into levels is due to the significant differences in the types of input data, models, outputs, and inferencing applicable to problems at the different levels. Note that data processing and flow from one level to the next is not required in any specific order. That is, any level may be processed independently, given that the required input data are available. Consequently systems operating on different levels may also be seen as independent systems, capable of producing results, given the correct inputs. Of course, quality or quantity of data resulting from a system on a lower level may result in more significant results on higher levels.

For the purposes of this paper, the assumption is made that level 0 fusion resides within the various sensor systems observing the tactical environment in real-time, producing *sensor tracks* for observed craft. These sensor tracks are then fused into a single *system track* (consisting of kinematic and non-kinematic craft data), during so-called *track management* level 1 DF processes.

Level 2 fusion processes are not realized within a single independent functional system. These processes are rather classified into two categories: (1) in cases where aggregation of tracks imply variations of system track data, functions are implemented as part of the track management process and (2) in cases where aggregations may be used to measure the intent or capability of a track, functions are implemented as part of the TE system. Both these parts contribute amply to the SA of Air Defence Control (ADC) operators.

However, TE is essentially a level 3 DF process[12]. System tracks received from level 1 data processing are evaluated, considering pre-deployment database values (*e.g.* values describing the expected attack techniques of enemy aircraft) and situation assessment fusion level 2 data, so as to measure the threatening behaviour of a target with respect to a DA. Note that the TE process takes system tracks, already classified as *hostile* or *unknown* by the level 1 and 2 fusion processes, as inputs. This implies that all tracks received by the TE (and later the WA) process may be treated as threats. That is, the operator is afforded permission to take countermeasures or engage the threat evaluated. WA may also be classified as a level 3 DF process. The efficiency of WSs for the engagement of threats are estimated in real-time, taking into account WS parameters and the predicted flight paths of the threats (also predicted by level 3 fusion processes). Assignment of WSs to threats is then attained by optimization (*e.g.* minimizing the survivability of all threats received from the TE process). To some extent this optimization process may be seen as a level 4 DF process, since the MOEs of the ADC system are analyses and are refined by prediction of future system or threat states.

From the paragraphs above it is clear how data flow from a "sensing" process (observing the tactical environment — DF level 0), to a track management process (DF levels 1 and 2), to a TE process (DF levels 2 and 3), and finally to a WA process (DF levels 3 and 4). At this stage, all the data are presented to the Operator In the Loop (OIL) by means of a DS process, improving his or her *observation* and SA of the tactical environment, and his or her *orientation* with regards the OPFOR. Evidently the OPTEMPO is increased, since the cognitive OODA C2 processes of the operator are accelerated.

For some DF levels, one may argue that accurate and proper data renders DF superfluous. [97]. On the other hand, good algorithms in DF cannot compensate for lacking or poor data. Nevertheless, in cases where DF may make a difference, the quality of DF algorithms are of significant importance. A meagre DF algorithm at a low DF level may produce poor and unexpected results or proposals at higher levels of the C2 process. In the words of

[12]Indeed, in the original JDL DF model, level 3 fusion was named "Threat Assessment" [114], a name later changed to "Impact Assessment" to broaden the scope of the model [103].

Rao [105], "the fusion method must be designed carefully, because an inappropriate fuser can render the system worse than the worst individual sensor."

5 TEWA and situation awareness

The concept of SA has its roots in the fields of air traffic control, airplane cockpit control, manufacturing process control, military C2 and information warfare[13]. Although the impact of SA on operators in complex systems has been recognized [31, 93], no single accepted theory for SA has emerged. SA is an understanding of the state of the environment, including relevant parameters of the system — simply put, knowing what is going on around one. It provides the primary basis for subsequent decision making (the OODA process, see §3) and performance in the operation of complex, dynamic systems. The following are some technical definitions of SA:

- "the ability to maintain the 'big picture' and think ahead" — Dennehy and Deighton [25],
- "the continuous extraction of environmental information along with integration of this information with previous knowledge to form a coherent mental picture, and the end use of that mental picture in directing further perception and anticipating future need" — Dominquez *et al.* [27],
- "all knowledge that is accessible and can be integrated into a coherent picture, when required, to assess and cope with a situation" — Sarter and Woods [93],
- "the combining of new information with existing knowledge in working memory and the development of a composite picture of the situation along with projections of future status and subsequent decisions as to appropriate courses of action to take" — Fracker [36], and
- "cognitive state or process associated with the assessment of multiple environmental cues in a dynamic situation" — Isaac [53].

A tractable definition (according to [117], so popular that the notion of SA has become almost synonymous with it) is provided by Endsley [31], who defines SA as "the perception of the elements and cues in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." Furthermore, Endsley divides SA into three levels [29, 30, 31, 32, 33]. *Level 1* represents the perception of the elements in the environment within a volume of space and time. *Level 2* represents the meaning of the level 1 SA elements, promoting an accurate understanding of the current real-world situation. *Level 3* represents the projection of the level 1 SA element states or events in the near future.

[13]According to [98], the concept of SA was born within the specialist (and rather secretive world) of military ergonomics and air accident investigation during the mid-1970s, as an attempt to explain the large number of individual variables known to affect the cognitive performance of military and civilian air crew.

For the purposes of this paper, SA is seen as a purely cognitive process, enhanced by DS and DF algorithms at various DF levels. Wallenius [112] proposes an interpretation of SA within the context of C2. A version of this interpretation (revised by Roodt *et al.* [90]) is provided in Figure 4.

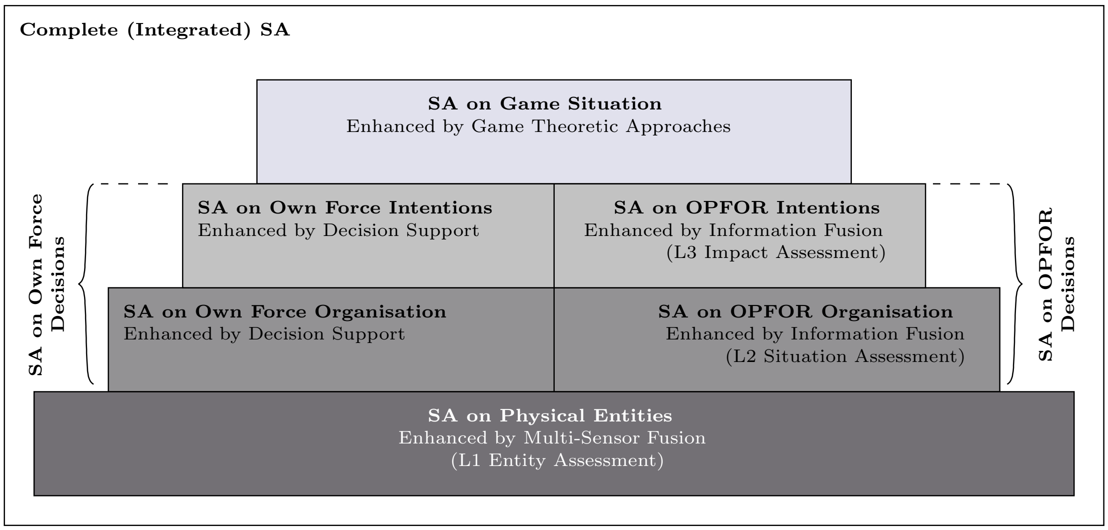

Figure 4: *Levels of Situation Awareness(SA) [90].*

In Figure 4, entity assessment at a physical level concerns entity properties (data) such as kinematics, which may be converted into usable information through DF. For example, sensor tracks (encompassing the aircraft's kinematic properties) are fused into system tracks and then provided to the operator to improve SA (aiding with the *observation* part of his or her OODA loop).

At intermediate levels, the model provided in Figure 4 further differentiates between own forces and OPFOR environments, as two sides of the SA coin [90]. The aim is to achieve an enhanced understanding of the OPFOR's organization and intentions (understanding or predicting the OODA processes of the OPFOR) through level 2 and 3 DF of the track management and TE processes.

On the other side of the coin (left-hand side of Figure 4), the ability of the own forces to react to the OPFOR is assessed and provided to the operator via DS. Of course, the states of the own force elements are known and by predicting a threat's flight path, for example, the efficiency of own force WSs against these threats may be assessed — for the purposes of this paper, this is achieved by level 3 and 4 DF processes encompassed by the WA process. Hence, on the intermediate levels shown in Figure 4, the operator is provided with SA which improves the *orientation* process of his or her OODA loop.

At the highest level in Figure 4, DS in the form of game theory (war games — see [43, 67, 87]) may contribute towards decision-making by allowing the decision-maker to exploit *what-if* scenarios.

It is evident that the sensing, track management (§4), TE and WA processes (§2) contribute to SA to some extent (or on some level, see §4). Thus, by improving these processes the SA of the OIL is escalated, increasing the OPTEMPO (see §3). In the words of Pasteur [13] "fortune favors a prepared mind."

6 TEWA and decision support

Information systems researchers and technologists have built and investigated computerized DSSs for more than 35 years [85]. In this ever changing Fourth-Generation of Warfare (4GW)[14], DSSs are required to adapt to the emerging theories of warfare (*e.g.* NCW) and to keep up with the pace at which technology advances, while still satisfying operator-specific needs. The design approaches of DSSs often vary between two extremes, namely *technology-driven* and *status-quo-driven*[15]. We suggest an attempt to tread on the fine line between an *user-driven* and *problem-driven* approach towards TEWA.

6.1 The cognitive domain

The commander is clearly central to the C2 process. In fact, one may argue that the entire C2 OODA loop of the operator is a cognitive process. In the ADC domain all relevant information, raw data and DS results (*i.e.* TEWA process results) are provided to the operator. The human mind perceives this information, *processes* it in different ways and then decides on a relevant action to take within the given tactical situation. To investigate this process further, an information hierarchy diagram from [66] and a cognitive hierarchy figure from [90] are combined and extended to arrive at Figure 5.

In Figure 5, data are processed and converted to information by placing it within a situational context[16]. This information (or *processed data* according to [66]) encompasses all DS data provided to the operator — raw data processed by level 0–4 DF models of the sensing, track management, TE and WA processes (see §4). Hence, all information intended to aid the operator with his or her SA are provided. Of course, on this *information* level (see Figure 5) the right information must be supplied to the right person at the right time.

According to [54], information may be provided to the OIL under two basic paradigms, namely a *supply-push* paradigm or a *demand-pull* paradigm. A supply-push system pushes information from source to user either as the information becomes available or according to some schedule. Advantages of this approach include the fact that the operator is not required to request (poll for) the information and that information generally arrives in a timely fashion. However, the challenge is to be able to anticipate the operator's needs and

[14]"Roughly speaking, 4GW includes all forms of conflict in which the other side refuses to stand up and fight fair. What distinguishes 4GW from earlier generations is that typically at least one side is something other than a military force organized and operating under the control of a national government, and one that often transcends national boundaries" [38].

[15]In the first case, the problem solving strategy is determined by a technology, such as mathematical optimization, decision analysis, or a favoured Artificial Intelligence (AI) reasoning method, without regard for the method used or preferred by the user. In the second case, the users' current method is simply automated without regards to whether it is the best way to solve the problem [85].

[16]According to [90], a working definition for *information* is: "data collected from the environment and processed into a usable form."

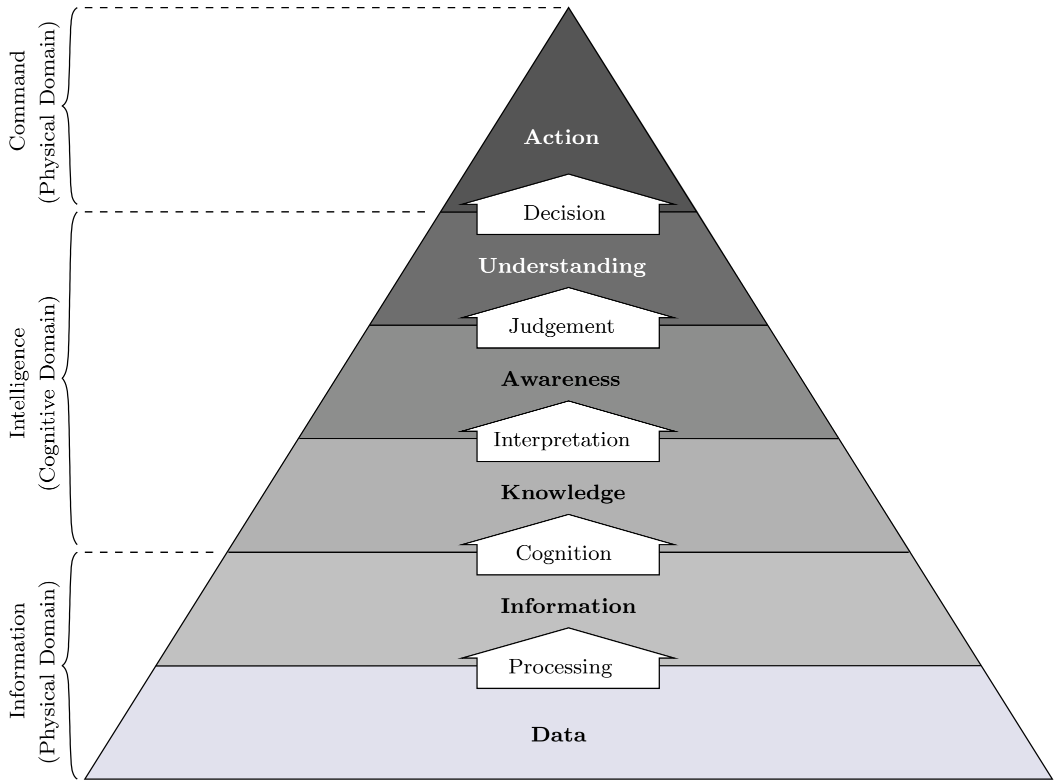

Figure 5: *From information to action via the cognitive domain.*

to avoid overloading him or her with information. In contrast, a pure demand-pull system does not rely on an ability to anticipate information needs — it is inactive until a demand is made on it [66]. In a demand-pull system, information requirements are specified by the OIL. If information is readily available (*e.g.* in some local database), the demand may be satisfied in a fast and efficient manner. However, if the information is not readily available, the demand typically triggers a *demand cascade*, as the requirement filters through the chain of command until it reaches the appropriate level for gathering. A demand-pull paradigm may thus be adopted to optimize the use of limited resources in order to focus on those tasks identified by the operator as critical. That is, OIL tailored information is sent only upon request. Although the strengths of tailored information are evident, the demand-pull paradigm may also introduce weaknesses into the ADC system. Firstly, important information may be "missed," since not all information may be requested by the operator. Secondly, since an information search may only commence on order of the operator, an unwanted time delay may be introduced.

Information management (on level two of Figure 5) may also be viewed within the context of how the information is transmitted. Information may be transmitted by either *broadcast* or *point-to-point* transmission. When broadcasting, information is sent simultaneously to a broad audience — typically in the shortest amount of time [66]. If information is of a generic nature (*e.g.* the system tracks of threats), this method of transmission may be extremely effective. However, since the information is sent to a wide audience (with varying requirements), information may not be tailored to suit the needs of specialized operators.

Furthermore, undisciplined use of this method may result in information overload. The alternative to broadcasting is point-to-point (or "narrowcast") transmission where information is sent to a specific user or users. That is, only the appropriate information is passed sequentially from one user to the next. Point-to-point transmission has two basic advantages: (1) Information may be tailored to meet specific needs of the recipient, and (2) nodes passing the information may have built-in control mechanisms (filtering and fusing appropriate information) to reduce the risk of overload. On the other hand, the disadvantages of point-to-point transmission are that information reaches a broad audience more slowly and that the chances of distortion increase with each node through which the information passes.

Now, assuming that the information reaches the node of the operator, the DS information must be presented to the operator in a germane manner. This DS information may then be processed (by means of cognition) into *knowledge* residing on the third level of Figure 5. People generally think in terms of ideas or images — mental pictures of a given situation. Not only do people generally think in images, they understand things best as images and are inspired most by images [84]. According to Von Clausewitz [14, 111], the ability of a gifted commander to intuitively grasp what is happening on the battlefield is called *coup d'oeil* — literally meaning "stroke of the eye." In general, the higher the level of C2, the more the operator (commander) relies on information from others and the less on own observations. Of course, when observing a situation directly, an intuitive appreciation of the level of uncertainty may be obtained. This sense is usually lost when secondhand information is received. The cognitive process of the OIL (starting with *knowledge* on level three of Figure 5) thus commences with the operator *observing* the DS information provided on the *information* level (level two). Von Clausewitz also refers to the *coup d'oeil* of the operator as a "quick recognition of the truth," or in other words, a high level of SA.

The operator reaches the *awareness* (SA) level (level four) by interpretation of the *knowledge* (level three) obtained from the DS *information* (level two). Within this context, the cognitive process of interpretation uses *observation* information (*e.g.* system tracks), *orientation* information (*e.g.* track management and TE process results), experience and training. The SA achieved on this level thus refers to the intermediate levels of SA in Figure 4, where the intentions and organization of the OPFOR are assessed (see §5).

To advance to the *understanding* level of the OIL cognitive process (level five in Figure 5) judgement regarding various *what-if* scenarios is required, taking into consideration the own force and OPFOR organizations and intentions (see Figure 4). Judgement may not only depend on operator SA and experience, but also on specific orders or doctrine and *orientation* information (*e.g.* WA process results). The product of this judgement, residing on the *understanding* level, may thus include the projection of the level one SA element states or events in the near future.

At this point, the operator has *observed* the tactical situation and *orientated* him- or herself within the given situational context, and is ready to move on to the next steps of his or her OODA loop — making the *decision* and *acting* accordingly (the top level in Figure 5). Decisions are typically made under some degree of uncertainty. Theoretically, uncertainty may be reduced by gaining information, but any such decrease in uncertainty occurs at the expense of time [66].

According to Klein [57, 58, 59], there are two basic approaches towards making decisions, namely an *analytical* or an *intuitive* approach. The analytical approach to decision making is based on the generation of several different options, comparing all the options according to some set of criteria, and identifying the best option. The intention is to compare multiple options concurrently and to produce an "optimal" solution. Consequently this approach tends to be methodical and time-consuming — reasoning power matters more than experience. In contrast, the intuitive approach rejects the computational approach and relies on an experienced operator's intuitive ability to recognize the key elements of a particular problem and arrive at the proper decision. This approach thus aims at satisficing — finding the first solution that will satisfactorily solve the problem — rather than on optimization [95]. Patton [12] once remarked that: "A good plan violently executed now is better than a perfect plan next week."

The choice of approach towards decision making should consequently be based upon the current tactical situation, the time available and the knowledge and SA of the operator. For efficient decision making a combination of these two decision making approaches (computational and intuitive) are proposed. The goal of DSSs (*e.g.* a TEWA system) should be to automate parts of the decision making process, reducing the time required to decide. Especially analytical approaches may fairly easily be automated, providing the operator with options or an optimal solution depending on operator preference. The operator then has time to consider the computational results and to react on it using his or her intuition.

6.2 Automation of decision support

DSS by means of automation of cognitive processes may increase the OPTEMPO of the operator's cognitive OODA loop. Automation has been included in the designs of various ADC systems, mainly in an effort to improve performance and to overcome high operator workload (especially under stressful conditions). However, Bainbridge [5] has noted that when workload is the highest, automation is often of the least assistance, as it can usually handle routine tasks only. Furthermore, research has demonstrated a certain degree of independence between SA and workload [33], indicating that even if workload is successfully reduced, this may not translate into higher SA.

The technology-driven approach to automation has created new operational problems for operator performance and new kinds of failure modes in the overall human-machine system (see [82], for example). In complex systems, where automated functions have replaced many tasks previously performed manually, the role of the operator has changed dramatically. Instead of performing tasks actively, the operator's job has become that of a monitor over an automated system. Interestingly, Parasuraman [82] concluded that operators may be poor passive monitors of an automated system, irrespective of the complexity of events being monitored. However, the *out-of-the-loop performance problem*, a major potentially negative consequence of complete automation, leaves operators of automated systems handicapped in their ability to take over manual operations in the event of automation failure [33].

Many of the issues surrounding the negative impact of automation on processes such as TEWA and operator performance may be attributed not to the automation itself, but rather to the way automation has traditionally been implemented [7]. Design approaches (such as OIL) are being explored where the assignment of functions to people and automation are redefined in terms of an integrated team approach that maintains operator involvement [32]. One way to minimize the negative effects of automating cognitive tasks is to employ a method of keeping the operator actively involved in the decision making loop, while simultaneously reducing the workload associated with performing the whole process manually [33]. Another design approach, namely *adaptive automation*, attempts to optimize a dynamic allocation of tasks by creating a mechanism for determining in real-time when tasks need to become automated or manually controlled [32]. In direct contrast to fixed task allocations, adaptive automation provides the potential for improving operator performance by keeping operators in the loop.

Endsley [33] distinguished between five levels of automation, assuming that a task may be accomplished in a number of modes: (1) *Manual* — the task is accomplished manually by the human, he/she performs an interpretation of the data/situation, conjures up various action alternatives, and decides on an action and implements the action; (2) *Advisory* — the computer suggests various options, the human selects the best option and implements the action — so the human need not follow the recommended option; (3) *Consensual* — the computer recommends the best option, and implements the action if the human consents; (4) *Monitored* — the computer generates options, implements the best option (selects the action) automatically and implements action unless vetoed by the human; (5) *Fully Automated* — the computer performs the whole task automatically, without any human interaction. This classification may assist in determining a level of automation that is optimal for the operator performance in a particular situation.

According to Qureshi [86], automation technology has the potential to enhance the SA development process. However, a technology-driven approach has shown that increased computational power does not guarantee improved system performance. Instead a human-centred design approach [7] is required for the smooth and effective introduction of automation. This approach entails both an analysis of the goals and activities of human operators and an understanding of the factors that contribute to good and poor performance of the related DSS. Qureshi proposes the design of an automated operator assistant, based on the concept of flexible automation that includes OIL approaches, various modes of automation, dynamic task allocation and transparency in the automation process.

South African doctrine requires an OIL approach towards FC in a GBADS environment. For example, a proposed engagement (engagement between WS and threat) from the WA process should only be executed if the FCO manually sends an Engagement Order (EO) to the related WS. Thus, the idea is not to replace or contradict the operator or his/her choices — choices which consider instincts, experience and the given doctrine [99]. The focus of the TEWA processes should rather be to aid operator decisions by execution of complex computations, flagging of suspicious aircraft behaviour or, in some cases, only to confirm operator thought, especially under stressful conditions[17]. It is essential that the operator should have confidence in the DSSs supporting him/her. The operator's *level of confidence* may be used as guideline to arrive at an eventual equilibrium between machine

[17]In 1996 the Tactical Decision Making Under Stress (TADMUS) programme was conducted in the US to apply developments in cognitive theory and human-system interaction technology in order to design a DSS for enhancing tactical decision-making under the highly complex conditions involved in littoral settings or short-fused, dynamic decision-making situations [50, 51, 52, 71, 72, 73, 74, 99].

and operator involvement levels in a TEWA system.

6.3 Personalization and adaptive flexibility

The complexity of DSS design is greatly amplified by the requirement to reproduce or confirm operator thought in real-time [61]. As mentioned earlier, this forms part of the cognitive domain of NCW and since its sub-domains (individual minds) are unique, attributes are extremely difficult to measure or define. This statement is supported by evidence in a variety of contexts that people use different decision making strategies[18] for different tasks and at different stages of the same task [83, 104, 119]. For example, in the case of uncertainty, some decision makers prefer to evaluate actions with respect to the worst case possible, while others prefer to evaluate options against average or expected outcomes [20].

There is little evidence that the same individual is consistent across tasks in the decision making strategies employed (see, for example, [44, 60, 92]). According to [49], decision makers may well differ in such cognitive styles as adopting an *intuitive* or an *analytic* approach, but there has not yet been a reliable mapping of such course traits onto consistent patterns of information input or output. Furthermore, many variations in strategy are determined by features of the *task*, rather than the *individual*. For example, decision makers are more likely to screen options with respect to cut-offs or goals when there is a large number of options to consider, but are more likely to look at trade-offs among goals when there are only a few options [83]. Hammond *et al.* [44] have also shown how a difference in the way information is presented may lead (in a very reasonable way) to processing strategies that appear intuitive or analytic.

Huber [49] argued that a system which attempts to infer and model enduring cognitive characteristics of a user and impose an appropriate decision making strategy on him is both impractical and undesirable. It is also not likely to be very successful in predicting a consistent strategy across widely varying tasks and situations. Furthermore, when it is wrong, user frustration is likely to be high, even if the user may override the system's choice.

Cohen and Tolcott [21] proposed the exploration of a system which can flexibly and quickly accommodate user strategies for adapting to different kinds of tasks. According to Cohen and Tolcott "flexibility to accommodate individual differences is not sufficient in and of itself. A vast number of logically possible strategies could be made equally easy. But such a system is more likely to overwhelm users with too many choices than it is to facilitate performance. A more reasonable objective is to identify a relatively small subset of strategies (like worst case *versus* expected case evaluation, or evaluation with cut-offs versus trade-offs) that are (a) most often utilized by decision makers in a particular domain and (b) which appear to be adaptive. Decision aids may then be *tuned* to facilitate selection by the user from this smaller group of strategies. Such aids are *adaptively flexible* in their responsiveness to likely user needs and task demands. They adapt to the problem

[18] A *strategy* is any consistent pattern of actions in response to perceived conditions, where the actions may include information gathering and evaluation, and where the conditions may include the results of previous actions [21].

at the same time as they adapt to the user."

It is clear that a TEWA system should provide the operator with various levels of support and solutions, clustered into various categories which may be filtered according to modes, specific doctrine or personal preference. Furthermore, the operator should be able to select the level of automation of various specialized functions. For example, a specialized filter may be set to remove infeasible or inconclusive solutions automatically if certain algorithms underachieve because of a lack of data or data update rate regarding a threatening aircraft.

In order to achieve the above mentioned level of flexibility and customization we advocate that the various components of a TEWA system should be designed in a modular fashion, so that functionality may be added or changed according to expert end-user preference.

6.4 Air defence operators

Functionalities of the DS processes are of course determined by the role and rank of the specific operator. Integrated hierarchies of ranks exist within the military. Firstly, a number of OPFOR operators form part of a typical tactical situation. Within the GBADS context, these operators are assumed to include the operators piloting the aerial threats as well as the operators responsible for the C2 of the OPFOR's aerial missions. The actions and responsibilities of these operators are of course not known, but are estimated by a number of processes residing on the second and third levels of SA in Figure 4. These estimates are important results provided to the own force operators via DSSs and are, in turn, used for own forces C2. The actions and movements of the OPFOR operators are observed by various sensor systems in real-time. Some of these systems work in an autonomous fashion, while others require a single operator or various operators.

The second class of AD operators is thus the class responsible for operating the various sensor systems observing the tactical environment in real-time. The data from these sensor systems are typically sent to a common *place* and processed by a system implementing the track management process. The output from this track management process may then be used to form a comprehensive Air Picture (AP) with regards to the current tactical situation. Typically, an operator, called the Air Picture Manager (APM), is responsible for managing the AP by application of various filters and doctrines. Hence, the track management output serves as DS to the APM (OIL) who is capable of changing the outcome and taking further actions with regards to track management.

The AP, along with positions of the own force elements, are provided to an operator responsible for FC — the FCO (see §2.3). The FCO is the principal user of the TEWA DSS (within the context of this paper) and acts as the OIL when execution of proposed engagements is required. Furthermore, although the responsibilities of the APM and FCO should ideally be separated, the FCO is typically authorized to override APM decisions or to perform additional track management if required.

The actual engagement of the OPFOR threats are executed by the effector operators. Again, a single effector or Fire Unit (FU) may require various operators. Nevertheless, a single operator is typically in command of a FU and it is this operator who is of importance for the purposes of this paper. During an engagement, important feedback information regarding the active engagement (*e.g.* messages regarding tracking, firing and kill assessment) is sent to the TEWA system and the FCO.

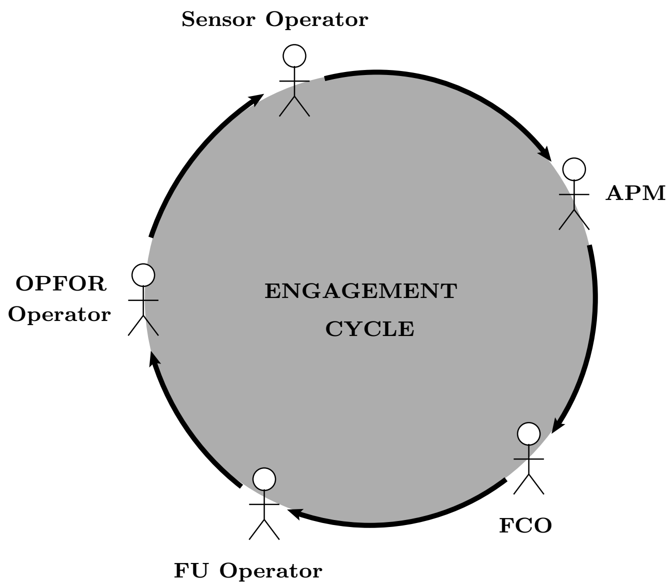

Figure 6: *The classes of operators as part of an AD engagement cycle. These operators include, an Opposing Force (OPFOR) Operator, a Sensor Operator, an Air Picture Manager (APM), a Fire Control Operator (FCO) and a Fire Unit (FU) Operator.*

Note that all the operators discussed above require different levels of DS and SA. Furthermore, each of these operators has his/her own OODA loop process for completion of their respective responsibilities. Figure 6 shows the various operator classes as part of an AD engagement cycle. The arrows simply represent interaction between operators. Consider examples of the OODA loop processes involved at every node (class of operator) presented in Figure 6. The OPFOR pilot may *observe* the current tactical situation, *orientate* himself with regards to the DA, *decide* whether an attack is feasible and then *act* accordingly. The OPFOR commander may *observe* the damage done by the OPFOR pilot, *orientate* himself with regards to the overall OPFOR strategies, *decide* whether to execute new missions and *act* by commanding the OPFOR pilots.

The sensor operator may *observe* the actions of the OPFOR pilot, *orientate* himself with regards to doctrine and DS provided, *decide* on appropriate feedback to send and *act* by providing the feedback using the interfaces available.

The APM may *observe* the feedback provided by the sensor operator, *orientate* himself with regards to the available ASCM and his SA, *decide* whether the system track observed is of a specific platform type and *act* by setting the platform type flag of the system track accordingly.

The FCO may *observe* the platform type change of the OPFOR threat, *orientate* himself with regards to the current AP and TEWA DS provided, *decide* whether a FU is required to be assigned and *act* by sending an EO to the related FU operator.

The FU operator may *observe* the EO received, *orientate* himself by tracking the threat, *decide* whether engagement is possible and *act* by actually firing at the OPFOR pilot.

At this stage, the OPFOR pilot *observes* the missile fired and the OODA sequence and engagement cycle starts again. Note that different OODA cognitive sequences are followed by the various operators, depending on the current tactical situation.

7 TEWA and network centric warfare

NCW has been identified as one of the key concepts for future warfare. According to [81], the concept of NCW refers to the "linking of sensors, engagement systems and decision makers into an effective and responsive whole" and is achieved through "shared SA, clear procedures and the information connectivity needed to synchronize the actions of the defence force to meet the commander's intent." Network Centric Operations (NCOs) are military operations that are enabled by the networking of the force [16], and provide the force with a new, previously unreachable region of the information domain. The ability to operate in this region provides decision makers with a new type of information advantage, an advantage broadly characterized by significantly improved capabilities for sharing and accessing of information. NCW enables decision makers to leverage this information advantage in order to increase combat power dramatically through self-synchronization and other NCOs [39].

The evidence provided in [2] demonstrates that war fighters employing NCW concepts may leverage shared SA and knowledge to achieve situational dominance and dramatically increase survivability, lethality, speed, timeliness and responsiveness — increasing the own force OPTEMPO. This evidence also points to the fact that the source of the transformational combat power enabled by NCW concepts may only be understood by focusing on the relationships in warfare that take place simultaneously in and among the physical, the information, the cognitive and the social domains.

The *physical domain* is the traditional domain of warfare, where strike, protect and manoeuvre take place across the tactical environments of air, land, surface (*e.g.* sea), subsurface and potentially space [8]. The physical elements and the communications networks that connect them reside in this domain. Consequently, challenges in this domain arise from constraints imposed by the laws of physics. Comparatively, the elements of this domain are the easiest to measure, and consequently, combat power has traditionally been measured primarily in this domain [2].

The *information domain* is the domain where information is created, stored, manipulated and shared. It is the domain that facilitates the communication of information among war fighters and hence the domain where the C2 of modern military forces are communicated. "Consequently, it is the information domain that must be protected and defended to enable a force to generate combat power in the face of offensive actions taken by an adversary. And, in the all-important battle for information superiority[19], the information domain is ground zero" [39].

[19] *Information superiority* is a condition in the information domain. This condition is created when one competitor is able to establish a superior information position *vis-á-vis* an adversary [39].

The *cognitive domain* is the domain of the mind of the war fighter, the domain where battles and wars are lost or won. Elements of this domain include the intangibles of leadership, morale, unit cohesion, level of training and experience, SA and public opinion. According to Booz [8], a commander's intent, doctrine, tactics, techniques and procedures also reside in this domain. Much has been written about this domain and key attributes of this domain have remained relatively constant since Sun Tzu wrote *The Art of War* [109]. Since the attributes of this domain are extremely difficult to measure, explicit treatment of this domain by means of analytic models of warfare is rare. However, a methodology that begins to addresses key attributes and relationships has been proposed by Harmon [45] in the context of entropy based warfare.

The *social domain* describes the necessary elements of any human enterprise [18]. It is the domain where humans interact, exchange information, form shared awareness and understandings, and make collaborative decisions. Other elements of this domain include culture, sets of values, attitudes, and beliefs held and conveyed by leaders to the society, whether military or civil. Although this domain overlaps with the information and cognitive domains, important differences exist. Cognitive activities by their nature are individualistic (they occur in the minds of individuals), whereas shared sense making (the process of going from shared awareness to shared understanding to collaborative decision making) is a socio-cognitive activity, because the individual's cognitive activities are directly impacted by the social nature of the exchange and *vice versa* [17].

A visual representation of the intersections of the domains described above is provided in Figure 7. According to [18], the intersections represent important, dynamic areas within which concept-focused experimentation should be conducted.

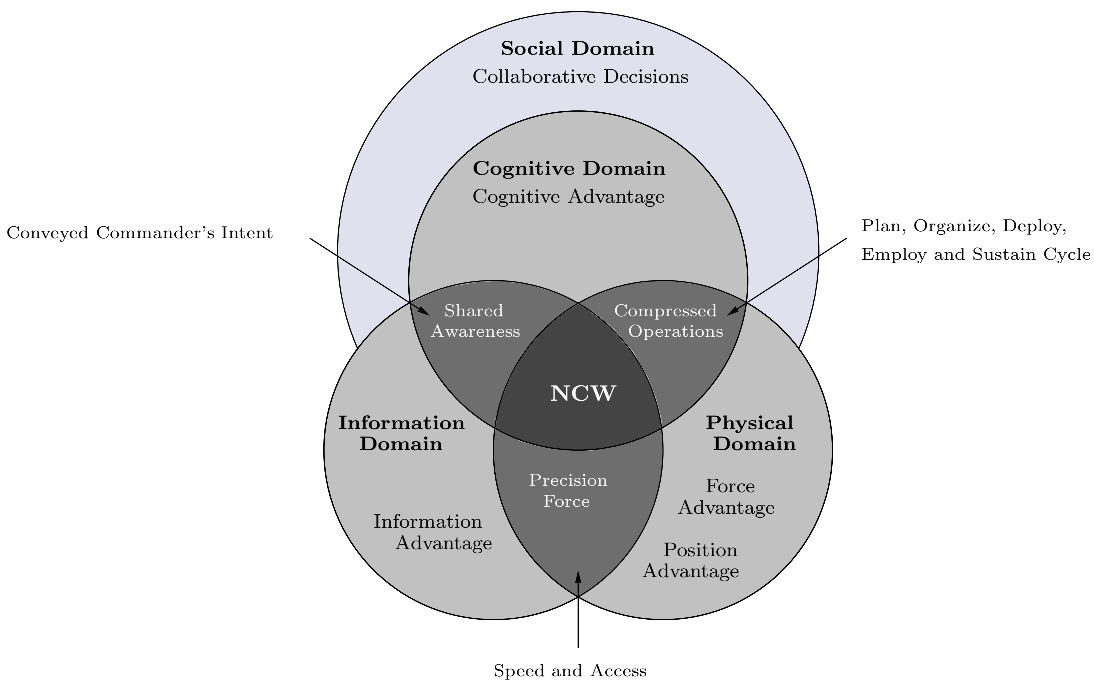

Figure 7: *The four domains of NCW [18].*

A precision force[20], vital to conducting successful joint operations, is created at the intersection of the information and physical domains (see Figure 7). Shared awareness and tactical innovation occur at the intersection between the information and cognitive domains. Furthermore, the intersection between the physical and cognitive domains is where the time compression and "lockout" phenomena occur [18] — where tactics achieve operational and even strategic effects, and where high rates of change are developed. Of course, to execute NCOs effectively, a thorough investigation into the intersection of all four domains is required.

This conceptual model of the four domains builds upon a construct proposed initially by Fuller in 1917 [37], and refined in a report entitled *Measuring the Effects of Network Centric Warfare* [8]. Evidently the scope of the TEWA process extends over all four domains of NCW. For example, the TEWA process may use data from sensor systems (part of the physical domain), and create and share DS information (part of the information domain), in accordance with (or as close as possible to) operator and collaborative thought residing in the cognitive and social domains. Cebrowski [16] proposed a structure or logical model for NCW which may be visualized as in Figure 8.

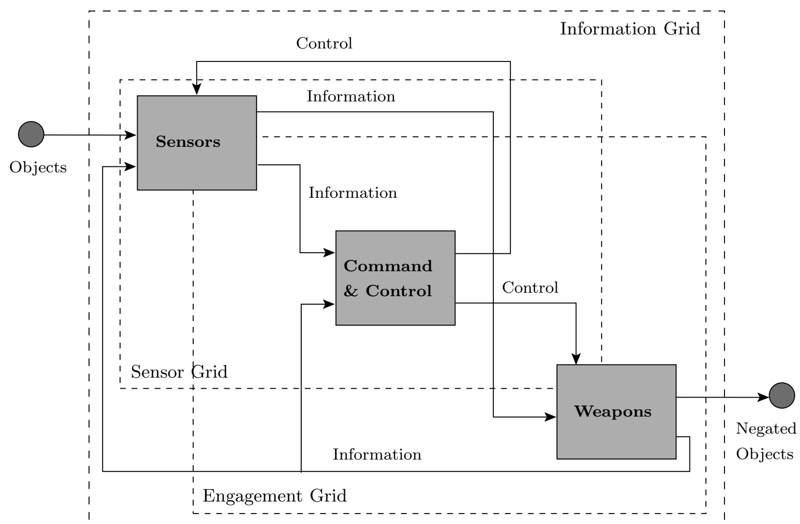

Figure 8: *A logical model for NCW [16].*

Figure 8 highlights the network centric information flow between sensors, C2 and weapons. It suggests three potential building blocks or sub-architectures [16]. The infrastructure for network centric computing and communications is provided by the *information grid.* This infrastructure provides a means to receive, process, transport, store and protect information of a *joint force*[21]. The information grid's embedded capabilities for information

[20] "Precision Force is the capability to destroy selected high-value and time-critical targets or inflict damage with precision while limiting collateral damage. This capability includes precision-guided munitions, surveillance, and targeting capabilities" [34].

[21] A general term applied to a force composed of significant elements, assigned or attached, of two or more military departments, operating under a single joint force commander [24]. In the context of this paper, "joint forces" refers to a network centric based force controlled by "joint war fighters" operating in a "joint battle space."

assurance[22] prevent intrusive attack and assure commanders that their information is valid [91]. Elements of the *sensor grid* include dedicated sensors, sensors based on weapon platforms, man portable sensors and embedded logistics sensors operating in the air, land, surface, subsurface and space environments. Sensor grids provide a joint force with a high degree of awareness of friendly forces, enemy forces and the environment across the joint battle space. The operational architecture of *engagement grids* enables a joint war fighter to employ speed of command and achieve overwhelming effect at precise places and times [91]. Elements of this grid may include air, land, water surface, subsurface and space weapons.

Note the similarities with regard to the AD operator classes discussed in §6.4. The *objects* node in Figure 8 may represent a fixed wing aircraft operated by an OPFOR operator, the *sensors* node encompasses a number of sensor systems operated by sensor operators and the *weapons* node encompasses a number of effectors (or FUs) operated by FU operators. Finally, the C2 in Figure 8 are carried out by an APM and a FCO. Evidently, the TEWA DSS aiding the FCO is at the heart of the NCW process and of significant importance.

Both the concept of interoperability and the specific tenets of NCW focus on maximizing combat capabilities. Combat operations of the future will most likely be conducted in an alliance or coalition environment and will inevitably be joint as well as combined — underscoring the importance of interoperability with allies and coalition partners [39]. More than ever before, technology provides one with the tools necessary to achieve the desired levels of NCO capabilities, greater sharing of improved data (by means of DF) in near real time and better SA. Hence, it is of great importance that developers of military systems, such as a TEWA system, should build their products or applications with these concepts of NCW in mind.

8 TEWA and the engagement process

It is evident from the preceding sections that the TEWA DS process aids the FCO with perhaps the most important process of an AD system, namely the *engagement* of aerial threats (the *act* of the FCO OODA loop). Although the FCO is the final OIL (see Figure 6) before an engagement is executed, an engagement is, in fact, the result of a number of processes — processes residing in the physical, information or functional, cognitive and social domains of NCW (see §7). Consider Figure 9, which combines a number of processes (discussed in §§2–7) directly affecting the engagement cycle of a typical tactical situation.

Starting at the *tactical environment* (cloud) in Figure 9, the OPFOR commander strives to create OPTEMPO by C2 of aerial craft delivering air-to-ground armament in order to damage (or *kill*) the own force DAs. The OPFOR commander uses the elements of the tactical environment (*e.g.* terrain and weather) to minimize the exposure time of the attacking aircraft to own force sensor systems, hence adding to own force deception. It is these strategies (intentions and organization) of the OPFOR which the FCO attempts to grasp on the second and third levels of his/her SA (see Figure 4).

[22]Information assurance includes the products, procedures and policies that allow the timely transfer of information in an accurate and secure way among all parties involved [69].

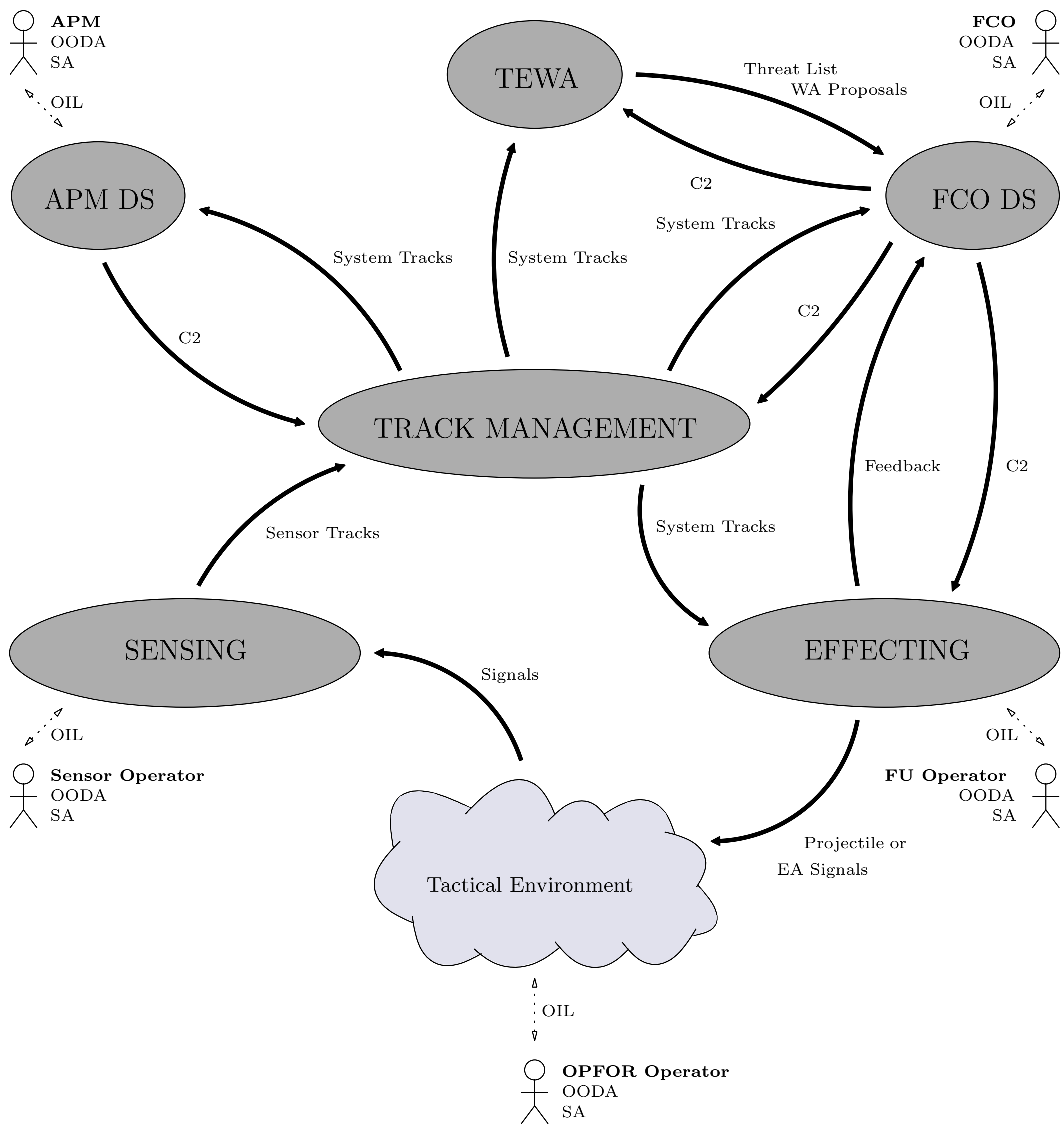

Figure 9: *The TEWA and related processes — including Air Picture Manager (APM) Decision Support (DS), Fire Control Operator (FCO) DS, track management, sensing and effecting — involved in a typical engagement of an aerial threat are provided. The various Operators-In-the-Loop (OILs) are also shown, each possessing a certain level of Situation Awareness (SA) and an Observe, Orientate, Decide and Act (OODA) cognitive process.*

The first step towards achieving higher levels of SA is having an effective *sensing* process (see Figure 9). This process is part of the first level of SA (see Figure 4) and includes all possible means to obtain (sense) data from the tactical environment regarding the OPFOR threats. The sensing process may thus be distinguished as part of the *observe* node within the engagement OODA loops — with each individual sensor collecting data. Furthermore, these sensors may utilize Level 0 DF techniques (see Figure 3) to produce results. Results (outputs) are in the form of sensor tracks, whereas the inputs are any form of data (*i.e.* signal or feature — see Figure 3) regarding an OPFOR entity. Of course, the data to and from these sensor systems are filtered or controlled by sensor operators (see Figure 6), each with his/her own cognitive OODA loop. Because of these OILs, all four levels of NCW (see Figure 7) are present, even in a single sensor context. Finally, when looking at the logical model for NCW provided in Figure 8, it is evident that the sensing process of Figure 9 represents all the processes inherent to the *sensor grid* of NCW.

All the sensor tracks (from the sensing process) are fused into a system track for each observed OPFOR aircraft by Levels 1 and 2 DF processes (see §4) encompassed within the *track management* process of Figure 9. Hence, the system tracks produced contain all available information regarding OPFOR threats and are routed to the TEWA process, APM and FCO DS processes, and even the effecting process (see Figure 9).

The principal custodian of system track data is the APM (see Figure 6) who serves as the OIL of the APM DS process (see Figure 9). DS information comprises all track related SA information such as ASCM and Identify Friend/Foe (IFF) interrogations, aiding the APM when sending commands that change track attributes (*e.g.* the hostility, platform type or the raid size of a specific system track). Operator changes are thus made according to the perceived intentions and organization of the OPFOR (on SA levels 2 and 3 in Figure 4).

Typically, only system tracks classified as either *unknown* or *hostile* (depending on TEWA ROE set up by the FCO) are sent to the TEWA process. As mentioned earlier, the TEWA process is at the heart of the engagement process and uses level 3 and 4 DF processes (see Figure 3) to provide the FCO with a prioritized list of threats and a set of possible WA proposals. These important results, together with other information (*e.g.* DA deployment information), are provided to the FCO by means of the FCO DS process (see Figure 9).

The FCO DS process provides the FCO (see Figure 6) with the interfaces to filter and control information from and to the TEWA process, C2 of effectors (part of the *effecting* process) and, in some cases, full APM functionality. Furthermore, a high level of SA is achieved since DS regarding both own force and OPFOR intentions and organization (see Figure 4) are provided to the FCO. Consequently the FCO may orientate himself/herself with respect to the information provided — the FCO DS process thus provides the FCO with all functionalities represented by the C2 node in Figure 8.

After considering his/her choices, the FCO acts by sending EOs to the related effector systems (part of the larger *effecting* process). In some cases, so called Local Warning Orders (LW Orders) may be sent to effectors — warning the FU operator (see Figure 6) about the threat and creating the opportunity to start tracking the target before an EO is sent by the FCO. Furthermore, the status (*e.g.* Will Comply [WILCO], Cannot Comply [CANTCO], tracking, firing, success, *etc.*) of an active engagement are provided as feedback to the FCO in real-time. The effecting process thus represents the *weapons* node in Figure 8. Finally, the effecting process closes the loop of the engagement cycle, since the action of the FU operators will, in turn, affect the next decision taken by the OPFOR operators.

9 Conclusion

We conclude by noting that the main purpose of a TEWA DSS is to increase OPTEMPO in general, but specifically under stress conditions, by means of improved:

- *C2*. Speed is an essential element of effective C2. Shortening the time required to make decisions, plan, coordinate, and communicate is highly desirable. This may be achieved by providing germane DS with regards to the TE and WA processes. The speed differential need not be a large one; a small advantage exploited repeatedly may quickly lead to a significantly improved situation.
- *DF*. High quality data presented to the OIL at the right time accelerates his/her cognitive OODA loop.
- *SA*. Efficient sensing, track management, TE and WA DS processes contribute to an improved SA of the OIL, increasing his/her OPTEMPO.
- *Automation of cognitive processes*. Efficient automation of certain operator cognitive processes may lead to effective DS, thereby accelerating the cognitive OODA loop of the operator.
- *NCW facilitation*. War fighters employing NCW concepts may leverage shared SA and knowledge to achieve situational dominance and dramatically increase survivability, lethality, speed, timeliness and responsiveness — increasing the own force OPTEMPO.

We advocate that any TEWA DSS design should:

- make a clear distinction between track management and TEWA processes (track related classification and identification should not form part of TEWA processes),
- attempt to tread the fine line between a user-driven and a problem-driven approach,
- attempt to display results graphically as far as possible (people generally think in terms of and understand things best as images; they are inspired most by images),
- pay careful attention to the level, flexibility and customization of automation employed (as dictated by the tactical situation, the time available and the knowledge and SA of the operator — the aim should be to aid operator decisions by execution of complex computations, flagging of suspicious aircraft behaviour or, in some cases, only to confirm operator thought),
- be modular in nature (so that functionality may easily be added or changed according to expert end-user preference), and

- embrace the concept of NCW (combat operations of the future will most likely be conducted in an alliance or coalition environment and will inevitably be joint as well as combined).

Finally, a number of serious pitfalls and difficulties should be borne in mind when designing a TEWA DSS:

- The practice of re-inventing the wheel to some extent with the design of each new TEWA DSS is largely unavoidable, because of the scarcity of related information and because the inner workings of previously designed TEWA systems are typically kept secret.
- A typical tactical situation in a combat environment exhibits all the hallmarks of a complex system. There is a real danger of subsequently over-complicating the working of a TEWA DSS.
- Designers of a TEWA DSS should guard against the serious error of overloading an operator with information during the DS process.
- The major difficulties facing developers of a TE DSS are weak spatio-temporal constraints on relevant evidence, weak ontological constraints on relevant evidence, and weakly-modelled causality (see §2.1).
- The major difficulties facing developers of a WA DSS include vital choices with respect to perspective (*e.g.* single platform *vs* force coordination) and optimization methodology (*e.g.* threat-by-threat *vs* combined multi-threat) — see §2.2.

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References

[1] Ahuja RK, Kumar A, Jha KC & Orlin JB, 2003, *Exact and heuristic algorithms for the weapon target assignment problem*, University of Florida Press, Gainesville (TE).

[2] Alberts DS, 2004, *Network centric warfare: Executive report*, [Online], [Cited 2004, November 3], Available from: http://www.dod.mil/nii/NCW/

[3] Anderson AA & Breuning R, 2002, *Combat system crchitecture of the F124*, Naval Forces, **5(97)**, pp. 108–111.

[4] Applied Physics Lab, 2005, *Ship self-defense system (SSDS) testing on USS Nimitz (CVN 68)*, [Online], [Cited 2005, January 25], Available from: http://www.jhuapl.edu/

[5] Bainbridge L, 1983, *Ironies of automation*, Automatica, **19**, pp. 775–779.

[6] UC Berkeley: Naval Classes, 2005, *Process of naval command and control*, [Online], [Cited 2007, March 5], Available from: http:// www.navsci.berkeley.edu/

[7] Billings CE, 2005, *Human-centered aircraft automation: A concept and guidelines*, [Online], [Cited 2005, January 19], Available from: http://www.ifp.uiuc.edu/

[8] Booz A, 1999, *Measuring the effects of network-centric warfare*, Volume 1, Office of the Secretary of Defense (Net Assessment), Washington DC.

[9] Borum R, Fein R, Vossekuil B & Berglund J, 1999, *Threat assessment: Defining an approach for evaluating risk of targeted violence*, Behavioral Sciences and the Law, **17**, pp. 323–405.

[10] Boyd JR, 1976, *Destruction and creation*, [Online], [Cited 2007, March 5], Available from: http://www.goalsys.com/books/documents/ DESTRUCTION_AND_CREATION.pdf

[11] Boyd JR, 1987, *A discourse on winning and losing*, Unpublished Lecture Notes — Maxwell AFB (Air University), Montgomery (AL), pp. 5–7.

[12] BrainyQuote, 2007, *George S. Patton quotes*, [Online], [Cited 2007, April 3], Available from: http://www.brainyquote.com/

[13] BrainyQuote, 2007, *Louis Pasteur quotes*, [Online], [Cited 2007, March 20], Available from: http://www.brainyquote.com/

[14] Caraccilo DJ & Pothin JL, 2000, *Coup d'oeil: The commander's intuition in Clausewitzian terms*, [Online], [Cited 2007, March 28], Available from: http://www.airpower.maxwell.af.mil/airchronicles/cc/Caraccilo2.html

[15] Carothers CD, Hybinette MI & Fujimoto RM, 2004, *Towards parallelization of large-scale ADA simulations using time warp*, [Online], [Cited 2004, 12 November], Available from: www.cs.rpi.edu/

[16] Cebrowski AK, 1998, *Network centric warfare: Its origin and future*, Proceedings of the Naval Institute, **124(1)**, pp. 232–235.

[17] Cebrowski AK, 2003, *Network centric warfare and information superiority*, [Online], [Cited 2005, May 10], Available from: http://www.oft.osd.mil/

[18] Cebrowski AK, 2005, *The implementation of network-centric warfare*, [Online], [Cited 2007, April 9], Available from: http://www.oft.osd.mil/

[19] Cilliers P, 1998, *Complexity and postmodernism: Understanding complex systems*, Routledge, New York (NY).

[20] Cohen MS, 1987, *Mental models, uncertainty, and in-flight threat responses by air force pilots*, Proceedings of the Fourth Biennial Symposium on Aviation Phychology, Columbus (OH).

[21] Cohen MS & Tolcott MA, 1992, *A cognitive basis for automated target recognition interface design*, [Online], [Cited 2007, January 5], Available from: www.cog-tech.com/papers/HReD/hred.pdf

[22] Cramer ML, 1996, *Command and control warfare: OODA loop countermeasures*, Proceedings of the 33rd Annual AOC International Electronic Warfare Technical Symposium and Convention, Washington DC.

[23] Cutler PRE & Nguyen XT, 2003, *Description of a rule-based model for the automatic allocation of airborne assets*, Proceedings of the Sixth International Symposium on Information Fusion "Fusion 2003", Cairns.

[24] Davis MT, 2004, *Separate definitions hobble 'joint' forces*, [Online], [Cited 2004, November 7], Available from: http://www.govexec.com/features/

[25] Dennehy K & Deighton C, 1996, *Development of an interactionist framework for operationalising situation awareness*, Proceedings of the First International Conference in Engineering Psychology and Cognitive Ergonomics, Stratford-on-Avon.

[26] Department of Health and Senior Services, 2006, *Biological threat evaluation guidelines for health care providers*, [Online], [Cited 2006, July 13], Available from: http://www.state.nj.us/health/er/phyinfo1017.htm

[27] Dominguez C, Vidulich M, Vogel E & MacMillan G, 1994, *Situation awareness: Papers and annotated bibliography.*, Technical Report AL/CF-TR-1994-0085, Human System Center – Armstrong Laboratory, Dayton (OH).

[28] Eckler AR & Burr SA, 1972, *Mathematical model of target coverage and missile allocation*, Military Operations Research Society, Alexandria (VA).

[29] Endsley MR, 1988, *Situation awareness global assessment technique (SAGAT)*, Proceedings of the National Aerospace and Electronics Conference (NAECON), New York (NY).

[30] Endsley MR, 1995, *Measurement of situation awareness in dynamic systems*, Human Factors, **37(1)**, pp. 65–84.

[31] Endsley MR, 1995, *Toward a theory of situation awareness in dynamic systems*, Human Factors, **37(1)**, pp. 32–64.

[32] Endsley MR, 1996, *Automation and situation awareness*, Lawrence Erlbaum Associates, Mahwah (NJ).

[33] Endsley MR & Kiris EO, 1995, *The out-of-the-loop performance problem and level of control in automation*, Human Factors, **37(2)**, pp. 381–394.

[34] Federation of American Scientists, 1998, *Precision force*, [Online], [Cited 2007, April 26], Available from: http://www.fas.org/

[35] Federation of American Scientists, 2004, *Intelligence preparation of the battlefield in support of MANPADS operations*, [Online], [Cited 2004, June 12], Available from: http://www.fas.org/

[36] Fracker M, 1991, *Measures of situation awareness: Review and future directions*, Technical Report AL-TR-1991-0128, Wright Patterson Air Force Base – Armstrong Laboratories, Dayton (OH).

[37] Fuller JFC, 1925, *The foundations of the science of war*, Hutchington and Co Ltd, London.

[38] The Guardian, 2005, *Fourth generation warfare*, [Online], [Cited 2005, May 12], Available from: http://publish.uwo.ca/

[39] Garstka JJ, 2004, *Network centric warfare: An overview of emerging theory*, [Online], [Cited 2004, November 1], Available from: `www.mors.org/publications/`

[40] Glinton R, 2004, *Intelligence preparation of the battlefield*, [Online], [Cited 2004, November 7], Available from: `http://usl.sis.pitt.edu/`

[41] Glinton R, Grindle C, Giampapa J, Lewis M, Owens S & Sycara K, 2004, *Terrain-based fusion and interence*, [Online], [Cited 2004, November 6], Available from: `http://usl.sis.pitt.edu/ulab/fusion04.pdf`

[42] Hamilton S, 2006, *Operational threat development*, [Online], [Cited 2007, March 5], Available from: `http://www.mors.org/meetings/bar/briefs/hamilton.pdf`

[43] Hamilton T & Mesic R, 2004, *A simple game-theoretic approach to suppression of enemy defenses and other time critical target analyses*, Rand Corporation, Santa Monica (CA).

[44] Hammond KR, Hamm RM, Grassia J & Pearson T, 1984, *The relative efficacy of intuitive and analytical cognition: A second direct comparison*, (Unpublished) Technical Report No 252, University of Colorado, Boulder (CO).

[45] Harmon M, 1997, *Entropy based warfare: A united theory for modeling the revolution in military affairs*, Booz-Allen & Hamilton, San Diego (CA).

[46] Hobart B & Patel SH, 2004, *Evaluation distributed combat decision algorithms*, [Online], [Cited 2004, November 2], Available from: `www.mitre.org/`

[47] Hosein A & Athans M, 1988, *Dynamic weapon-target assignment problem*, Massachusetts Institute of Technology Press, Cambridge (MA).

[48] Hosein A, Walton T & Athans M, 1988, *Dynamic weapon-target assignment problems with vulnerable C^2 nodes*, Massachusetts Institute of Technology Press, Cambridge (MA).

[49] Huber GP, 1982, *Cognitive style and a basis for MIS and DSS designs: Much ado about nothing?*, Management Science, **29(5)**, pp. 567–579.

[50] Hutchins SG, *Principles for intelligent decision aiding*, (Unpublished) Technical Report TR 1718, Naval Postgraduate School, Monterey (CA).

[51] Hutchins SG, Kelly RT & Morrison JG, 1996, *Decision making for tactical decision making under stress*, Naval Postgraduate School, Monterey (CA).

[52] Hutchins SG, Morrison JG & Kelly RT, 1996, *Principles for aiding complex military decision making*, Naval Postgraduate School, Monterey (CA).

[53] Isaac AR, 1996, *Situational awareness in air traffic control: Human cognition and advanced technology*, Proceedings of the First International Conference in Engineering Psychology and Cognitive Ergonomics, Stratford-on-Avon.

[54] James P, Kahan D, Worley R & Stasz C, 1989, *Understanding commanders information needs*, Rand Corporation, Santa Monica (CA), pp. 37–55.

[55] Joint Chiefs of Staff, 1991, *Joint warfare of the US armed forces. (Joint Pub 1)*, National Defense University Press, Washington DC.

[56] Joint Chiefs of Staff, 1996, *Joint doctrine command and control warfare (C2W) (JP 3-13.1)*, National Defense University Press, Washington DC, pp. A1–A2.

[57] Klein GA, 1988, *Naturalistic models of C3 decision making*, in Johnson SE, Alexander H & Levis IS (Eds), *Science of command and control*, AFCEA International Press, Washington DC.

[58] Klein GA, 1989, *Strategies of decision making*, Military Review, May, pp. 5664.

[59] Klein GA, Orasanu J, Calderwood R & Zsambok CE, 1993, *Decision-making in action: Models and methods*, Ablex Publishing Corporation, Norwood.

[60] Libby R & Lewis BL, 1977, *Human information processing research in accounting: The state of art*, Accounting, Organizations and Society, **2(3)**, pp. 245–268.

[61] Liebhader MJ & Smith CAP, 1997, *Naval air defense threat assessment: Cognative factors and model*, Pacific Science & Engineering Group, San Diego (CA).

[62] Llinas J, Bowman CL, Rogova G, Steinberg AN, Waltz E & White F, 2004, *Revisiting the JDL data fusion model II*, [Online], [Cited 2006, November 30], Available from: http://www.infofusion.buffalo.edu/ reports/LLINAS/papers/

[63] Lloyd SP & Witsenhausen HS, 1986, *Weapons allocation is NP-complete*, Proceedings of the Summer Conference on Simulation, Reno (NA).

[64] Maethner SR, Robinson BI & GE Wood, 1996, *Worldwide information control system (WICS)*, [Online], [Cited 2007, March 7], Available from: http://www.fas.org/spp/military/docops/usaf/2025/index.html

[65] Malcolm P, 2004, *On the character and complexity of certain defensive resource allocation problems*, Technical Report DSTO-TR-1570, Defence Science and Technology Organisation (DSTO), Edinburgh.

[66] Marine Corps Doctrinal Publication (MCDP), 1996, *Chapter 2: Command and control theory*, [Online], [Cited 2007, March 7], Available from: http://www.au.af.mil/au/awc/awcgate/mcdp6/ch2.htm

[67] Martin B, 1978, *The selective usefulness of game theory*, Social Studies of Science, **8**, pp. 85–110.

[68] Matlin SM, 1959, *A review of the literature on the missile-allocation problem*, Operations Research, **17**, pp. 322–326.

[69] McKnight WL, 2004, *What is information assurance?*, [Online], [Cited 2004, November 7], Available from: http://www.stsc.hill.af.mil/crosstalk/

[70] Mettler WA & Preston FL, 1988, *Algorithm suite for defensive weapon allocation*, Technical Report 6289, United States Navy, Washington DC.

[71] Morrison JG, Kelly RT & Hutchins SG, 1996, *Impact of naturalistic decision support on tactical situational awareness*, NCCOSC RDT&E Division (NRaD), San Diego (CA).

[72] Morrison JG, Kelly RT, Moore RA & Hutchins SG, 1996, *Implications of decision making research for decision support displays*, NCCOSC RDT&E Division (NRaD), San Diego (CA).

[73] Morrison JG, Kelly RT, Moore RA & Hutchins SG, 1996, *Tactical decision making under stress (TADMUS) decision support system*, NCCOSC RDT&E Division (NRaD), San Diego (CA).

[74] Morrison JG, Marshall SP, Kelly RT & Moore RA, 1996, *Eye tracking in tactical decision making environments: Implications for decision support evaluation*, NCCOSC RDT&E Division (NRaD), San Diego (CA).

[75] Nguyen XT, 2002, *Threat assessment in tactical airborne environments*, Proceedings of the Fifth International Symposium on Information Fusion "Fusion 2002", Annapolis (MD).

[76] Orr GE, 1983, *USAF combat operations C3I: Fundamentals and interactions*, Technical Report AU-ARI-82-5, Airpower Research Institute, Air University Press, Montgomery (AL), pp. 24.

[77] Oxenham MG, 2000, *Automatic air target to airlane association*, Proceedings of the Third International Symposium on Information Fusion "Fusion 2000", Paris.

[78] Oxenham MG, 2003, *Enhanced situation awareness for air defence via automated threat analysis*, Proceedings of the Sixth International Symposium on Information Fusion "Fusion 2003", Cairns.

[79] Oxenham MG, 2003, *Using contextual information for extracting air target behaviour from sensor tracks*, Proceedings of the Signal Processing, Sensor Fusion, and Target Recognition XII Conference at the 17$^{\text{th}}$ SPIE Annual AeroSense Symposium, Kadar.

[80] Oxenham MG, Percival J, Price R & Lambert D, 2003, *Information fusion and extraction priorities for Australia's information capability*, Proceedings of the NATO Military Data and Information Fusion Conference, Prague.

[81] Paradis S, Benaskeur A, Oxenham MG & Cutler P, 2005, *Threat evaluation and weapon allocation in network-centric warfare*, Proceedings of the Seventh International Conference on Information Fusion (FUSION), Stockholm, pp. 1078–1085.

[82] Parasuraman R, 1997, *Humans and automation: Use, misuse, disuse, abuse*, Human Factors, **39(2)**, pp. 230–253.

[83] Payne JW, 1976, *Task complexity and contingent processing in decision processing: An information search and protocol analysis*, Organizational Behavior and Human Decision Processes, **16**, pp. 366–387.

[84] Peters TJ, 1987, *Thriving on chaos: Handbook for a management revolution*, Alfred A. Knopf, New York (NY).

[85] Power DJ, 2003, *A brief history of decision support systems*, [Online], [Cited 2007, January 4], Available from: `http://dssresources.com/history/ dsshistory.html`

[86] Qureshi Z & Urlings P, 1999, *Situation awareness and automation: Issues and design approaches*, Defence Science and Technology Organisation, Salisbury.

[87] Ravid I, 1990, *Military decision, game theory and intelligence: An anecdote*, Operations Research, **38(2)**, pp. 260–264.

[88] Roy J, Paradis S & Allouche M, 2002, *Threat evaluation for impact assessment in situation analysis systems*, Proceedings of SPIE (Vol 4729), Signal Processing, Sensor Fusion, and Target Recognition XI, Orlando (FL).

[89] Roodt JHS, 2006, *Complexity: How to recognise it and why it matters*, Proceedings of the 2nd LEDGER Conference, Simon's Town.

[90] Roodt JHS, Nel JJ & Oosthuizen R, 2007, *Framework and roadmap for DERI decision support to the Joint Command & Control and Intelligence (JC2 & Int) capability portfolio*, (Unpublished) Technical Report Draft J (Restricted), Council for Scientific and Industrial Research, Pretoria.

[91] Roux JN, 2006, *Real-time threat evaluation of fixed wing aircraft in a ground based air defence environment*, MScEng Thesis, University of Stellenbosch, Stellenbosch.

[92] Sage AP, 1981, *Behavioral and organizational consideration in the design of information systems and processes for planning and decision support*, IEEE Transactions on Systems, Man, and Cybernetics, **11(9)**, pp. 640–678.

[93] Sarter N & Woods D, 1991, *Situation awareness: A critical but ill-defined phenomenon*, International Journal of Aviation Psychology, **1**, pp. 45–57.

[94] SAS, 2006, *Solution lines/risk management*, [Online], [Cited 2006, July 13], Available from: `http://www.sas.com/solutions/riskmgmt/`

[95] Simon HA, 1956, *"Satisfice" versus "optimize"*, Psychological Review, **63**, pp. 129–138.

[96] Sloan-C Wiki, 2006, *Input-process-output model*, [Online], [Cited 2007, March 5], Available from: `http://www.sloan-c-wiki.org/`

[97] Smestad T, *Data fusion — for humans, computers or both?*, [Online], [Cited 2004, October 25], Available from: `http://www.vistg.net/`

[98] Smith DJ, 2007, *Situation(al) awareness (SA) in effective command and control*, [Online], [Cited 2007, March 19], Available from: `http:// www.smithsrisca.demon.co.uk/situational-awareness.html`

[99] St John M, Manes DI, Moore RA & Smith CAP, 1996, *Development of a naval air warfare decision support interface using rapid prototyping techniques*, Pacific Science & Engineering Group, San Diego (CA).

[100] Steinberg AN, 2005, *An approach to threat assessment*, Proceedings of the 8th International Conference on Information Fusion (Volume 2), Philadelphia (PA).

[101] Steinberg AN & Bowman CL, 2001, *Revisions to the JDL data fusion model*, pp. **2**-1–**2**-18 in Hall DL & Llinas J (Eds), *Handbook of multisensor data fusion*, CRC Press, Boca Raton (FL).

[102] Steinberg AN & Bowman CL, 2004, *Rethinking the JDL data fusion levels*, Proceedings of the Military Sensing Symposia (MSS) National Symposium on Sensor and Data Fusion (NSSDF), Columbia (SC).

[103] Steinberg AN, Bowman CL & White FE, 1998, *Revisions to the JDL data fusion model*, Proceedings of the Third NATO/IRIS Conference, Quebec City.

[104] Svenson O, 1979, *Process descriptions of decision making*, Organizational Behavior and Human Performance, **23**, pp. 86–112.

[105] Tebo A, 1997, *Sensor fusion employs a variety of architecture, algorithms, and applications*, [Online], [Cited 2007, March 19], Available from: `http://www.spie.org/web/oer/august/aug97/sensor.html`

[106] Threat Assessment Group, 2006, *TAG home page*, [Online], [Cited 2006, July 13], Available from: `http://www.taginc.com/`

[107] Tighe T, Hill R & McIntyre G, 2006, *A decision for strategic effects: A conceptual approach to effects based targeting*, [Online], [Cited 2007, March 5], Available from: http://www.airpower.maxwell.af.mil/airchronicles/cc/Hill.html

[108] Turner P, 2001, *Enhanced command and control modelling within HiLOCA*, British Crown, Malvern.

[109] Tzu S, *The art of war*, [Online], [Cited 2004, August 10], Available from: http://www.druglibrary.org/schaffer/general/artofwar/index.htm

[110] Vincent GA, 1992, *In the loop: Superiority in command and control*, [Online], [Cited 2007, March 8], Available from: http://www.airpower.maxwell.af.mil/

[111] Von Clausewitz C, 1873, *On war: The complete translation by Colonel JJ Graham*, N Trübner, London.

[112] Wallenius K, 2004, *Support for situation awareness in command and control*, Proceedings of the Seventh International Conference on Information Fusion "Fusion 2004", Stockholm, pp. 1117–1124.

[113] Waltz E & Llinas J, 1990, *Multisensor data fusion*, Artech House, Norwood.

[114] White FE, 1987, *Data fusion lexicon*, Naval Ocean Systems Center, San Diego (CA).

[115] White FE, 1988, *A model for data fusion*, Proceedings of the 1st National Symposium on Sensor Fusion, Volume 2, Orlando (FL).

[116] Wikipedia, The Free Encyclopedia, 2007, *John Boyd (military strategist)*, [Online], [Cited 2007, March 4], Availablbe from: http://en.wikipedia.org/wiki/John_Boyd_(military_strategist)

[117] Wikipedia, The Free Encyclopedia, 2007, *Situational awareness*, [Online], [Cited 2007, March 18], Available from: http://en.wikipedia.org/wiki/Situational_Awareness

[118] Wilton D, 2000, *The application of simulation technology to military command and control decision support*, [Online], [Cited 2007, March 5], Available from: http://www.siaa.asn.au/get/2395362604.pdf

[119] Wright P & Barbour F, 1977, *Phased decision strategies: Sequels to an initial screening*, pp. 91–109 in Star MK & Zeleny M (Eds), *Multiple criteria decision making: TIMS studies in the management sciences*, North-Holland Publishing, Amsterdam.

Appendix

The meanings of military acronyms used in the paper are listed below:

4GW	4th Generation Warfare
AD	Air Defence
ADC	Air Defence Control
AP	Air Picture
APM	Air Picture Manager
ASCM	Air Space Control Means
C2	Command & Control
C3	Command, Control & Communications
CANTCO	Cannot Comply
DA	Defended Asset
DF	Data Fusion
DoD	Department of Defence
DS	Decision Support
DSS	Decision Support System
EO	Engagement Order
FC	Fire Control
FCO	Fire Control Operator
FU	Fire Unit
GBADS	Ground Based Air Defence System
IFF	Identify Friend/Foe
IPB	Intelligence Preparation of the Battlefield
JDL	Joint Directors Laboratories
LW Order	Local Warning Order
MAPE	Monitor-Assess-Plan-Execute
MOEs	Measures of Effectiveness
MOPs	Measures of Performance
NCO	Network Centric Operation
NCW	Network Centric Warfare
OIL	Operator in the Loop
OODA	Observe-Orient-Decide-Act
OPFOR	Opposing Force
OPTEMPO	Operational Tempo
ROE	Rules of Engament
SA	Situation Awareness
TADMUS	Tactical Decision Making under Stress
TE	Threat Evaluation
TEWA	Threat Evaluation & Weapon Assignment
WA	Weapon Assignment
WILCO	Will Comply
WS	Weapon System
WTA	Weapon Target Assignment