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"The Evolution of C2"

Network Centric Command and Control by means of Picture Compilation and Sensor Management

Topic 1: Concepts, Theory and Policy

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Abstract - A good picture of the actual situation is essential within (networked) Command and Control systems to support the execution of the actions required to achieve mission success. In this paper, the collection of processes that contribute to the construction of this picture is divided into two main categories. The paper firstly describes the set that gathers data from different types of sensors and compiles this data into an information store that is defined as the operational picture. The second set of processes analyses the quality of the information in the operational picture and assembles tasks that select and control the available sensors in order to improve the quality of the picture. Furthermore, the additional information required for optimal sensor deployment is discussed. Finally the two sets of processes are combined into a new flexible Command and Control framework that improves sensor deployment by providing better operator support and allows a more automated deployment of the available sensor systems and other resources.

Keywords: picture compilation, sensor management, situational awareness, threat assessment, command and control, sensor selection.

1 Introduction

In nearly all (military) operations, the gathering of information about the actual situation is of vital importance as this information provides the necessary *situational awareness* that can be used to execute the appropriate actions that eventually lead to mission success. Different sensor types like radars, electro-optical systems or sonars, either man-carried or mounted on vehicles, provide data in often-different forms. This data is compiled into a (Common) Operational Picture ((C)OP) by a set of processes that will be referred to in this paper as the picture compilation processes.

Another set of processes, the sensor management processes, analyses the information that is stored in the OP and determines whether this information can be improved upon by (re)tasking the available sensor systems. This paper analyses the sensor management processes and describes what information is required to determine how to set the controls of

the available sensor systems that result in sensor observations thus enabling the compilation of the best possible OP.
The combination of these two sets of processes results in a (virtual) sensor control loop; this loop is depicted in Figure 1.

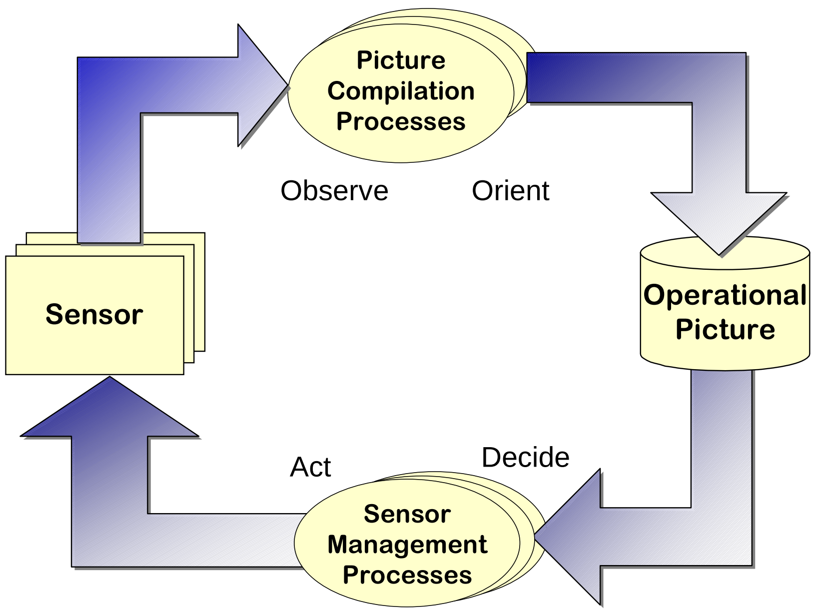

Figure 1. The Picture Compilation – Sensor Management loop

The term ‘virtual’ was introduced earlier in this section because it will be shown that both sets of processes interact directly with the OP and therefore need not necessarily be executed in a specific order. The combination of both sets of processes results in a new Command and Control (C2) framework that not only allows the utilisation of existing processes but also enables the exchange of information between those processes by means of the OP that now functions as an interface.
It is important to note that no statements are made about the role of the operator; depending on how the separate processes are implemented, the operator can be heavily involved in the execution of the processes or these processes may function completely autonomous depending on the functional requirements. The framework even allows for a dynamic level of user participation in the C2 system.
In Section 2 of this paper, the processes that compile the OP are categorised and described. Section 3 discusses the processes that are required to allocate and control the available sensors and Section 4 analyses the complete C2 process in more detail. In Section 5 conclusions are drawn and recommendations about future work are made.

2 Picture Compilation

In the introduction it was already stated that the availability of a good picture of the operational environment is of vital importance for mission completion. This is also the essence of Boyd’s well-known Observe-Orient-Decide-Act (OODA) loop [1], as correct actions can only result from right conclusions about the picture of the situation that is constructed from observations. In an operational environment, these observations are provided by sensors ranging from the naked eye to complex radar and high-resolution video systems. The different sensor types provide different types of information like oral comments, optical images, radar or sonar video, Identification Friend or Foe (IFF) data, Automatic Identification System messages and observations from Radar Warning Receivers (RWR). Besides, these sensors may either be located at fixed geographical positions or are fitted in moving vehicles like aircraft, submarines or cars. This makes the compilation of a *complete* and *accurate* (actual) picture of the operational environment (the OP) a challenging task. These two important performance indicators were derived from a number of interviews conducted with sensor operators, principle warfare officers and commanding officers within the Royal Netherlands Navy.

Bolderheij et al. [2] argued, that the OP can be defined as a set of objects that represents those entities in the operational environment that are important for mission completion. The properties of those entities are stored in their attributes and their behaviour is modelled in the accompanying methods. An initial set of object-attributes (properties) was defined as:

- position,
- velocity,
- acceleration,
- class (type),
- identity (hostile, neutral, friendly, suspect assumed friendly or unknown).

These attributes can be either directly observed, or have to be inferred from those attributes that can be observed. For instance, a radar can measure the different positions of an entity at short intervals (the Pulse Repetition Time) and from these position observations, the velocity of the object can be estimated. Due to the inaccuracy of a radar system there is some uncertainty related to the position observations and consequently to the estimated velocity. Figure 2 depicts a hidden Markov model that takes in position observations from a radar system and upgrades this information to velocity, acceleration, classification and finally identification estimates.

Modern military platforms are usually equipped with a wide variety of sensor systems that provide different types of information e.g.: an EO system like an Infrared (IR) camera provides imagery data that can be utilised to obtain the class of the entity. Therefore the upgrade model that is shown in Figure 2 needs to be adapted because here the *class* information is obtained first. From the class of the entity, the range information can be estimated by determination of the number of pixels occupied by the entity in the image and the actual size of the entity that can be derived from this class.

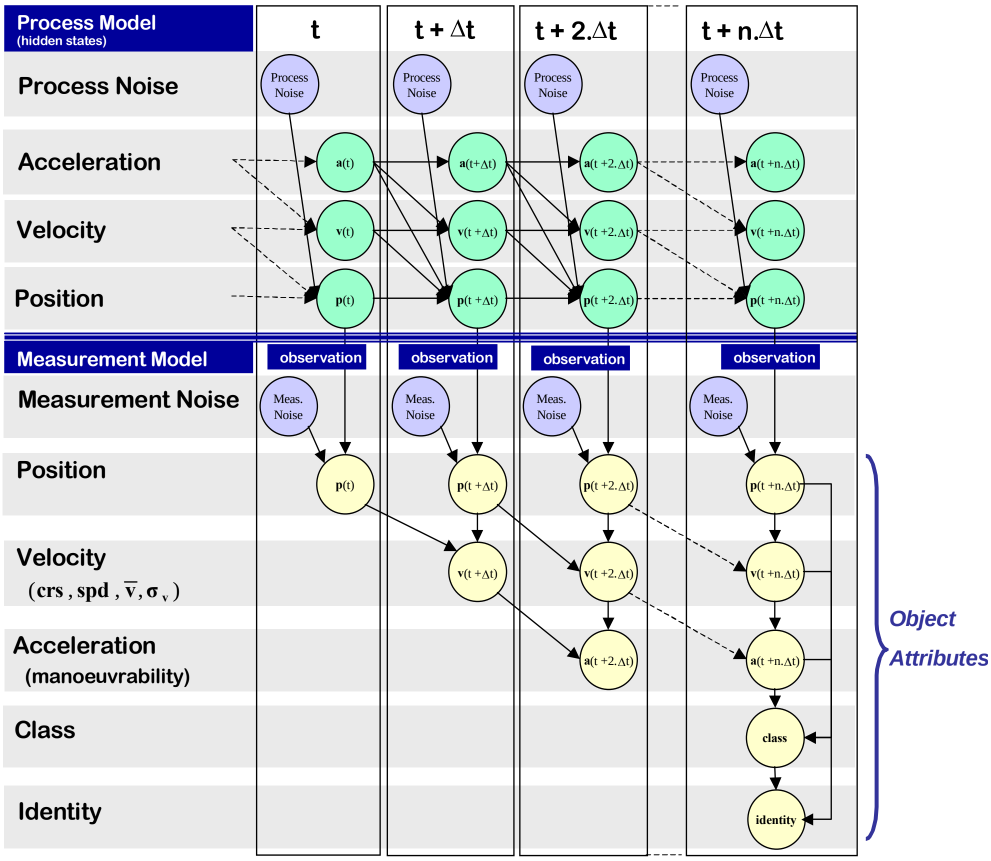

Figure 2. A scheme for upgrading the information derived from a radar system

In this example the processes need to be executed in a different sequence. Other sensor types may provide other types of data and therefore the model has to accommodate different types of information that are delivered by different types of sensors. A basic set of processes that deliver this information is represented in Table 1.

Process	*Provided Information*
Detect	Determination of the presence of an entity within the received signal.
Track	Estimation of the kinematic properties (position, velocity, acceleration) of an entity.
Classify	Establishing of the type/class an entity belongs to.
Identify	Determination and assignment of one of the standard labels: Friendly, Neutral, Hostile, Assumed Friendly, Suspect or Unknown to an entity.

Table 1. Basic set of picture compilation processes

The processes from Table 1 may also be incorporated in the sensor system itself as modern radar systems often provide all the kinematic data including the related uncertainty within an accompanying covariance matrix. These sensors may also provide (pre) classification information based upon internal Jet Engine Modulation (JEM) processing or High Range Resolution (HRR) functions. In a networked C2 system, the set of available sensors is likely to change in time as platforms like aircraft, ships or (individual) soldiers can join or leave the network. The networked system therefore must be equipped with a set of processes that transform the available information into the information that cannot directly be observed by the available sensors.

The observability of these attributes can be used to make a distinction between the *Observe* and the *Orient* stage of the OODA loop. The processes that belong to *Orient* category infer about the object properties that are not directly observable. It can be argued that these attributes are related to motives of the operator of the entity. Attributes that belong to this category are attributes that were not yet mentioned like *intent* and *risk.* Also the *identity* attribute fits better in this category because the broadcast of an IFF or AIS signal directly depends on the cooperation of the operator to switch on the equipment and transmit the *correct* signal. Processes that estimate these newly introduced attributes can be added to the picture compilation processes but their output heavily depends on the quality of the information in the observable attributes. These processes are very knowledge-intensive and are often executed by operators because their outcome is critical within decisions about the deployment of resources like weapon systems.

The cycle that is shown in Figure 1 functions during the *execution stage* of a mission, but this cycle has to be initiated at the start-up time of this mission stage. Within the *planning stage* of a mission, a priori information (intelligence) is analysed to determine what entities are likely to be present in the operation area. Those entities are inserted in the OP as *expected entities* to initiate the detection process. These objects are used to support the pursuit of *completeness*, as they will initiate a search for the entities they represent. In these *expected* objects, elements of the mission goals can be incorporated in the form of priorities and links (relations) to actions that have to be taken once these objects are detected. In this context an action is described as the deployment of one or more of the available resources. This subject matter is described in more detail in Section 3.

To be able to measure the *accuracy* of the OP, Bolderheij and van Genderen [2] suggested the use of uncertainty as a *performance indicator*. Many probabilistic estimators and filters, model error as a (co)variance and this variance can be regarded as a measure of uncertainty. In our framework, this uncertainty needs to be expanded to all object attributes, which is by no means trivial. The classification process had to be redeveloped to deal with the concept of uncertainty. Van Norden describes a new approach to the classification process [3] that is also capable of dealing with contradicting information coming from different sensors. This classification process is also able to utilise classification information provided by image recognition.

In Section 1 it was mentioned that no statement is made about the amount of operator involvement. Depending on the requirements and availability of mature and reliable automated processes, these processes may either be executed by operators, be automated completely or be implemented as a combination of human and machine involvement. Especially the third option gives rise to the challenging opportunities provided by the concept of Levels of Automation (LoA) as described by Sheridan and Verplanck [4]. The processes that belong to the *Orient* part of the OODA loop still require a considerable amount of operator knowledge, as was already discussed earlier in this section. These processes require more research before they can be completely automated. Higher LoAs however support the strive of nowadays armed forces for reduced manning and also allows the introduction of onboard training, as inexperienced operators can learn from the advice that is generated by 'next generation' C2 systems.

The picture compilation process as defined above consists of a set of (parallel) processes that produces an OP, which contains all relevant information for the execution of those actions that support the achieving of the mission goals while allowing for the desired amount of operator interaction.

3 Sensor Management

In Section 2 it was stated that those picture compilation processes that can be categorised among the *Orient*-processes still require some amount of operator knowledge. This was also the case with the sensor management processes from Figure 1. Traditionally, these processes belong to the realm of the operator: it is the operator who decides about the allocation of sensor tasks and the priorities that are to be assigned to the targets. From interviews with operational experts was deduced that operators executed these processes often more on the basis of skills and experience than on knowledge. These interviews also revealed that sensor management was not directly related to the picture compilation process and as a consequence it turned out to be very difficult to formulate generically usable sensor management principles. However, the construction of the *sensor management - picture compilation loop* enabled the formulation of such principles and the awareness grew that this loop was in effect the central element in the C2 process as the resulting product forms the basis for consequent actions, which include the management of the sensor systems.

Section 2 showed that the picture compilation processes form a set of processes that use sensor information to continuously update the OP by adapting and/or upgrading the information in the attributes of the objects that represent the real-world entities. The sensor management processes can now use this information to determine how the quality of the OP, i.e. the *completeness* and the *accuracy,* can be improved upon by (re)deploying the available sensor systems. For this purpose Bolderheij and van Genderen [2] developed a sensor management system that consists of three stages:

1. a task composing stage,
2. a sensor selection stage,
3. a sensor control stage.

The first stage analyses the state of each object in the OP and decides what information is needed to reduce the uncertainty that is contained in the attributes [5]. The word *state* here involves more than the kinematic state because all the attributes of the object are taken into account. The second stage of the system selects the most appropriate sensor from the set of available sensors for obtaining this information and the last stage determines how the sensor controls should be set to acquire the optimal Quality of Information (QoI). Especially the last stage is very knowledge intensive and relies traditionally heavily on operator input. When operational experts were interviewed about the composition of this knowledge, they found it difficult to describe their operating methods and often referred to their training, traditional procedures (we have always done it like this) and ‘rules of thumb’. Further questioning revealed however that the knowledge necessary to function as an operator could be divided into three main types:

1. knowledge about the sensor (capabilities, performance, settings, location …),
2. knowledge about the environment (geography, meteorology,…) ,
3. knowledge about the (possible) target (possible location, speed, reflective surface).

These three categories can also be distinguished in the analysis of the parameters in the radar [6] and sonar equation [7]. These equations are used to determine the ratio of the received electromagnetic or acoustic signal strength and noise in the receiver given the environmental conditions, the distance to the target, the part of surface of the target that (re)transmits the signal. From this *Signal-to-Noise ratio*, and the form of the (expected) target, the probability of detecting the (returned) signal (P_d) in the receiver of a specific sensor can be estimated. Early detection of these objects directly contributes to the *completeness* of the OP, which is one of the performance indicators of the picture compilation process. The estimated P_d can be used to determine the *Quality of Information* (QoI) of the detection process and can be utilised to select the best available sensor. In order to be able to require a specific QoI from a sensor, it is necessary to model each sensor type in terms of the functions they can execute, the QoI that is provided by each sensor function and the parameters that control this observation function. This QoI can be described as a function of the three knowledge categories:

$$QoI_{sensor} = f(s,e,t), \qquad (1)$$

where :

- QoI_{sensor} = Quality of Information of the Observation function,
- s = sensor system information,
- e = environmental information,
- t = target information.

For instance: if this sensor is a radar, the sensor system information consists of information about the transmitter like the transmitted frequency (bandwidth), the pulse length in case of a pulse radar or the sweep time in case of a FMCW radar, information about the antenna: antenna form and size, number of array elements and the type of polarisation and information about the receiver: detection threshold, Doppler processing and Sensitive Time Control settings. The environmental information may contain moisture and temperature profiles, air pressure distributions and duct information. The target information may consist of the target type, its (likely) position, its velocity, etc. From the target type, properties like the Swerling case [8] and maximum manoeuvrability can be derived. For surveillance radars, the position of the *expected targets* is usually completely unknown and therefore the P_d needs to be calculated for a range of possible positions in a sufficiently fine grid, resulting in the so called *coverage diagrams* that are provided by sensor performance estimation tools like AREPS, CARPET [9] for radar systems and EOSTAR [10] for electro-optical systems. An example of a vertical coverage diagram generated by CARPET is shown in Figure 3; observe the categorisation of the different input parameters into the three earlier mentioned knowledge categories. These tools estimate amongst other parameters the P_d of different sensor types by utilising models like the here fore mentioned radar and sonar equations. If the space that surrounds the platform(s) on which these sensors are fitted is divided in sufficiently fine grid elements, horizontal and even 3-D coverage diagrams can be constructed. An example of a horizontal coverage diagram that also visualises line of sight effects is shown in Figure 4. It is very important to relate the sensor controls to the variables in the sensor models, as a specific combination of these variables will yield an optimal QoI. Thus, these models assist in the execution of the second and the third stage of the sensor manager as they determine the combination of settings that deliver the best QoI of each sensor, allowing the sensors that deliver this specific service to be ranked in accordance to the provided QoI. The sensor manager now has to determine whether the best sensor for the task is allowed to execute it or that it has to execute more important tasks. The task is then assigned to the next best sensor provided that this sensor has no more important tasks to accomplish too. The models therefore were combined with the scheduler that was developed by van Norden [11] in order to allocate as many tasks as possible to the most appropriate sensor.

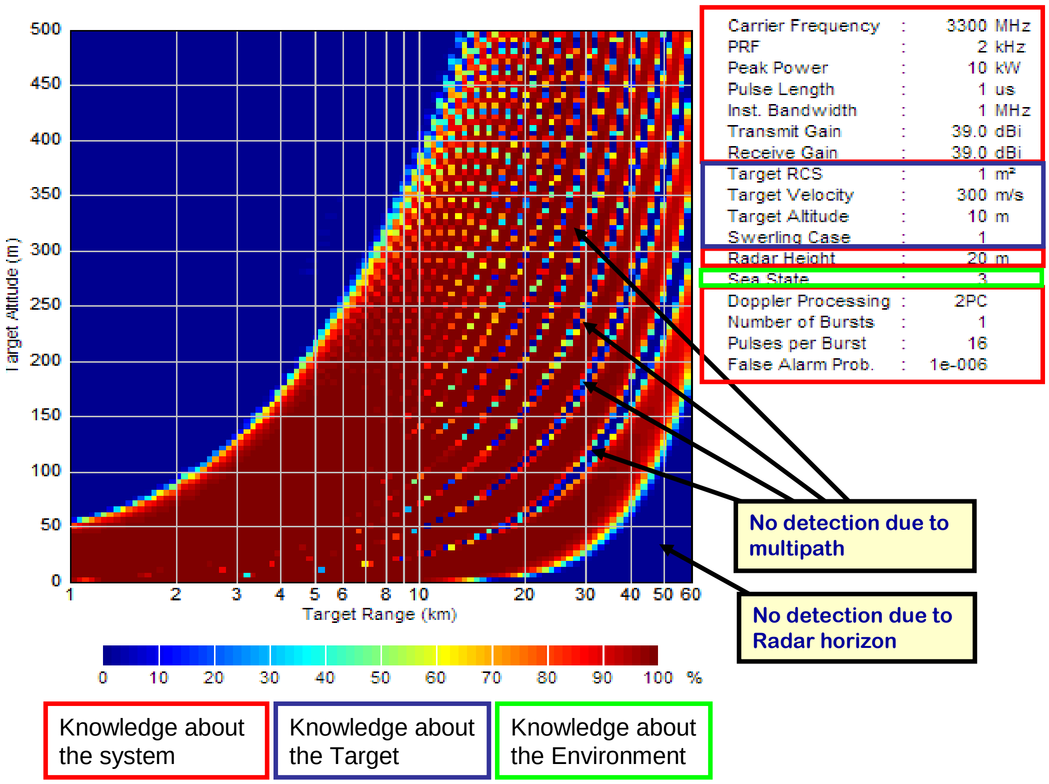

Figure 3. Vertical coverage diagram generated by CARPET

The coverage diagrams of the different sensors can also be merged to provide insight into the (optimised) coverage of the complete sensor suite as discussed by van Leijen and Bolderheij [12]. Analysis of the diagrams supports the manual selection of the most suitable settings and can also make suggestions about the best settings of the sensors in case a low LoA is desired for e.g. operator training purposes.

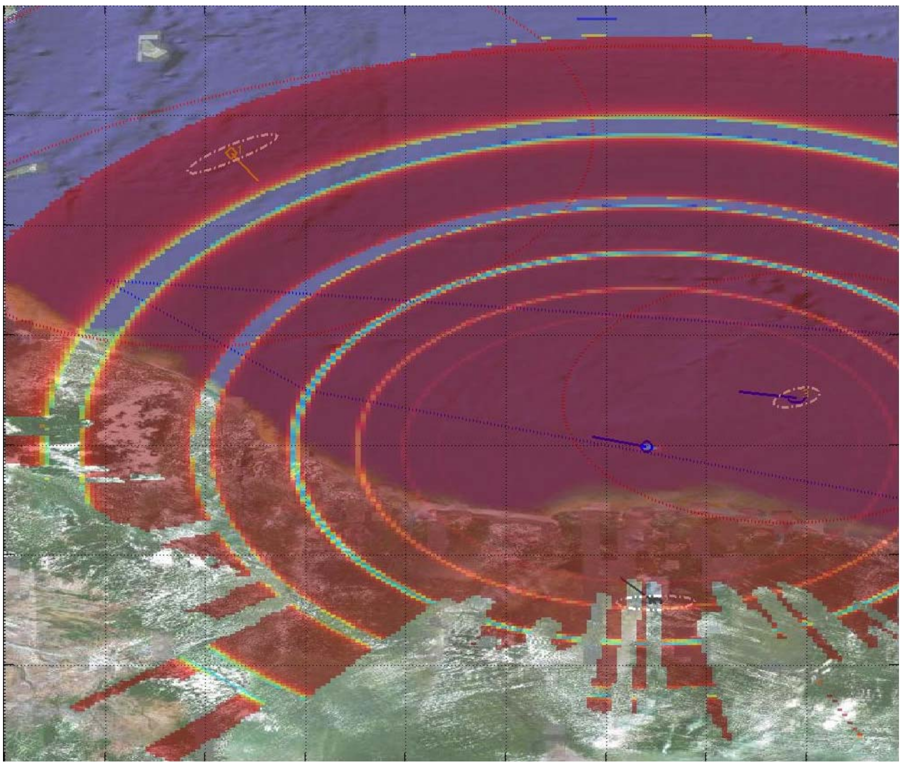

Figure 4. Horizontal coverage diagram

Furthermore, the fused diagrams support the determination of the best location of the sensor suite if the platform on which these sensors are fitted is mobile. The sensor coverage models therefore are of vital importance for the functioning of the sensor manager.
The derived P_d can also be used to select a sensor for performing one of the other *Observation* functions, but it is possible to devise more elaborate selection mechanisms. In the current approach, sensor selection for target tracking is performed by choosing the sensor with the highest P_d. For tracking purposes, a new sensor selection method was proposed for optimising the target track accuracy. This method compares the available sensors with respect to the best expected performance. At each time step the sensor with the best expected performance is selected and executes a measurement. This performance evaluation is based on the modified Riccati equation (MRE) [13]. It includes for each sensor the P_d, the sensor measurement accuracies, and the actual sensor platform position. The MRE also includes for all sensors the following parameters: the predicted target error covariance matrix (i.e., a measure for the estimated target state), the target prediction model (e.g., a constant velocity model) and a process noise measure. Ramdaras and Absil [14] describe how the MRE can be utilised to construct more elaborate performance demands: requirements on position accuracy or more specific on velocity accuracy (or heading, bearing, elevation or speed accuracy) can now be formulated. These performance-based sensor selection criteria contain elements from the expected target state error covariance matrix (i.e., the expected accuracy of the estimated target state). Which elements are considered depend on the required sensor task, or the stage of a military operation. With a properly working sensor selection process global sensor deployment (for the entire sensor suite in a network) can be optimised. Suppose that for a given target scenario one is able to identify the best sensor to observe that target, in the meantime the other sensors might be used for other tasks, reducing overlapping observations and redundant sensor measurements. An adaptive and real time sensor allocation mechanism would make better use of a distributed sensor suite.
The criteria can be used in multiple situations. For a long range surveillance task (e.g., in the range 100-200 km) one is not interested in a highly accurate estimate of target speed and heading; neither is the target altitude highly relevant, so the elevation angle need not be estimated with high precision. An acceptable range and bearing angle will do. If the target is incoming, a more accurate position, speed and heading estimate will become relevant. If at some point the target turns out to be a serious threat, the exact position must be known at each time instant. Now the elevation angle accuracy is as relevant as range and bearing angle accuracy.
Also, these criteria could be used for other tasks. Before deploying countermeasures one has to make sure that the target is within the operational envelope of defensive weapons. At weapon launch, a guided weapon will need a good estimate of the relative geometry between target and intercepting missile; a gun deployment will require a highly accurate estimate of the predicted hitting point of the projectiles (extremely high target position, speed and heading accuracy). In general, the cost function should be a variable, mission-related driver of the sensor selection process.
Sensor selection based on the MRE will yield a well-considered sensor deployment strategy for tracking tasks. If a sensor is allocated for more than one task at the same time, one should consider the previously mentioned task scheduling mechanism based on risk driven target priority assignment [2,11]. Note that the proposed sensor selection method may select sensors with a lower P_d. In that case their expected performance is better compared to sensors with a higher P_d. However, the P_d is still required: a sensor must be capable to detect an object before it can be used for other *Observation* functions.

The combination of these sensor management processes and the picture compilation processes that were described in Section 2 now enable the construction of a versatile C2 framework that is driven by the loop that was shown in Figure 1.

4 Command and Control

In the previous sections, the term Command and Control (C2) was introduced and used. The Allied Joint Doctrine defines C2 as the process that plans, directs, coordinates and supports an operation [15]. In order to be able to accomplish these tasks, resources are required. Depending on the level of command of the performer of these tasks, these resources may take different shapes and forms: the weapons of individual soldiers, the platform systems (e.g. energy generation and propulsion systems), combat systems and crew of ships and aircraft or even complete armies, air forces and navies that are deployed by supreme commanders. No matter at what level of command these resources are deployed, these commanders need a *complete* and *accurate* overview of the situation in order to be able to optimally deploy them. At the end of Section 3 was mentioned that the combination of the basic picture compilation processes that were described in Section 2 and the sensor management processes from Section 3, enabled the construction of a versatile and flexible C2 framework.
After the combination of the two sets of processes, it became clear that the term *sensor management* could be expanded into *resource management* because the sensor systems are an integral part of the resources. The three stages that were formulated for sensor management purposes were also applicable to the deployment of resources:

1. stage 1: the OP is analysed whether the situation is within the limits that were constructed during the planning stage of the mission,
2. stage 2 : the most appropriate resource(s) is (are) selected to keep the situation within these limits and to fulfil the mission objectives,
3. stage 3 : deploy the resources

The constructed framework is shown in Figure 5.

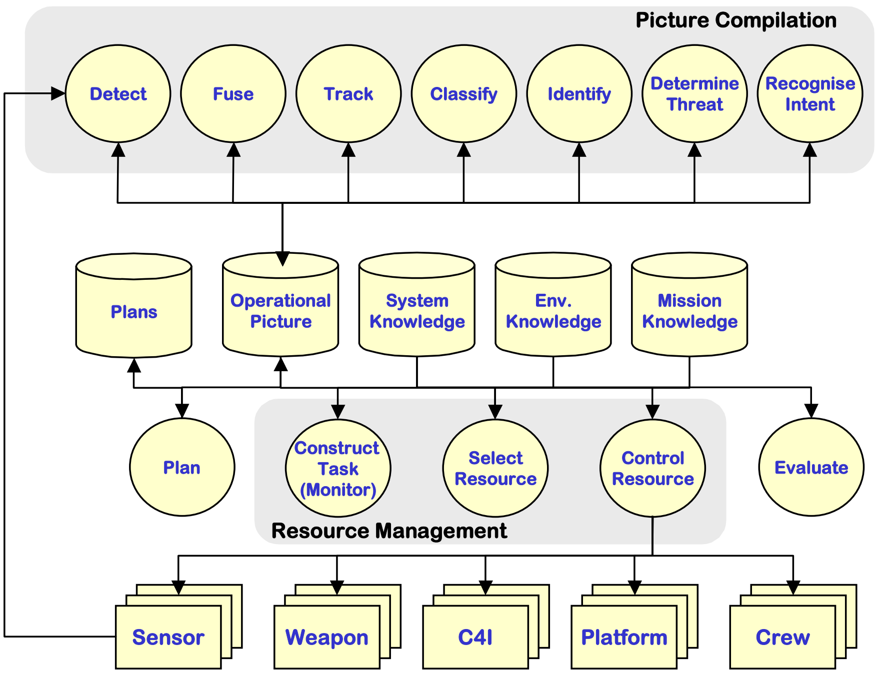

Figure 5. The new C2 framework

Note that this framework can be used during the three stages of a mission: the planning stage, the execution stage and the evaluation stage [16] and thus effectively combines the OODA loop [1] and Demings and Shewhart's Plan-Do-Check-Act (PDCA) cycle that is widely used in business management [17]. The model also solves the shortcomings of the OODA loop as described by Grant and Kooter [18]. During the planning stage of the mission, the three knowledge categories that were described in Section 3 can be used to determine the best Course of Action (CoA) for the mission given the a-priori knowledge that is available at that moment. At this stage, the resources of the opponent are analysed and inserted in the OP to represent the *expected entities*. Within the execution stage of the mission the feasibility of the CoA is constantly monitored by means of the analysis of the OP and resources are deployed if necessary. If the CoA cannot be maintained, the plans have to be adapted. The contents of the knowledge stores and the executed actions can be logged for analysis purposes during the review stage of the mission. This allows for the construction of a *lessons-learned* store that can be utilised within the planning stage of new missions.
The framework was earlier referred to as versatile as it is able to control a wide variety of resources: it is mandatory however that some sensors are incorporated in the set of resources because otherwise no OP can be compiled that is as *complete* and *accurate* as possible, given these sensors.
The picture compilation processes are not limited to those processes depicted in Figure 5; this set of processes can be refined if required by adding new processes and the implemented processes can be replaced by more appropriate ones. Within the framework only two types of interfaces exist:

1. The interface between a process and a resource: this interface can be managed by a *device driver* that regulates the information exchange between the resource and the process.
2. The interface between a process and the OP; this interface is defined by the structure of the objects that represent the real-world entities.

Because all *inter-process communication* is executed via the OP, no agreements about the structure of the exchange data have to be made as this structure is already defined by the structure of the OP-object. If the structure of the OP-objects is standardised, it becomes straightforward to exchange information about them in a general-purpose information layer of networked systems thus reducing or even eliminating the need for specific data/information-exchange networks like Link-11, Link-16 or Link-22.
Within the framework, the resources are not required to be collocated and by incorporating the location of a resource in the *System Knowledge*, the resource manager can select the most appropriate (most accurate, fastest deployable, nearest, most effective, etc.) resource for a certain task. This makes the framework particular suitable for controlling resource layers within *Network Centred Environments*.

5 Conclusions and Recommendations

A *complete* and *accurate* Operational Picture (OP) is vital for successful mission completion as it forms the basis for actions that pursue the operational goals. From this observation, a Command and Control (C2) framework was constructed that consists of two sets of processes: the *picture compilation processes* and the *resource management* processes. Both sets of processes use the OP as a common interface. As the sensor systems form a subset of the resources, a control loop was constructed that reconciles the OODA loop and de PDCA loop. At the *planning stage* of a mission, the Course of Action (CoA) is determined from prior knowledge consisting of information about the mission (opposing forces, goals, etc.), information about the environment (geography, meteorology, etc.) and information about the own resources (performance, capacity, limitations, etc.) from this knowledge *expected objects* are created that are inserted in the OP. During the *execution stage* these expected objects are used to optimise the available sensor systems to detect real-world entities and to track and classify them. The observed entities are also stored in the OP and their observed properties are logged in their attributes. Using this information, the objects are labelled (identified) as *friendly, neutral, hostile, assumed friendly, suspect or unknown* and their risk and intent is estimated and these estimation is also stored in their attributes. The uncertainty that is related to each attribute caused by the sensor accuracy and the subsequent processing or, more generically stated, to the quality of the source, can now be used to decide about new sensor measurements. To obtain observations of the best possible quality, knowledge about the available sensor systems, the environment and the entities that need to be observed is required. Utilising this knowledge enables the selection of the most appropriate sensor(s). This knowledge also enables the construction of coverage diagrams that provide insight to the operator about the performance of the complete sensor suite. The information from the OP can also be used to perform those actions that support the execution of the plans that were constructed during the planning stage: the relocation of platforms, the tasking of outside sensors or the deployment of weapon systems. These resources need not necessary to be collocated and therefore the framework is able to manage the resources in a networked system.

Because the processes in the framework are executed in parallel and all interact with each other by means of the OP, the structure of the OP functions as a *common interface*. It is therefore easy to revise and update the separate processes and change the amount of operator involvement. The processes can either be executed by operators or function completely autonomous. The framework even supports the utilisation of the concept of adaptive automation as it allows the dynamic change of the amount of operator involvement.

Many of the processes involved, especially those processes that can be categorised among the *Orient processes* cannot function in a completely autonomous mode and more research is needed to bring these processes on the highest level of automation. This can also be said from the second and third stage of the sensor manager: more research is required to determine the heuristics and algorithms necessary to automatically perform these tasks.

The software that is developed to execute the processes in the C2 framework will be integrated in the future Combat Management Systems of the Royal Netherlands Navy; a lot of intensive testing will be required to verify, validate and if necessary improve these processes.

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