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Implementation challenges associated with a threat evaluation and weapon assignment system

DP Lötter* & JH van Vuuren†

Abstract

A threat evaluation and weapon assignment system is typically employed in a military surface-based air defence environment to provide real-time decision support to fire control officers when they have to classify incoming aircraft as threats and evaluate the perceived level of threat that these aircraft pose to defended assets on the surface. In addition, such a system is also employed to aid the operator when he has to decide on the assignment(s) of available surface weapon system(s) to neutralise these threats. In this paper, a brief review is given of the current state of a large research project aimed at threat evaluation and weapon assignment decision support designed for a surface-based air defence environment. A number of shortcomings and implementation challenges associated with this decision support system are identified and possible ideas for overcoming these shortcomings are proposed.

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

1 Introduction to a TEWA decision support system

A military *Surface-Based Air Defence* (SBAD) environment typically consists of *Defended Assets* (DAs) on a ground or water surface which require protection from enemy aircraft. Command centres on the surface rely on a network of sensors to detect aircraft entering the defended airspace surrounding the DAs and to provide them with important aircraft attributes, such as their courses of direction, the speeds at which they are travelling and their altitudes. A collection of surface-based *Weapon Systems* (WSs) are deployed to provide protection to the DAs from possible attacks by these aircraft.

The problem of defending DAs is commonly known in the military operations research literature as *Threat Evaluation and Weapon Assignment* (TEWA). This problem is twofold: A TE subproblem is concerned with classifying observed aircraft as hostile or friendly, evaluating the level of threat posed by hostile aircraft to the DAs and prioritising these

*Department of Logistics, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa, email: danielotter@sun.ac.za

†**(Fellow of the Operations Research Society of South Africa)**, Department of Industrial Engineering, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa, email: vuuren@sun.ac.za

threats accordingly, while a WA subproblem is concerned with assigning available WSs to engage these prioritised threats effectively.

A *Fire Control Officer* (FCO) is responsible for decisions related to the assignment of WSs to threats in real-time. While solving the above-mentioned subproblems may be simple when only a small number of aircraft enter the defended airspace, it becomes extremely challenging for the FCO when the defended airspace is saturated with aircraft, an attack strategy often adopted by enemy forces in an attempt to overwhelm operators. Furthermore, the speed at which enemy aircraft travel typically results in a very short time-frame during which the FCO has to solve these subproblems and make assignment decisions. Combined with the severely stressful situations in which these decisions usually have to be taken, the rapidly unfolding attack scenario may require almost super-human effort on the part of the FCO to identify good WS-to-threat assignment pairs.

One way of providing relief to the pressure experienced by an FCO is to furnish him with a computerised TEWA decision support system [10]. The aim of such a system is first to classify aircraft observed in the defended airspace as friendly, unknown or hostile, and to provide the FCO with a prioritised list of all the hostile aircraft, each with a suitable threat value assigned to it. This threat value may be an estimation of the perceived level of threat that a specific aircraft poses to a specific DA or a collection of DAs. A second aim of such a decision support system is to provide the FCO with a proposed WS-to-threat assignment list for the engagement of hostile aircraft by available WS(s) with a view to optimising some objective, such as minimising the overall accumulated survival probabilities of the hostile aircraft. The FCO may then use the information provided by the system in conjunction with his own experience and judgment to make final WS-to-threat assignment decisions.

Extensive basic research has been conducted with respect to the design of an SBAD TEWA decision support system at the TEWA Centre of Expertise of Stellenbosch University during the period 2005–2014. Although the system has been greatly refined over this period, a number of implementation challenges and shortcomings still remain. The aim in this paper is to briefly review the current local state of knowledge related to the design of a TEWA decision support system within an SBAD environment and to put forward a number of suggestions for overcoming these implementation challenges.

The paper is organised as follows. A review of the current state of local SBAD-based TEWA knowledge is provided in §2, followed, in §3, by a detailed description of the prevailing implementation challenges. The paper closes, in §4, with a number of conclusions.

2 The current state of local TEWA knowledge

Each computational cycle within a typical TEWA decision support system consists of a series of events which occur consecutively and these computational cycles are repeated until a stopping criterion is reached [10]. The natural progression of these events are illustrated graphically in Figure 1 and are discussed in some detail in this section.

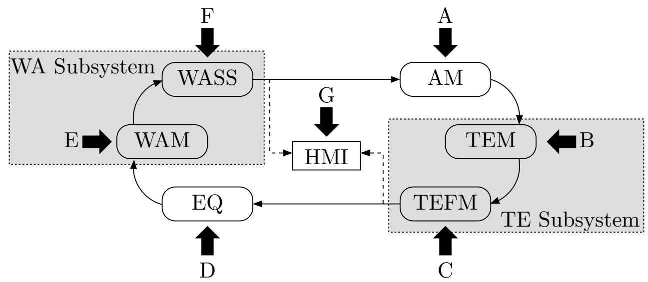

Figure 1: *Implementation challenges related to the design of an SBAD TEWA system.*

2.1 Research conducted on the TE subsystem

In 2008, Roux and Van Vuuren [11] designed a first-order automated TE subsystem architecture. In this architecture, an *Attribute Management* (AM) component analyses aircraft attributes (*e.g.* the speed or altitude at which aircraft are travelling) obtained from sensor systems, calculating a number of derived aircraft attributes (*e.g.* the acceleration of a threat) for each aircraft. This is also the first process in a TEWA computation cycle, as depicted in Figure 1. Next, the architecture includes a *Threat Evaluation Model* (TEM) component, which is the heart of the TE subsystem, and contains a number of mathematical TE models which utilise the output from the AM component to estimate the level of threat posed by each of the hostile aircraft.

Later in 2008, Heyns [3] developed four deterministic TE models for populating the TEM component described above. These models for fixed-wing aircraft are designed to evaluate a threat based solely on derived model-related attributes such as bearing, course, or course variation of aircraft — no specific consideration was given to possible weapon delivery profiles that the aircraft may execute.

Roux and Van Vuuren [11] also developed a variety of fixed wing TE models, thereby expanding the range of TE models of Heyns [3] for inclusion in the TEM component. They classified these models into three distinct hierarchical groups, based on model complexity, and proposed that the models function concurrently, with the more sophisticated, data-hungry models being phased in as high-quality data become available and they start producing realistic results.

At the lowest level of sophistication a suite of binary flagging models was proposed. These models are qualitative in nature and are only able to flag an aircraft for operator attention if there is a significant change in the observed kinematic behaviour of aircraft. These models are not able to distinguish between different levels of threat posed by aircraft.

The next suite of TE models are the deterministic models developed by Heyns [3]. These models are quantitative in nature, and are able to distinguish in a deterministic, kinematic-based manner between different levels of threat posed by aircraft.

Finally, the most sophisticated level of TE models contain a suite of stochastic models. These models are also quantitative in nature, also being able to distinguish between different levels of threat posed by aircraft, and further take into consideration enemy arsenal intelligence and doctrine when estimating a single threat value for each aircraft with respect to each DA. This estimation is typically the probability that an aircraft will attack and/or kill a particular DA.

In 2013, Van Staden [14] developed a mathematical model for classifying the so-called *Formative Element Combinations* (FECs) associated with enemy aircraft — that is, the aircraft type, the weapon types carried and the aircraft attack technique adopted rather than estimating these parameters individually based on expert judgement and pre-deployment intelligence reports, as originally suggested by Roux and Van Vuuren [11]. The model is based on a hidden Markov modelling paradigm and predicts the most probable attack technique adopted by aerial threats, based on their observed kinematic data. This information may then be used in conjunction with the enemy's known arsenal of aircraft and WS types carried to determine the most probable FEC for each threat. Incorporating the results of this model into the stochastic TE models is expected to yield more reliable estimated threat values of aircraft.

The final component in the TE subsystem architecture of Roux and Van Vuuren [11] is a *Threat Evaluation Model Fusion* (TEFM) component. This component is designed to combine the results produced by the various models in the TEM component so as to produce a global threat value for each aircraft. This is achieved by a multi-criteria decision analysis technique, such as a value function procedure or additive model.

The results of the TEFM are relayed to the FCO via a *Human Machine Interface* (HMI), which displays the airpicture as well as the threat values of the various aircraft and other TEWA-related information on a series of computer screens.

2.2 Research conducted on the WA subsystem

In 2008, Potgieter [8] proposed a basic first-order WA subsystem architecture. The design included an *Engagement Efficiency Matrix* (EEM) component in which the efficiency values achieved by WSs, when assigned to engage threats, are discretised and filtered for external elements (such as adverse weather conditions and/or terrain feature interference). Furthermore, the design included a model framework component, which is the heart of the WA subsystem, and contains a variety of mathematical assignment models for solving the WA subproblem. This component uses the results of the TE subsystem and the output from the EEM component to propose the assignment of WSs to threats. A number of WA models (including models of a static[1] and dynamic[2] nature) as well as rule-based weapon assignment heuristics, which may be used in this framework, were also presented.

Du Toit [1] built on the dynamic WA models of Potgieter [8] by formulating the WA problem dynamically in two different ways in 2009 — first under the assumption that the number of threats and locations of targets are all known in advance and secondly under the assumption that not all targets are observable (at each time interval the locations of targets present is only known stochastically).

[1] In the context of WA models, the term *static* refers to models in which the numbers and locations of WSs and threats are known with certainty at some time instant τ and a single assignment of WSs to threats is sought at time τ such that all the WSs are committed [1].

[2] In contrast, the term *dynamic* refers to the class of WA models in which suitable future time instants are sought at which to assign a subset of the available WSs to the threats observed [13].

In 2013, Lötter *et al.* [6] modelled the WA problem as a multi-objective decision problem in which a number of objectives are pursued simultaneously. The research included the identification of useful objectives by applying objective identification techniques from the multi-criteria decision analysis literature to a carefully selected audience of military experts. Two of these objectives were used to formulate a bi-objective, static WA model.

Also in 2013, Van der Merwe and Van Vuuren [13] modelled the WA problem in a dynamic framework as a vehicle routing problem with time windows in which WSs are modelled as vehicles having to deliver commodities (ammunition) to customers (threats). The use of time windows, in the sense that the model is required to suggest time frames during which WSs should assign threats, adds a scheduling element to the WA problem. A hybrid approximate solution approach towards solving the model was also proposed, based on the metaheuristics of simulated annealing and tabu search.

Lötter and Van Vuuren [7] went on to design an improved WA subsystem architecture for use in the context of a SBAD environment in 2014. The design provides for an *Engagement Quantisation* (EQ) component, a *Weapon Assignment Model* (WAM) component and a *Weapon Assignment Solution Selection* (WASS) component, as depicted in Figure 1. This is also the order in which events occur in a TEWA computational cycle. The core of the EQ component rests on the EEM component proposed earlier by Potgieter [8], while the WAM component serves the same purpose as the model framework component proposed by him. However, the WAM component is designed to include four classes of WAMs ranging in different levels of complexity, from which the FCO may configure a model for use in the WAM component before or during a combat situation.

The least complex class of WAMs proposed by Lötter and Van Vuuren [7] involve a single-objective WAM in a static framework. The next class of WAMs contains multi-objective, static WAMs. They differ from the first class of WAMs in the sense that they consider multiple objectives simultaneously when proposing the assignments of WSs to threats. The next level of WAMs contains single-objective, dynamic WAMs. Although these models accommodate only a single objective when considering the assignment of WSs to threats, they include a dynamic scheduling element. The final class of WAMs is also the most complex class of WAMs, containing multi-objective, dynamic WAMs. These models consider multiple objectives over the entire time continuum to propose assignments of WSs to threats as well as the scheduling of appropriate time windows for the assignments.

The final component in the WA subsystem architecture of Lötter and Van Vuuren [7] is the WASS, which employs various solution techniques to solve the WAM configured by the FCO in order to produce a collection of WS-to-threat assignment decision alternatives. The WASS component combines all these results and filter out dominated solutions by employing a sorting algorithm, so as to present the FCO with a set of Pareto-optimal solutions via the HMI.

3 Implementation challenges associated with a TEWA DSS

A number of shortcomings and implementation challenges have been identified within the components of the TEWA system design described in §2. These challenges involve (1) the quality and quantity of TE-related input data (which may affect the working of the AM and TEM components, as indicated by the arrows labelled A and B in Figure 1), (2) the problem of potentially overwhelming the FCO with excessive decision support information (which may affect the implementation of the TEFM, WASS and HMI components, as indicated by the arrows labelled C, F and G in Figure 1), (3) incorporating FCO preferences and biases into TEWA results (which may affect the results presented by the WASS component, as indicated by the arrow labelled F in Figure 1), (4) the problem of potentially rapid switching of TEWA decision support results over time (as a result of the suggested working of the TEFM and WASS components, as indicated by the arrows labelled C and F in Figure 1), and (5) the requirement of testing and evaluating the level of performance of the TEWA system as an integrated system (which involves all the components, as indicated by the arrows labelled A – F in Figure 1).

3.1 Quality and quantity of TE-related data

A TE subsystem will only be able to perform to its full potential if sufficient quality and quantity of input data are available. These data are typically provided by sensor systems and intelligence reports and should be analysed and preprocessed thoroughly in order to provide high-quality input to the TE subsystem. A number of ways in which the quantity and quality of these input data may be improved are outlined in this section.

The scope of the TE subsystem design of Roux and Van Vuuren [11], as well as the FEC model proposed by Van Staden [14], were restricted to only include fixed wing aircraft. It may, however, be beneficial to expand the scope of the aerial threats by additionally including models for other platform types, such as rotary wing aircraft [9, 14]. By expanding the range of platform types, a more realistic TE subsystem may be obtained.

Furthermore, the identification of influential measured and derived aircraft attributes (for all aircraft types) obtainable from sensors and intelligence reports may also result in more accurate and reliable FEC classification of aircraft as well as a more appropriate estimation of the level of threat posed by aircraft. However, the availability and classification of such data are typically restricted [9]. If such information were available, existing data mining procedures may be employed for extracting significant measured attributes or discovering derived attributes from the data which influence aircraft threat values significantly.

3.2 Overwhelming the operator with information

The objective of a TEWA system is ultimately the provision of high-quality TEWA solution suggestions at any given time stage. It is, however, important to provide the FCO with only the information that he needs rather than to provide him with excessive information which may overwhelm him and may compromise his ability to make effective WS-to-threat assignment decisions. On the other hand, a sufficient store of information should be available in case the FCO wishes to access more detailed information in order to motivate decisions. When designing a TEWA HMI display, careful consideration should thus be given as to what information is deemed important to provide to the FCO. Gruhn [2] suggests that an effective HMI should be based on a user-centered design which integrates information in ways that fit the tasks and needs of the user. This implies that the FCO should be included in the design of an effective HMI and that he should be able to configure the HMI pre-deployment and even during a mission.

One way of minimising clutter when designing an HMI is to hide excess information by employing pop-up windows on the HMI display screen. The FCO may then use a computer mouse to hover over a particular solution, resulting in the opening of a pop-up window which displays more detailed information related to a suggested WS-to-threat assignment suggestion. For example, in the case where a list or graph of approximately Pareto-optimal solutions (in objective space) is presented to the FCO, the pop-up windows may display the actual assignments of WSs to threats (in solution space) when hovering over one of the solutions. When the FCO then chooses one of these solutions, the progress of unfolding assignments may then be displayed on the screen over time.

3.3 Incorporating FCO preferences and biases

Furthermore, care should also be taken in the implementation of the WASS component proposed by Lötter and Van Vuuren [7], since presenting the FCO with too many approximately Pareto-optimal solutions may cause indecision on the part of the FCO when picking one of these solutions for implementation. One way of reducing the number of solutions presented is to ask the FCO to specify sufficient bounds on the objective function values.

Another way of reducing the number of solutions presented to the FCO is to filter out approximately Pareto-optimal solutions from the suggested list according to the operator's biases and preferences, by employing a pre-determined FCO utility function.

3.4 Switching of results between consecutive time stages

An undesirable phenomenon, which may occur when WS-to-threat assignment suggestions are reported to the FCO during a combat situation, is one called *switching*. Switching refers to the excessively rapid changing of assignment suggestions during a small subset of consecutive time stages. This kind of behaviour may be ascribed to small changes in the single shot hit probabilities that WSs are capable of achieving with respect to threats during these time stages. However, switching may cause confusion and compromise the FCO's confidence in the results produced by the TEWA system which may, in turn, lead to the FCO making sub-optimal decisions when choosing to rely on his own judgment rather than trusting the seeming indecision of the decision support system.

The problem of switching may be solved by implementing threshold values in the system in such a way that assignment suggestions are only allowed to change from one time stage to another once a variation in the results equivalent to the threshold value is reached (*i.e.* if the two solutions in question are deemed significantly different).

3.5 Evaluating the performance of the system

Although the designs of the TE and WA subsystems proposed by Roux and Van Vuuren [11] and by Lötter and Van Vuuren [7], respectively, seem to be able to provide acceptable quality decision support to FCOs, the performances of these subsystems have not yet been tested in an integrated manner. It may be useful to employ a military expert or a group of military experts to evaluate and analyse the results produced by these subsystems. A more robust method of evaluating TEWA system performance is, however, required. It is also important that this method of evaluation be generic in the sense that should future changes be made to any of the components in the TEWA subsystems, the method should be easily adaptable to incorporate these changes and to re-evaluate the system's performance.

Truter and Van Vuuren [12] are currently designing various measures for evaluating the performance of TEWA systems. Roux [9] suggested that a simulation environment be used to test and evaluate a TEWA system's performance and that testing procedures be performed in an incremental manner. First-order examples of evaluating the performance of TEWA systems in this manner were put forward by Kok [5] and by Johansson and Falke [4].

4 Conclusion and discussion

A brief review of the design of a TEWA decision support system within an SBAD environment was provided in this paper, touching on the functions of and interactions between the various components and substructures comprising such a system. Furthermore, a number of important concerns were raised in terms of testing and implementing the system. Finally, some suggestions were made with respect to overcoming these concerns.

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