Target Engageability Improvement through Adaptive Tracking

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This paper addresses the joint problem of target engageability assessment and engageability improvement in naval Anti-Air Warfare operations. An integrated approach that aims to minimize the detect-to-engage sequence is proposed. It uses an estimation of the search-to-lock-on time of the fire control radar to evaluate the engageability of targets. The latter is then improved through the control of tracking operations. Weapons assignment process and the resulting engagement plan are adjusted based on the results of both the assessment and the improvement of the engageability. A quantitative evaluation of the proposed approach was performed using a simulation and performance evaluation environment developed at Defence Research and Development Canada–Valcartier. Although simple sensors and weapons models used in the presented work, encouraging results were obtained with scenarios involving generic supersonic Anti-Ship Missiles. In such scenarios, the proposed adaptive tracking strategy was able to provide timely engagements compared to a conventional engagement strategy.

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1. INTRODUCTION

Reaction time of current and future naval warships is eroded since they are expected to operate in a large variety of situations with constantly increasing complexity. To cope with diverse air and surface threats, the warships, either operating in a single ship configuration or within a task group, will require their combat power resources to be efficiently managed. The coordination and tight integration during the deployment of these resources will also be required. Decision support aids can help in overcoming the inherent complexity of the naval Command and Control (C^2) process and the underlying combat resource management problem [15].

This paper addresses two problems related to target engageability in naval warfare operations: engageability assessment and engageability improvement. Engageability is defined as the feasibility of engagement actions against designated targets. Engageability assessment is concerned with the evaluation of the feasibility of engagement actions based on the involved combat resources, the environmental condition, and the geometry of the engagement. The problem of engageability improvement goes beyond the assessment and aims at making non-feasible engagements feasible by changing the engagement geometry and dynamics.

The focus of this paper is on on Anti-Air Warfare (AAW) [7], and more specifically the problem of *combat power management* to counter Anti-Ship Missiles (ASM). This problem is very constrained by the availability of the combat resources, the most important ones being hardkill and softkill weapons. Furthermore, most of the weapons rely on supporting resources for their deployment. An example of such supporting resources is given by the Fire Control Radars (FCR) [22] that offer a limited number of concurrent channels. Since typical AAW hardkill weapons require FCR support, the engageability of targets using hardkill is very dependent upon the availability of FCR. This is not the case for softkill, which can be fired without the need of FCR.

In this work, the availability of FCRs is used as a key parameter in the assessment of the target engageability using hardkill weapons. When required and possible, the engageability is improved by adapting the object[1] tracking functionality [1, 4] using an on-line estimation of the FCR search-to-lock-on time. This represents a new approach, which is partly inspired from the work of [10, 11] on covariance control. If the target is not and cannot be made engageable, softkill engagements are advocated. As detailed in the sequel and under given conditions, both engageability assessment and improvement exploit the dependency of the FCR search and lock-on duration on the error covariance of the track of the target to be engaged; the track being provided by the surveillance system. Scenarios involving

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[1] Here we make a clear distinction between objects and targets, since not all objects will become targets (from the engagement perspective).

generic supersonic Anti-Ship Missiles (ASMs) are used to demonstrate the proposed approach. The evaluation is performed within a simulation and evaluation environment developed at Defence Research and Development Canada–Valcartier. This environment is a combination of a set of tools, including the Simulation Environment for the Analysis of the Tactical Situation (SEATS) test-bed [16], Ship Air Defense Model (SADM) simulator [21] and Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE-ATTI) test-bed [20].

This paper is original in that it is one among the very few to address the engageability assessment problem, and the first to propose an engageability improvement approach, and to integrate it with object tracking and weapons assignment functionalities.

The paper is organized as follows. Section 2 presents the naval Command and Control (C^2) problem. Section 3 discussed the target engageability concept and the role of fire control operation in the detect-to-engage sequence. A method for assessing the target engageability based on FCR search-to-lock-on time is presented in Section 4. The result of engageability assessment is exploited in Section 5 to proposed a target engageability improvement solution. The simulation results and their discussion are given in Section 6.

2. COMMAND AND CONTROL PROBLEM

Military Command and Control (C^2) is a very complex problem and often this complexity rises from the multitude, the heterogeneity and the inter-relationships of the systems and resources involved. This is in general the case when simultaneous engagements, involving heterogeneous sensor and/or weapon systems, can take place. Decision support aids can help in overcoming the inherent complexity of simultaneous engagements.

Naval tactical C^2, which defines the context of this work, can be decomposed into a set of generally accepted functions that must be executed within some reasonable delays to ensure mission success. A very high-level description of those functions, related to battlespace management, is given below (Fig. 1). Note that the presented C^2 model is proposed here for our specific target engagement application. Waltz and Llinas [23] present a more generic description and review of the more the general Command, Control and Communications (C^3) problem.

2.1. Surveillance

Surveillance includes *object detection*, *object tracking*, and *object identification*. Object detection is very dependent upon the sensors performance. Object tracking uses the sensor data to estimate the current kinematical properties of the object, and predict their future positions. Object identification (and classification) assesses the identity and the class of objects. This also results in the resolution of true objects from decoys.

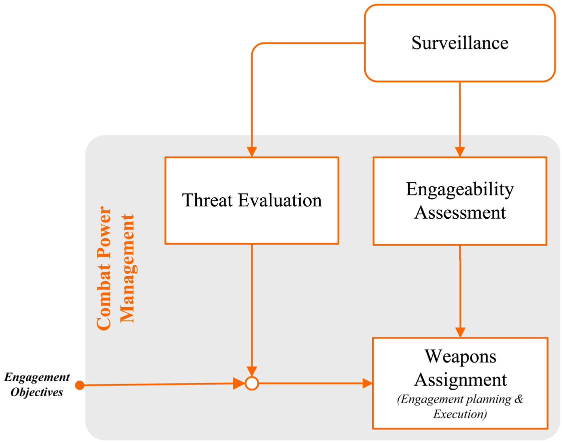

Fig. 1. Global view of C^2 process.

2.2. Combat Power Management

To defend itself, a warship relies on a set of tactical resources, which we will refer to as Combat Power (CP). These consist mainly of weapons, sensors, navigation, and communication systems. For a typical frigate, such as the Canadian Halifax Class, the Anti-Air Warfare (AAW) weapons include hardkill and softkill. Hardkill weapons are directed to intercept its target and actively destroy it through direct impact or explosive detonation in the proximity of the target. Hardkill weapons for a typical frigate include Surface to Air Missiles (SAM), an intermediate range Gun, and a Close-In Weapons System (CIWS). Softkill weapons use techniques to deceive or disorient the target to cause it to destroy itself, or at least lose its lock on its intended target (*i.e.*, ownship or the high value unit). The AAW softkill weapons for a typical frigate include decoys (Radio Frequency/Infrared) and jamming systems (on-board/off-board).

Combat Power Management[2] (CPM) functionalities include, as depicted on Fig. 1, *threat evaluation*, *engageability assessment* and *weapons assignment*, which are described below.

2.2.1. Threat Evaluation

Threat evaluation establishes the intent and the capability of the non-friendly entities within a certain Volume Of Interest (VOI) and for a specific reference point. It refers to the ongoing process of determining if an entity intends to inflict evil, injury, or damage to the defending forces and/or their interests, along with the ranking of such entities according to the level of threat they pose. In this work, threat value computation is based on the Closest Point of Approach (CPA).

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[2] Also referred to as Threat Evaluation and Weapons Assignment (TEWA).

2.2.2. Engageability Assessment

Engageability assessment [9, 12, 8] concerns the evaluation of own force's engagement options feasibility against the non-friendly entities within the VOI. This process is intended to help the weapons assignment process by eliminating candidate solutions that violate one or more hard constraints. The latter will therefore not be feasible. Several aspects can be taken into consideration during this process, such as Rules Of Engagement (ROE), blind zones, ammunition availability, etc.

2.2.3. Weapons Assignment

Weapons assignment makes decisions on how to deal with the identified threats (and that become targets now). This process can be subdivided into several subproblems that include mainly a *response planning* and *response execution and monitoring*. Response planning ensures that one or more weapons are assigned to engage each target, including the assignment of supporting resources (as sensors, communications, etc.). This is about assignment of both resources (a pure allocation problem) and start and end times to activities (a pure scheduling problem). We talk about joint resource allocation and scheduling problems, that generates a ranked engagement list of the targets for the response execution module. Response execution and monitoring is the process by which the planned response is executed in realtime. This also includes the execution monitoring functionality. Since the responses are executed in a dynamic environment, subject to uncertainty, changing goals, and changing conditions, the actual execution contexts will be different from the projected ones.[3] Monitoring is required to help detect, identify and handle contingencies caused by uncertainty and changing nature of the environment.

3. FIRE CONTROL AND ENGAGEABILITY PROBLEM

To provide response to an ASM attack, human operators in charge of AAW go through a standard sequence of operations referred to as *detect-to-engage sequence*. This temporal sequence starts with the object detection by the surveillance system and ends with the object (now a target) engagement. Fig. 2 illustrates the main operations within this sequence. These include the object detection and tracking by the surveillance system, FCR cueing, acquisition by FCR (that relates to the FCR search-to-lock-on) and engagement.

The duration of the detect-to-engage sequence is crucial to the ship survival. Short detect-to-engage sequence provides room for the re-engagement of the same target (in the case of a target miss assessment) or the engagement of one or more different targets (in the case of a target kill/seduction assessment).

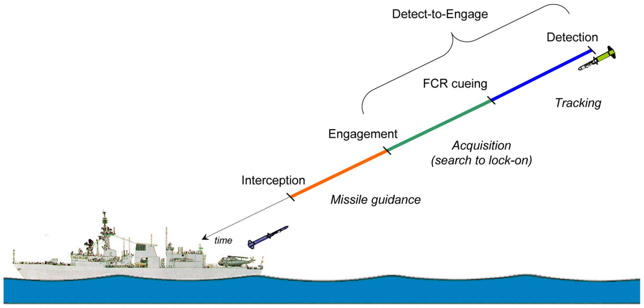

Fig. 2. Detect-to-engage sequence.

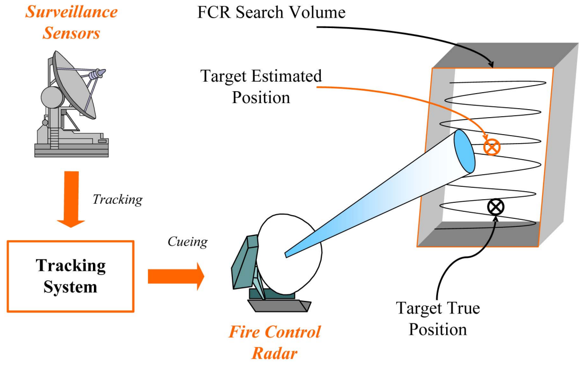

Fig. 3. Fire control cueing.

The duration of the whole detect-to-engage sequence depends on the individual durations of the composing functions, over which the decision making (human, automation or both) has some control. This is especially the case for the FCR search-to-lock-on. This control will be used, as explained in the sequel, to evaluate and optimize the duration of the detect-to-engage sequence in order to improve the engageability of targets.

3.1. FCR Cueing

The FCR system effectively offers two concurrent fire channels for the hardkill weapons that provide high accuracy track data for target engagements. Fig. 3 illustrates how the surveillance sensors and the related tracking system cue the FCR system to help it acquire the target and provide a hardkill firing solution [17]. It is assumed here that FCR cueing includes the designation phase in which the FCR is directed to the estimated location of the target.

Upon detection by the 2D surveillance radars, the contact information is provided to the tracking system that maintains a more accurate estimation of the object position and infers its identity and classification. In the sequel, only the object position will be considered. It is given by the state estimate $\hat{\mathbf{x}} = [\hat{x}, \hat{y}, \hat{\dot{x}}, \hat{\dot{y}}]^T$ and the related error covariance matrix $\mathbf{P}$ that represents some measure of the tactical picture accuracy. Note that in [19], accuracy is defined in terms of the Root Mean Square Error (RMSE) of a track. Here we will assume a consistent tracking and optimal filter [3],

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[3] The ones that motivated the construction of the original response.

where the target behavior follows the motion model used by the tracking filter, so that the RMSE and the error covariance will converge towards the same value.

Given its high-risk consequences, the engagement phase requires more precise information than the surveillance operations. This is why the (3D) FCR must take over the less accurate (and 2D) surveillance radars. To provide such accurate information, the FCR will have to acquire and then track the designated target by itself. Therefore, once a decision is made to engage a given target, the corresponding positional information is used to cue the FCR, *i.e.*, to delimit its search region (Fig. 3) for its search and lock-on phase. This phase starts once the FCR begins its scan[4] and ends when the FCR locks on the target.

3.2. FCR Search-to-Lock-on Time

Following a specific pattern, the FCR will scan the specific region of the Volume Of Interest (VOI) until it detects and locks on the target for which a track is then maintained. The target course and speed contained in this FCR track is then used to compute a Predicted Intercept Point (PIP) inside the weapon engagement envelope. The goal is to provide guidance (for the missile) or the pointing (for the gun) information toward the engaged target.

During this target acquisition, or search-to-lock-on, phase, the FCR has a search time that depends on several factors, such as: the ownship weapons properties, Command and Control System (CCS) performance, the operator skill/training, the engaged target characteristics, etc. Nevertheless, the search-to-lock-on duration should be limited to avoid wasting the valuable and scarce reaction time.

3.3. Track Accuracy, Search-to-Lock-on, and Engageability

The accuracy of the information cued to the FCR determines the volume it must scan. The time it will take to re-acquire the target, that is the duration of the search-to-lock-on operation, depends in a non-linear manner of the volume to be scanned and the detection probability of the FCR. This duration is subtracted from the total reaction time available to the decision-maker and/or combat power management capability. Note that the ship survival is very depending upon this reaction time.

A poor track accuracy causes the FCR to search in a large volume, so that it will take more time to acquire the target. This may lead to grave consequences on ownship safety. Therefore, the engageability of the targets is a function of the accuracy of their tracks as provided by the surveillance system. Hence, controlling the track accuracy, on the surveillance side, offers a means to improve the targets engageability and increases the chance of ownship to achieve its engagement objectives.

4. ENGAGEABILITY ASSESSMENT

Engageability assessment defines the process of evaluating the engageability of a specific target, *viz.*, evaluating the ability to successfully execute a specific engagement action against a specific target. Success here is related to the ability to undertake the action, given the tactical situation, and not to the outcome of the undertaken action. Actions refer to defensive strategies where one or more weapons are assigned to the target. Engageability is assessed over a multi-dimensional space, which includes time, space, frequency spectrum, etc.

In this work, the focus is on time. The engageability is defined as the feasibility, in terms of scheduling or time-lining, of a specific engagement as defined by the duration of the detect-to-engage process. The evaluation also considers target state and characteristics as well as characteristics of the defensive weapons and of their related resources. This evaluation aims at reducing the combat power management problem complexity and save the weapons assignment planning time by discarding inconsistent candidate solutions. Thus, a feasible alternative must verify a set of constraints and will be eliminated if it violates any one. For example, an alternative is retained if, for each considered hardkill engagement,

1) the requested FCR is available;
2) the target to be engaged is within the range of the selected FCR;
3) the interception will occur within the weapon envelope; and
4) the target is not in the blind zones of FCR and weapons.

In the remaining, only the availability of the FCR is considered for the engageability assessment, where the assessment process considers time constraints over the predicted timeline of the interception.

4.1. FCR-Based Engageability Assessment

The proposed engageability assessment computation is based on estimations of both the search-to-lock-on time (t_s) and of the detect-to-engage duration (t_{de}). The engageability of a specific target depends on its kinematics as well as on the properties of the weapons ($\mathcal{W}$) and the characteristics of the FCR.

There is a minimum admissible range of interception $r_i^{\min}$ that depends on both the weapon and the FCR. Here it is assumed that $r_i^{\min}$ corresponds to the weapon's minimum effective range $r_w^{\min}$. Accordingly, the predicted target intercept range r_i should always be such that

$$r_i \geq r_i^{\min} = r_w^{\min} \tag{1}$$

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[4] Upon cueing from the surveillance system.

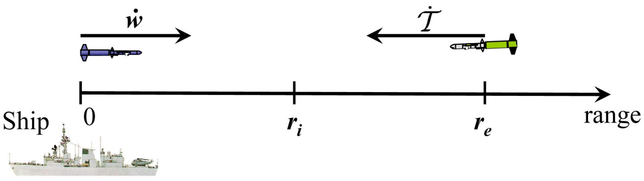

Fig. 4. Target interception range r_i.

where r_i is determined based on the target velocity $\dot{\mathcal{T}}$, the target range r_e at the beginning of the engagement, and the weapon velocity $\dot{w}$ (see Fig. 4)

$$r_i = \left[\frac{\dot{w}}{\dot{w} + \dot{\mathcal{T}}}\right] r_e. \tag{2}$$

The assessment of engageability is performed as by equation (1), with focus on specific steps in the engagement. First, given $r_w^{\min}$ there is a minimum target range $r_e^{\min}$ at which the weapon must be fired to make the interception happen within its effective range. If the weapon $\mathcal{W}$ is launched while the target $\mathcal{T}$ has already passed $r_e^{\min}$, it will be too late, *i.e*, $r_i \notin [w^-, w^+]$. Therefore, the weapon $\mathcal{W}$ must be fired while the target $\mathcal{T}$ is beyond $r_e^{\min}$. To make this interception possible, the target $\mathcal{T}$ must be acquired by the FCR at a range r_l such that

$$r_l \geq r_e \geq r_e^{\min}. \tag{3}$$

From Equation 2, it is clear that the intercept range r_i is dependent on r_e (target range at the end of the detect-to-engage sequence). The sequence includes detection, surveillance sensor tracking, FCR cueing, FCR search-to-lock-on, FCR tracking, and finally weapon launch. The duration t_{de} of the whole sequence is function of the different phases, as follows

$$t_{\text{de}} = t_{\text{tr}} + t_s + \Gamma\,(t_{\text{det}}, t_{\text{cue}}, t_{\text{tr}f}, t_{\text{wi}}) \tag{4}$$

where the durations of detection (t_{det}), FCR cueing (t_{cue}), FCR tracking ($t_{\text{tr}f}$), and weapon launch initialization (t_{wi}) are assumed non-controllable (for this work) and gathered in a single function Γ. t_{tr} and t_s designate respectively the durations of tracking (with the surveillance sensors) and search-to-lock-on of the FCR. A limit $t_{\text{de}}^{\max}$ on the detect-to-engage time t_{de} is set using the limit $r_e^{\min}$ defined by the minimum range beyond which the target must be engaged

$$t_{\text{de}} \leq t_{\text{de}}^{\max} = \frac{r_d - r_e^{\min}}{\dot{\mathcal{T}}} \tag{5}$$

where r_d is the range at which the threat is detected by the surveillance sensors, and $r_e^{\min}$ is given by

$$r_e^{\min} = r_w^{\min}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right]. \tag{6}$$

Consequently, the detect-to-engage time t_{de} has an influence over the predicted intercept range r_i. Thus, any constraint on r_i can be reformulated as a constraint on t_{de}. Furthermore, the duration t_{de} is mainly determined by the length t_s of the search and lock-on phase of the FCR and by the duration t_{tr} of the tracking phase (by the surveillance system). Therefore, the constraint on t_{de} can be re-expressed as a constraint on t_s

$$t_{\text{de}} = t_{\text{tr}} + t_s \leq t_{\text{de}}^{\max} \Rightarrow t_s \leq t_s^{\max} \tag{7}$$

where

$$t_s^{\max} = t_{\text{de}}^{\max} - t_{\text{tr}} \tag{8}$$

$$= \frac{r_d - r_e^{\min}}{\dot{\mathcal{T}}} - t_{\text{tr}} \tag{9}$$

$$= \frac{r_d - r_w^{\min}}{\dot{\mathcal{T}}} - \frac{r_w^{\min}}{\dot{w}} - t_{\text{tr}}. \tag{10}$$

Moreover, since the duration of the search and lock-on phase of the FCR depends on the uncertainty related to the track of the target (**P**), the established constraints on t_s can be re-expressed as constraints on **P**. Note also the all of the constraints described above can be re-expressed in terms of time instead of range. The next section will show how the search-to-lock-on time and the detect-to-engage time can be estimated.

4.2. Estimation of the Sequences Duration

The core idea of the presented work is to generate engagement strategies that exploit contextual information. This information is given, in this work, by an estimate of the duration of the engagement sequence, focusing on the search-to-lock-on time of the FCR. These estimated values, shown in Fig. 2, will be used both for assessing and improving target engageability. As mentioned above, the estimated search-to-lock-on time ($\hat{t}_s$) of the FCR is a key parameter of the engagement sequence. It is evaluated based on both the characteristics of the target and of the FCR.

Error covariance of the track handed-over to the FCR also influences the estimation in the determination of the search volume and conditional detection probabilities. Assuming Gaussian noise for both the target dynamics and the measurement process, let $\hat{\mathbf{x}}$ and **P** represent the target state estimate and its error covariance matrix respectively, **Q** the process noise covariance matrix for the discrete time interval h and **R** the measurement error covariance matrix. Considering regular measurement updates at an update interval h, the track accuracy represented by **P** can be expressed in terms of the tracking time t_{tr}:

$$\mathbf{P} = \mathcal{F}(t_{\text{tr}}) \tag{11}$$

$\mathcal{F}$ is evaluated recursively by applying the Kalman covariance update equations given by

$$\mathbf{P}_{k+1|k+1} = \mathbf{P}_{k+1|k} - \mathbf{W}_{k+1}\mathbf{H}_{k+1}\mathbf{P}_{k+1|k} \tag{12}$$

with

$$\mathbf{W}_{k+1} = \mathbf{P}_{k+1|k}\mathbf{H}_{k+1}^T[\mathbf{H}_{k+1}\mathbf{P}_{k+1|k}\mathbf{H}_{k+1}^T + \mathbf{R}]^{-1} \tag{13}$$

and

$$\mathbf{P}_{k+1|k} = \mathbf{F}_k \mathbf{P}_{k|k} \mathbf{F}_k^T + \mathbf{Q} \tag{14}$$

where **H** and **F** are the measurement and state transition matrices respectively. Thus, for a tracking duration of $n \times h$ seconds, **P** is obtained recursively by evaluating equation (15) n times. The estimated search-to-lock-on time can be expressed in terms of **P**

$$\hat{t}_s = \mathcal{G}(\mathbf{P}) = \mathcal{G}(\mathcal{F}(t_{\mathrm{tr}})) \tag{15}$$

where $\mathcal{G}$ is the estimation function. As more to **P**, $\mathcal{G}$ depends on other variables that include the characteristics of the FCR. There is no explicit analytical form for the function $\mathcal{G}$, which instead is computed recursively. More details on the computation of $\mathcal{G}$ are given in [18] for a standard fixed swath search pattern of the FCR. In short, the estimation function defined in [18] considers

1) a FCR model that comprises beam shape, direction displacement speeds and search pattern;
2) a search area that is defined by delimiting an amount of the localization probabilities given by **P**;
3) conditional detection probabilities for the FCR;
4) a multi-scan time estimation related to a cumulative detection probability;

Let $p_a(t)$ be the density function associated with the probability that the FCR detects and acquire the target at time t. Then the search-to-lock-on time estimation function $\mathcal{G}$ is defined as

$$\hat{t}_s = \mathcal{G}(\mathbf{P}) = \int_0^{+\infty} p_a(t)t\,dt \tag{16}$$

where t_s can be seen as a random variable with mean $\hat{t}_s$. p_a depends on the target localization probability p_L and on the conditional detection probability $p_{D|L}$ that depends on the properties/performance of the sensor used. This is where the track accuracy represented by **P** has an influence since p_L is defined according to the Gaussian target distribution subsumed by the error covariance matrix **P** [18, 17]. Note that the fact that p_L is Gaussian does not imply that t_s has a Gaussian distribution. Also, in this work, $\hat{t}_s$ will be considered as an exact estimation of the search-to-lock-on, as a primary study, although it is acknowledged that future work should consider the probabilistic nature of t_s. $p_{D|L}$ depends on the properties/performance of the FCR.

Moreover, the discretized form of (16) is

$$\hat{t}_s = \sum_k p_a(t_k)t_k \tag{17}$$

where $p_a(t_k)$ represents the probability mass function. Note that $p_a(t_k)$ does not have an explicit analytical form. It is computed recursively [18].

Finally, substituting (15) into (7), the estimated detect-to-engage time is

$$\hat{t}_{\mathrm{de}} = t_{\mathrm{tr}} + \sum_k p_a(t_k)t_k \tag{18}$$

$$\hat{t}_{\mathrm{de}} = t_{\mathrm{tr}} + \mathcal{G}(\mathcal{F}(t_{\mathrm{tr}})) \tag{19}$$

which shows that the detect-to-engage time t_{de} (or its estimate $\hat{t}_{\mathrm{de}}$) can be expressed as a function of t_{tr}.

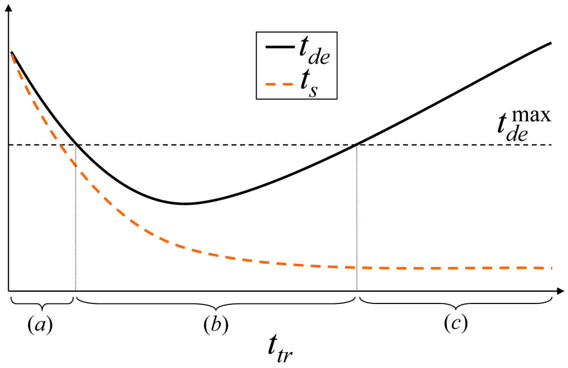

Fig. 5. Detect-to-engage (t_{de}) and search to lock-on (t_s) durations in terms of tracking time t_{tr}. Measurement updates are assumed to occur regularly so that their number is proportional to the tracking time t_{tr}. (a) & (c) Target not engageable. (b) Target engageable.

Before going further about the estimation of the search-to-lock and time, it must be acknowledged that the presented estimation functions are restrained to specific tracking conditions to produce useful results for the development of target engagement strategies. For instance, the presented strategies in the next paragraphs necessitate having a monotonically decreasing search-to-lock-on time function in terms of the tracking duration. This implies conditions on the tracking process that mainly involve the process noise, the measurement noise and the measurement update rate for the tracking filter. Also, it is also assumed that measurements are received regularly over time such that as the tracking process goes on more measurements are received and the track uncertainty gets reduced. As more, to obtain a monotonically decreasing track error covariance, a relatively high measurement update rate is needed and the ratio of the process noise over measurement noise must be low enough. This should allow having a monotonically decreasing search-to-lock-on time function and a corresponding detect-to-engage function that is characterized with a single minimum as in Fig. 5.

The functions for $\hat{t}_s$ and $\hat{t}_{\mathrm{de}}$ in terms of the tracking duration t_{tr} that we are needing to apply adaptive tracking strategies are illustrated on Fig. 5, where we have $t_{\mathrm{de}} = t_s + t_{\mathrm{tr}}$.

In comparison, Fig. 6 shows the same functions obtained experimentally with $h = 0.4$ and with surveillance sensor measurement noise standard deviations $\sigma_\beta = 0.035$ rad for bearing and $\sigma_r = 1$ m for range.[5] The process noise follows the pulse model with power spectral density (standard deviation) of 1 $\mathrm{m}^2/\mathrm{s}^3$ [4]. The tracking parameters were adjusted to provide the monotonically decreasing search-to-lock-on time and the minima of the detect-to-engage function.

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[5] The tracking system converts the sensor measurements from Polar to Cartesian coordinates using the conventional coordinate transformation [4, 2].

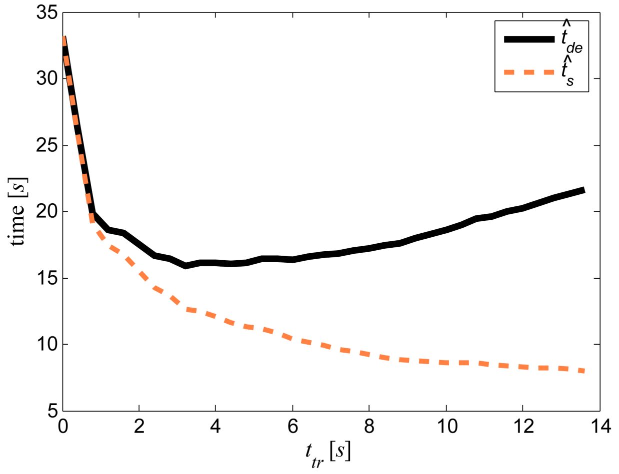

Fig. 6. Estimated detect-to-engage ($\hat{t}_{\mathrm{de}}$) and search to lock-on ($\hat{t}_s$) durations in terms of tracking time t_{tr} for a target initially situated at 75 km from the ship and with speed of 700 m/s in the direction of the ship.

Hence, controlling duration t_{tr} before cueing the FCR in order to satisfy the conditions expressed in (1) and (5) can ensure that the target is engageable. As explained below, three situations may occur (Fig. 5) based on the constraint $t_{\mathrm{de}}^{\max}$:

a) A too short tracking time causes a too low track accuracy, and therefore a too long search-to-lock-on time. The target is not engageable since the predicted target intercept range will be below its minimum limit defined in (1).

b) A good compromise between tracking time and search-to-lock-on time. The target is engageable since the predicted target intercept range will be above its minimum limit defined in (1).

c) A too long tracking time before cueing the FCR. The FCR takes a short time to lock on the target (due to the high accuracy of the track). Nevertheless, the gain in search-to-lock-on time cannot compensate for the long time spent in tracking. As for (a), the target is not engageable.

The proposed target engageability improvement solution, presented in the next section, will help maintaining situation (b) for different engagement scenarios.

5. TARGET ENGAGEABILITY IMPROVEMENT

As stated in the previous section, the engageability assessment aims at supporting the weapons assignment planning process. Instead of performing it in open-loop manner (Fig. 1), we propose a closed-loop approach that combines the engageability assessment and engageability improvement, as shown in Fig. 7.

The concept of engageability improvement goes beyond the assessment concept by changing the engagement geometry and dynamics, to make non-feasible engagements feasible. In this work, it is shown that the engageability can be improved through the minimization of the detect-to-engage time in given in equation (19). The proposed target engageability improvement approach is based on the control of the FCR cueing time. This is achieved through feedback to the object tracking function, such as illustrated in Fig. 7. Both the engageability assessment and the engageability improvement functions use an estimation of the FCR's search-to-lock-on time, and interact with the data fusion (*i.e.*, object tracking), threat evaluation and weapons assignment processes.

The engageability improvement function controls the cueing time of the FCR by setting a tracking duration t_{tr} for each target based on the desired search-to-lock-on time and the underlying track accuracy (Fig. 8). Practically, the tracking duration is determined itera-

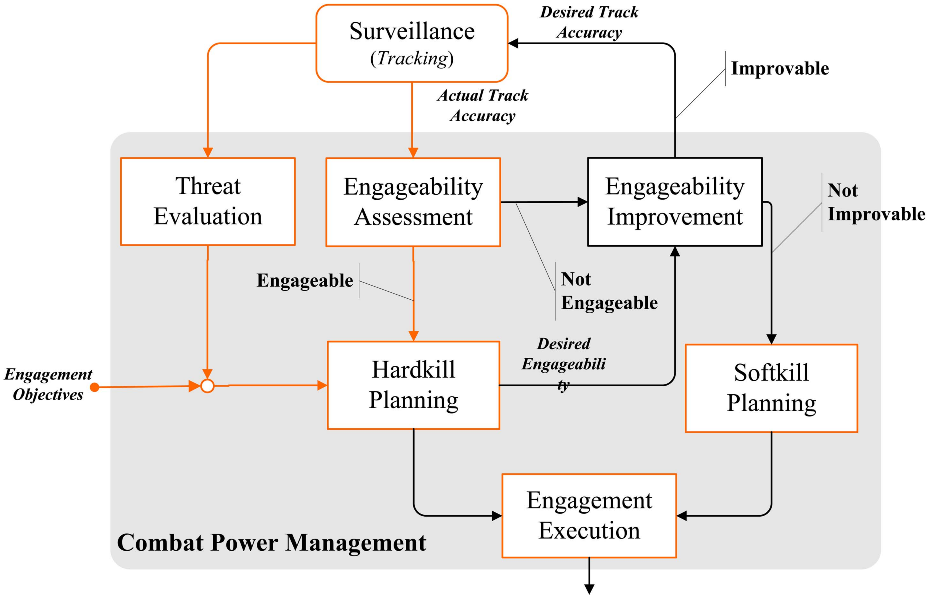

Fig. 7. Target engageability improvement in the C^2 process.

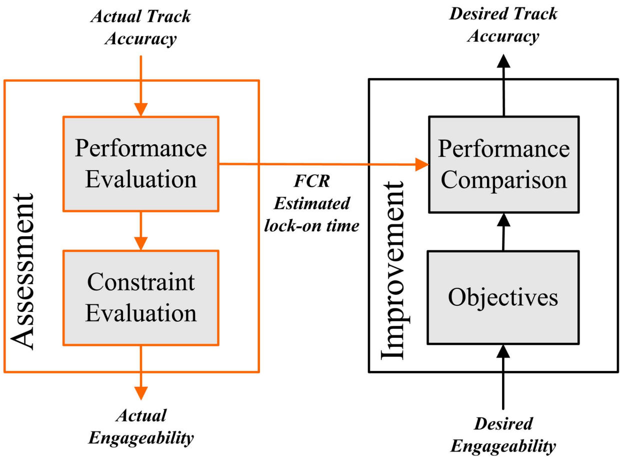

Fig. 8. Engageability assessment and engageability improvement interaction.

tively at the instant where the estimated search-to-lock-on time (and the underlying error covariance of the track) reaches an objective threshold shown in Fig. 8. It is chosen such that some operational objectives on the detect-to-engage and search-to-lock-on durations are achieved. These objectives depend mainly on the number of planned engagements and their configurations. In the followings, two operational objectives (labeled respectively O_1 and O_2 on Fig. 9) are considered.

O_1—aims at intercepting the target as close as possible to the weapon's minimum intercept range $r_i^{\min}$. This translates in long tracking time, minimum[6] search-to-lock-on time ($t_s = t_s^{\min}$) and high probability of interception. On the other hand, this corresponds to the maximum detect-to-engage duration ($t_{\mathrm{de}} = t_{\mathrm{de}}^{\max}$), as illustrated on Fig. 9).

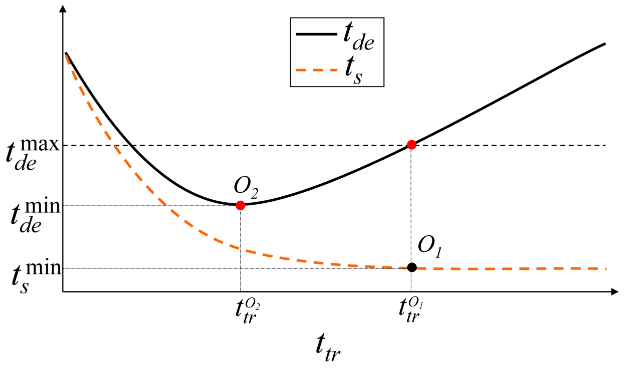

Fig. 9. Objectives of the detect-to-engage sequence.

O_2—aims at intercepting the target such as to minimize the total detect-to-engage duration ($t_{\mathrm{de}} = t_{\mathrm{de}}^{\min}$). This consists in finding the tracking duration and cueing time that guarantee the achievement of this objective.

The proposed engageability improvement approach considers the initial hardkill engagement plan for each target. Then, based on the engageability assessment, the detect-to-engage objectives are adjusted to improve engageability. When the target is not engageable, and there is no room for improvement, hardkill engagements are dropped and softkill is recommended instead for the concerned targets. When the engagement objectives are met and the engageability of each target is satisfactory, the hardkill plan is made available for execution and the FCR is cued following the computed engagement schedule. The execution also includes the softkill strategies for the targets that were not considered engageable.

Fig. 10 illustrates an engagement sequence example of two targets, the engageability the second target is improved through the minimization of the detect-to-engage duration for the first target. It is shown that both targets can be intercepted in time with the appropriate selection of the tracking durations t_{tr1} and t_{tr2}.

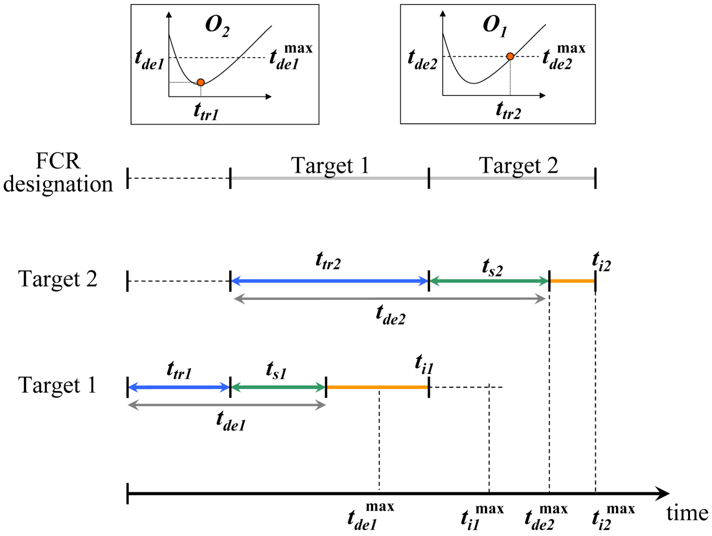

Fig. 10. Engagement sequence of two targets, with detect-to-engage time minimization on the first target (t_{dk} is detection time and t_{ik} is interception time for target k).

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[6] Which makes FCR more available for other engagements and also minimizes the signature (*i.e.*, detectability) of ownship.

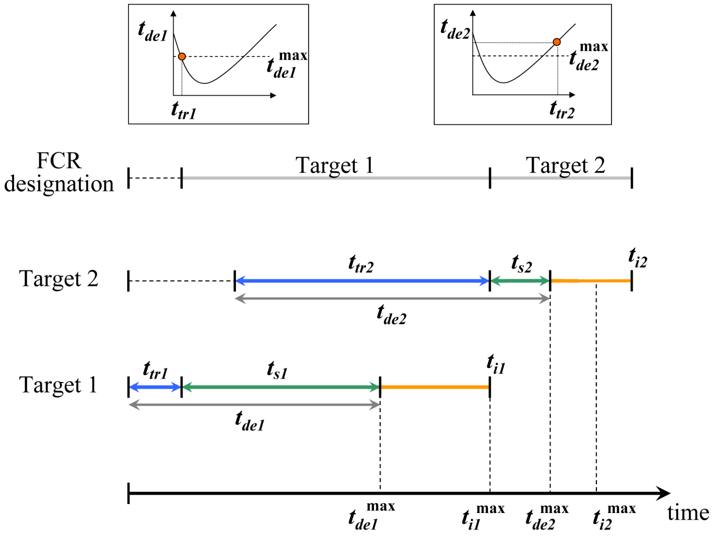

Fig. 11. Engagement sequence of two targets, without detect-to-engage time minimization on the first target (t_{dk} is detection time and t_{ik} is interception time for target k).

On the other hand, Fig. 11 shows the engagement sequence of the same two targets where no improvement of engageability was used. Because the tracking durations $t_{\mathrm{tr}1}$ and $t_{\mathrm{tr}2}$ are not set correctly, one of the targets will not be engageable.

6. SIMULATION AND RESULTS

A quantitative evaluation of the proposed target engageability improvement approach was performed using a combination of the SEATS test-bed [16], SADM simulator [21] and CASE-ATTI test-bed [20]. The target engageability improvement approach is based on minimization of the detect-to-engage time. The demonstration uses the search-to-lock-on time estimator and the FCR model presented in [17].

Two scenarios, featuring a warship that is attacked respectively by one or two supersonic ASMs, are presented. The scenarios were defined such that the duration of the detect-to-engage sequence is critical to the ship survival. The simulated scenarios, including weapons and targets characteristics, are kept simple to avoid incorporating any military CLASSIFIED information. Nonetheless, the simulation remains rich enough to illustrate the benefits of the proposed approach as a first study.

The ship is assumed equipped with SAMs as primary hardkill weapons. The SAM minimum intercept range is assumed to be $r_w^{\min} = 1000$ m. Any interception below this range is considered to be highly unlikely successful. In this case, the defending ship would be hit by the ASM. Also, it is assumed that the ship has only one FCR available.[7] Fig. 12 and Fig. 15 illustrate the two used scenarios as scripted in the simulation environment, using STAGE$^{\mathrm{TM}}$.

For each of the two scenarios presented in the next sections, the performance of the defending ship is evaluated using two different defensive strategies. The first one is a conventional engagement method that does not rely on the estimation of the search-to-lock-on time. With this strategy, the FCR is cued as soon as the ASM is detected and a confirmed track is established. This corresponds to the typical tactic used by most navies in the world. The second strategy exploits engageability assessment and improvement concepts. Although more sophisticated hardkill and softkill coordination strategies exist [14, 13, 5, 6], softkill combat resources are used, in this work, as second resorts in cases where hardkill engagements are deemed not feasible. Finally, it must noted that the actual search-to-lock-on time t_s and its estimated value $\hat{t}_s$ are considered identical in this simulation. Hence the results should be treated as average results rather than single instances out a probability distribution. However, a future work that will consider the probabilistic aspect of the search-to-lock-on time will offer a natural extension to this work.

6.1. Single Target Scenario

The first scenario (Fig. 12) considers a closing single supersonic ASM with a zero CPA relative to the ownship.

This scenario provides the ship with conditions for re-engagement should a miss occur. More precisely, it is assumed that the target is missed at its first engagement. The miss is due to the SAM performance and a second engagement is then required to intercept the target. In that case, a second SAM could be launched shortly after the miss assessment. The following will show how the minimization of the detect-to-engage sequence can provide the opportunity of a second engagement

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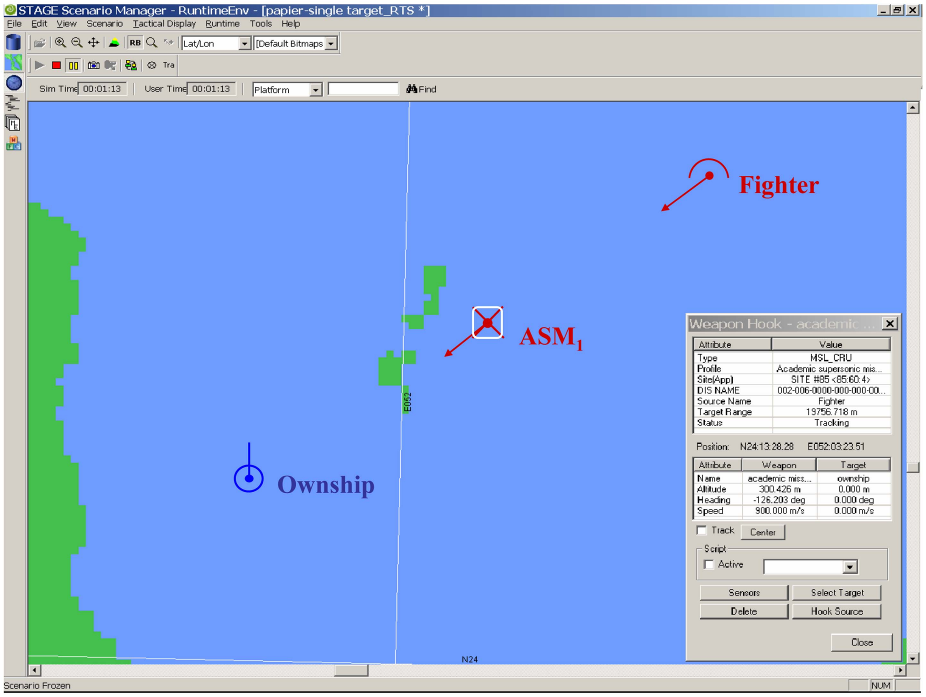
[7] Note that Canadian Frigates of Class Halifax have two FCRs.



Sim Time 00:01:13

User Time 00:01:13

Platform

Weapon Hook - academic ...

Attribute	Value
Type	MSL_CRU
Profile	Academic supersonic mis...
Site(App)	SITE #85 <85:60:4>
DIS NAME	002-006-0000-000-000-00...
Source Name	Fighter
Target Range	19756.718 m
Status	Tracking

Position: N24:13:28.28 E052:03:23.51

Attribute	Weapon	Target
Name	academic miss...	ownship
Altitude	300.426 m	0.000 m
Heading	-126.203 deg	0.000 deg
Speed	900.000 m/s	0.000 m/s

Fig. 12. Single target scenario in the STAGE (within SEATS test-bed).

compared to the conventional engagement method and under specific target conditions.

Suppose a scenario that starts at $t = 0.0$ s with the detection of the ASM by the surveillance system at the initial range of 26000 m. The ASM has and initial altitude of 300 m and a speed of 900 m/s. Under these conditions, the threat time-to-go (or time on flight) is about 29 s. The tracking parameters are given in Table I. Note that the parameters were set to study how the estimation of the search-to-lock-on time and related cueing strategies could improve the engageability of targets.

6.1.1. Conventional Engagement

With the conventional engagement strategy, the FCR is cued by the surveillance system as soon as a confirmed track is obtained, that is 2.9 s after the first detection. The FCR locks on the target at 21.3 s. One second later, a first SAM is fired. It misses the target at time $t_m = 26.5$ s, as illustrated in Fig. 13. According to the minimum intercept range ($r_w^{\min}$) of the SAM, the maximum intercept time is:

$$t_i^{\max} = \frac{r_d - r_w^{\min}}{\dot{T}} = \frac{26000 - 1000}{900} = 27.78 \text{ s} \qquad (20)$$

so that the target must be intercepted before $t = 27.78$ s. A second SAM could be fired not until $t = 27.5$ s, so it that would be too late to intercept the threat. The warship is hit by the target at 28.9 s, unless a softkill is used as a backup strategy.

TABLE I
Tracking Parameters for the Single-Target and Two-Target Scenarios

Track update period (h)	0.4 s
Search and surveillance radar accuracy in bearing (σ_β)	0.035 rad
Search and surveillance radar accuracy in range (σ_r)	1 m
Process noise power spectral density	1 $\mathrm{m}^2/\mathrm{s}^3$

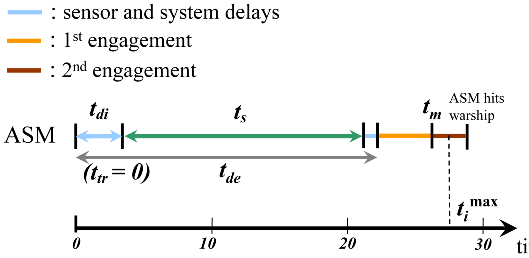


Fig. 13. Engagement sequence without detect-to-engage time minimization (single target scenario).

6.1.2. Detect-to-Engage Time Minimization

Using the minimization of the detect-to-engage time, the FCR is not cued as soon as a confirmed track is obtained. Instead, it is cued once the minimum value of the detect-to-engage duration is reached (*i.e.*, at $t_{\mathrm{tr}} = 9.9$ s). A shown in Fig. 14, this causes the FCR to lock on the target at 15.4 s, offering a gain of 5.9 s even if cueing occured 7.0 s later compared to the conventional engagement case. A first missile is then fired at 16.4 s and misses the target at 24.4 s, which leaves enough time for a re-engagement with a predicted interception

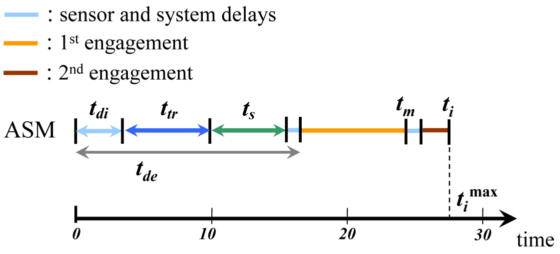


Fig. 14. Engagement sequence with minimization of the detect-to-engage time (single target scenario).

time below t_i^{max}. A second missile is fired at 25.4 s and hits the target at 27.7 s, at 1112 m from the ownship. Table II summarizes the results.

6.2. Two-Target Scenario

This second scenario (Fig. 15) illustrates the engagement of two closing supersonic ASMs, again with zero CPA relative to the defending ship.

ASM$_1$ has an initial range of 19000 m, an altitude of 300 m and its speed is 900 m/s. **ASM**$_2$ has an initial range of 23000 m, an altitude of 300 m and its speed is 900 m/s as well. **ASM**$_1$ pops up at 0.0 s, while **ASM**$_2$ pops up at 2.0 s. It is assumed that the ownship is aware that an attack by more than one ASM is potentially high.

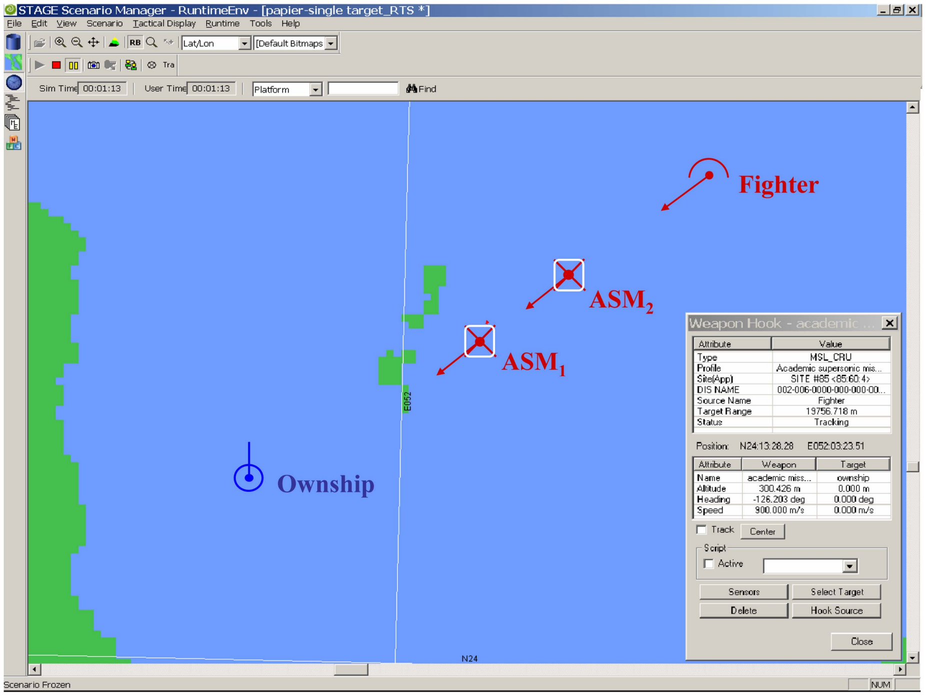
6.2.1. Conventional Engagement

Without minimization of the detect-to-engage time of its, **ASM**$_1$ is intercepted just before it reaches the minimum intercept range (1000 m) of the SAM. This leaves no time for engaging **ASM**$_2$, which is detected by the surveillance radar at 2.0 s. At that time, the FCR is busy on **ASM**$_1$. The assignment of the FCR to **ASM**$_2$ takes place at 20.9 s and the acquisition occurs at 23.9 s. Another SAM could be fired at 24.9 s, but it would be too late to prevent **ASM**$_2$ from hitting the ship (at 27.56 s).

TABLE II
Results of the Conventional Engagement and the Engageability Improvement Method for the Single Target Scenario

Function	Time ([s])	ASM range ([m])
Without Engageability Improvement		
Cueing	2.9	23390
Acquisition (lock-on)	21.3	6830
1st engagement	22.3	5930
1st miss	26.5	2114
2nd engagement	(27.5)	(1217)
Interception	none, the ASM hits the warship at 28.9 s	
With Engageability Improvement		
Cueing	9.9	17090
Acquisition (lock-on)	15.4	12140
1st engagement	16.4	11240
1st miss	24.4	4014
2nd engagement	25.4	3114
Interception	27.7	1112

This is shown in Fig. 16, where the cueing of the FCR as soon as **ASM**$_1$ is detected ($t_{tr1} = 0$) has resulted in a long search-to-lock-on time ($t_{s1} = 13.9$ s). The evaluation of the engageability before the engagement takes place will allow the recommendation of a softkill strategy.



Lat/Lon
[Default Bitmaps
Sim Time 00:01:13
User Time 00:01:13
Platform

Attribute	Value
Type	MSL_CRU
Profile	Academic supersonic mis...
Site(App)	SITE #85 <85:60:4>
DIS NAME	002-006-0000-000-000-00...
Source Name	Fighter
Target Range	19756.718 m
Status	Tracking

Position: N24:13:28.28 E052:03:23.51

Attribute	Weapon	Target
Name	academic miss...	ownship
Altitude	300.426 m	0.000 m
Heading	-126.203 deg	0.000 deg
Speed	900.000 m/s	0.000 m/s

☐ Track
☐ Active

Fig. 15. Two-target scenario in the STAGE (within SEATS test-bed).

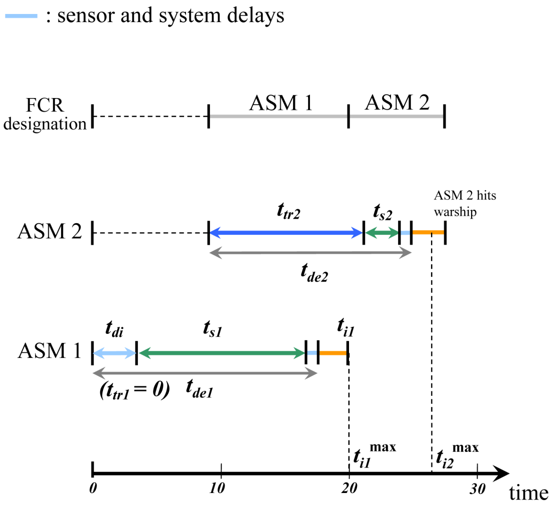


Fig. 16. Engagement sequence without detect-to-engage time minimization on the first target (two-target scenario).

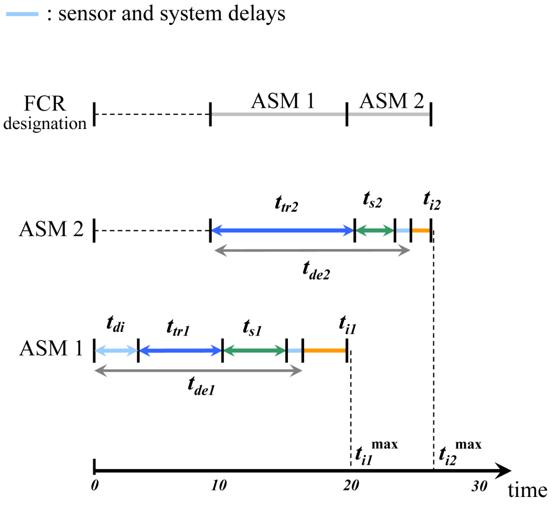


Fig. 17. Engagement sequence with detect-to-engage time minimization (two-target scenario).

6.2.2. Detect-to-Engage Time Minimization

With minimization of the detect-to-engage time, the FCR is assigned to the first detected target (**ASM**$_1$) at 9.9 s, that is 7.0 s after track confirmation. The FCR locks on the threat at 14.9 s (instead of 16.8 s with the conventional engagement method). A SAM is then fired at 15.9 s and hits **ASM**$_1$ at 19.25 s. Prior to that, the second target was detected by the surveillance radar at 2.0 s. The FCR was busy until made available once **ASM**$_1$ is assessed killed. The FCR is then assigned to **ASM**$_2$ at 20.25 s. It locks on it at 23.25 s (instead of 23.9 s with the conventional engagement method). A SAM is fired at 24.25 s against **ASM**$_2$, which is intercepted at 26.38 s. Fig. 17 shows the complete engagement sequence and Table III summarizes the results.

TABLE III
Conventional Engagement and the Detect-to-Engage Time Minimization Method for the Two-Target Scenario

Target	Function	Time ([s])	ASM range ([m])
	Conventional Engagement		
ASM$_1$	Cueing and designation	2.9	16390
	Acquisition (lock-on)	16.8	3880
	Engagement	17.8	2980
	Interception	19.9	1064
ASM$_2$	Cueing and designation	20.9	5990
	Acquisition	23.9	3290
	Engagement	24.9	2390
	Interception	none, **ASM**$_2$ hits the warship at 27.56 s	
	Detect-to-Engage Time Minimization		
ASM$_1$	Cueing and designation	9.9	10090
	Acquisition (lock-on)	14.9	5590
	Engagement	15.9	4690
	Interception	19.25	1675
ASM$_2$	Cueing and designation	20.25	6575
	Acquisition (lock-on)	23.25	3875
	Engagement	24.25	2975
	Interception	26.38	1063

6.3. Discussion

The two presented scenarios showed that the FCR cueing time t_{tr} can have a significant impact on the engageability of the targets and can be used as a control variable to influence the engagement sequence. The presented results are based on several assumptions regarding the engagement configuration, the shipboard resources, as well as the behavior of the different estimation algorithms used. For instance, for less critical situations (*e.g.*, single subsonic missile attack), cueing the FCR a few seconds later or a few seconds sooner may not impact much the outcome of the engagement. Also, the tracking parameters showed in Table I assumes that the error covariance to be monotonically decreasing in terms of the tracking time t_{tr}. A minimum detect-to-engage time strategy would be irrelevant in the cases where the error covariance does not decrease with time. Moreover, the results are very dependent on the model the FCR and the corresponding search-to-lock-on time, which can change considerably with the track error covariance [17, 18].

7. CONCLUSION

This paper considered the problem of target engagement in the naval Anti-Air Warfare operations. The naval Command and Control process was briefly described and an approach to improve the engageability of the targets was proposed. The proposed approach combines object tracking, threat evaluation, and weapons assignment in a closed-loop and integrated manner, and uses an estimation of the search-to-lock-on time of the FCR to control the tracking and cueing operations. Two scenarios, involving supersonic targets with the inherent short reaction time, were used to show the benefit of the proposed approach on the overall detect-to-engage sequence and the ownship survival. For the two presented illustrative scenarios, the conventional engagement method was unable to cope with the short reaction time constraints, and failed to defeat the threats using its hardkill resources. The engageability improvement strategy based on minimization of the detect-to-engage time provided a better way to exploit the same available and scarce reaction time.

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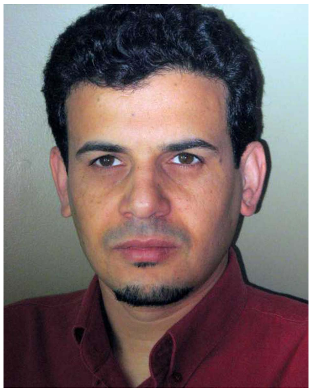

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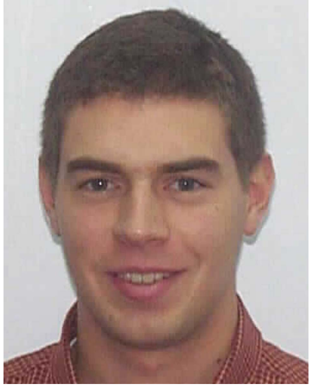

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