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Target engageability improvement through adaptive data fusion and sensor management: An approach based on the fire control radar search to lock-on time

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Defence R&D Canada – Valcartier
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Abstract

The Decision Support Systems Section (DSS) at Defence Research & Development Canada (DRDC) – Valcartier is conducting research activities aiming at developing and demonstrating advanced adaptive data fusion and resource management concepts. A typical application that can benefit from these concepts is the military naval Command and Control (C2). Military naval C2 systems are faced with an evermore increasing pace of the modern warfare, where increased threat sophistication and mobility demand shorter reaction time of the defending ship. Particularly, reaction time is of prime importance in Anti-Ship Missile Defence (ASMD) operations. When hardkill strategies are used to counter the threat, the latter must be engaged under a certain time in order to be intercepted. This work presents a practical example of an adaptive data fusion and resource management system that aims at improving the engageability of targets threatening a defending ship. Target engageability is improved by making use of the search to lock-on time estimation of the Fire Control Radar (FCR). A quantitative evaluation of the approach is presented using the SEATS-SADM-CASE_ATTI test-bed environment. For some specific Anti-Ship Missile Defence scenarios with short reaction time exigencies, it was shown that making use of the search to lock-on time estimation in the adaptive data fusion and resource management system leads to successful target engagements as opposed to failed engagements when the traditional engagement process was used.

Résumé

La Section des systèmes d'aide à la décision (SAD), à Recherche et développement pour la défense Canada (RDDC) – Valcartier, mène des activités de recherche visant à développer et démontrer des concepts avancés de fusion de données adaptative et de gestion de ressources. Les systèmes C2 navals militaires sont en grande partie appuyés par des technologies de fusion de données et de gestion de ressources. Le C2 naval militaire doit faire face au rythme toujours croissant de la guerre moderne, où une plus grande complexité de la menace et une meilleure mobilité requièrent des temps de réaction plus courts de la part du navire défendant. Le temps de réaction est d'une importance primordiale dans les opérations de défense contre les missiles antinavires. Avec la stratégie d'interception des missiles, les menaces repérées doivent être engagées avant un certain temps pour qu'elles puissent être interceptées. Ce rapport présente un exemple pratique d'un système adaptatif de fusion de données et de gestion des ressources appliqué au problème de l'amélioration de l'engageabilité de cibles dans la défense contre les missiles antinavires. L'engageabilité est améliorée grâce à l'utilisation de l'estimation du temps de recherche du radar de conduite de tir. Une évaluation quantitative de l'approche est présentée à l'aide d'un système simulé de défense contre les missiles antinavires. Une évaluation quantitative de la méthode est présentée à l'aide du banc d'essai regroupant SEATS, SADM et CASE ATTI. Pour certains scénarios de défense contre missiles anti-navire, on a démontré que l'utilisation de l'estimation du temps de recherche du radar de conduite de tir dans le système adaptif de fusion de données et de gestion de ressources résulte en des engagements réussis, contrairement à des engagements ratés lorsqu'une méthode traditionnelle d'engagement est utilisée.

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Executive summary

Target engageability improvement through adaptive data fusion and sensor management: An approach based on the fire control radar search to lock-on time

F. Rhéaume , A. Benaskeur ; DRDC Valcartier TR 2006-785; Defence R&D Canada – Valcartier; May 2008.

This report addresses the problem of hardkill target engagement in the context of Anti-Ship Missile Defence (ASMD) operations in maritime Above Water Warfare (AWW). Hardkill defence weapons aim at intercepting and destroying missiles by shooting them down before they hit their targets. ASMD operations involve naval Command and Control (C2). Military naval C2 is faced with an evermore increasing pace of the modern warfare, where increased threat sophistication and mobility demand shorter reaction time of the defending ship. Reaction time is of prime importance in ASMD operations. In hardkill ASMD strategies, threats must be engaged under a certain time in order to be intercepted.

Depending on the reaction time available to the C2 systems, a target may or may not be engageable. The engageability of a target is defined as the opportunity to engage a target successfully. It depends on the characteristics and capabilities of both the defensive and attacking parts.

Military naval C2 systems rely largely on data fusion and resource management technologies. The Decision Support Systems Section (DSS) at Defence Research & Development Canada (DRDC) – Valcartier is conducting research activities aiming at developing and demonstrating advanced adaptive data fusion and resource management concepts. The objective of the reported work is to define adaptive data fusion and resource management functionalities that improve target engageability in a ASMD context and that use the estimation of the search to lock-on time of the Fire Control Radar (FCR). The report presents a practical example of an adaptive data fusion and resource management system applied to the hardkill ASMD problem.

The adaptive data fusion and resource management system aims at improving the engageability of threatening targets directed against a defending ship. Target engageability is improved by making use of the search to lock-on time estimation of the FCR as a feedback to the adaptive data fusion and resource management system. A quantitative evaluation of the approach is presented using a simulated ASMD system. The simulated ASMD system is a combination of the SEATS testbed (Simulation Environment for the Analysis of the Tactical Situation), SADM (Ship Air Defense Model) and CASE_ATTI (Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification). For some specific ASMD scenarios with short reaction time requirements, it was shown that making use of the search to lock-on time estimation in the adaptive data fusion and resource management system leads to successful target engagements as opposed to failed engagements when the traditional engagement process was used.

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Sommaire

Target engageability improvement through adaptive data fusion and sensor management: An approach based on the fire control radar search to lock-on time

F. Rhéaume , A. Benaskeur ; DRDC Valcartier TR 2006-785 ; Recherche et Développement pour la Défence Canada – Valcartier ; mai 2008.

Ce rapport aborde le problème d'engagement des cibles dans le cadre de la guerre anti-aérienne et de surface. Ce problème fait partie des opérations de défense contre les missiles antinavires. Une des stratégies de défense contre les missiles antinavires consiste à détruire les missiles en les abattant avant qu'ils ne frappent leur cible. Les opérations de défense contre les missiles antinavires mettent en jeu les systèmes navals de commandement et contôle (C2). Le C2 naval militaire doit faire face au rythme toujours croissant de la guerre moderne, où une plus grande complexité de la menace et une meilleure mobilité requièrent des temps de réaction plus courts de la part du navire défendant. Le temps de réaction est d'importance primordiale dans les opérations de défense contre les missiles antinavires. Avec la stratégie d'interception des missiles, les menaces repérées doivent être engagées avant un certain temps pour qu'elles puissent être interceptées.

En fonction du temps de réaction disponible, une cible peut être engageable ou peut ne pas l'être. L'engageabilité d'une cible est définie comme la capacité d'engager une cible avec succès. Elle dépend de l'état de la défense et de la menace.

Les systèmes C2 navals militaires sont en grande partie appuyés par des technologies de fusion de données et de gestion des ressources. La Section des systèmes d'aide à la décision (SAD), à Recherche et développement pour la défense Canada (RDDC) − Valcartier, mène des activités de recherche visant à développer et démontrer des concepts avancés de fusion de données adaptative et de gestion des ressources. L'objectif du présent travail est de définir des fonctions de fusion de données adaptive et de gestion de ressources qui facilitent l'engageabilité de cible dans un contexte de défense contre missiles anti-navire. Le rapport présente un exemple pratique d'un système adaptif de fusion de données et de gestion de ressources appliqué au problème d'engagement des cibles dans la défense contre les missiles antinavires.

Le système adaptatif de fusion de données et de gestion des ressources vise à améliorer l'engageabilité des cibles menaçantes et dirigées vers le navire défendant. L'engageabilité est améliorée grâce à l'utilisation de l'estimation du temps de recherche du radar de conduite de tir. Une évaluation quantitative de l'approche est présentée à l'aide d'un système simulé de défense contre les missiles antinavires. Le système simulé de défense contre les missiles antinavires est une combinaison du banc d'essai SEATS (Simulation Environment for the Analysis of the Tactical Situation), de SADM (Ship Air Defence Model) et de CASE_ATTI (Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification). Pour certains scénarios de défense contre les missiles antinavires où de courts

temps de réaction sont requis, on a démontré que l'utilisation de l'estimation du temps de recherche du radar de conduite de tir dans le système adaptatif de fusion des données et de gestion des ressources résulte en des engagements réussis, contrairement à des engagements ratés lorsqu'une méthode traditionnelle d'engagement est utilisée.

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$\boldsymbol{C}$	Engagement capabilities
cu	Duration of FCR cue
d	Detect-to-engage time
dn	Duration of the target detection event
e	Target range when it is engaged
e_t	The time at which the target is engaged
$\boldsymbol{E}$	Engageability vector
f^-	FCR minimum range of operations
f^+	FCR maximum range of operations
$\mathbf{G}$	Goal
$\mathcal{G}$	Search to lock-on time estimation function
i	Predicted interception range
i_t	The time of the predicted target interception
l	Target range at lock-on time of the FCR
N_{FCR}	Number of available FCRs
N_T	Number of targets observed within the Volume Of Interest
$N_{\mathcal{W}}$	Number of available weapons
$\boldsymbol{P}$	Covariance matrix of the state estimate
$\boldsymbol{Q}$	Track quality
$\boldsymbol{R}$	Measurement error covariance matrix
r	Target range when it is detected by the surveillance sensors
r_t	The time at which the target is detected
$rank_E$	Engagement schedule
$rank_T$	Threat rank
$\boldsymbol{S}$	Situation
s	Search to lock-on time of the FCR
s_t	Cueing time of the FCR
$\mathcal{T}$	Target identifier
$\dot{\mathcal{T}}$	Target speed
t	Time label
t_f	Tracking duration of the FCR
t_s	Tracking duration of the surveillance system
$\mathcal{W}$	Weapon
$\dot{w}$	Weapon speed

$[w^-, w^+]$	Weapon effective range
w_l	Weapon launch initialization duration
$\boldsymbol{X}$	Track list
$\boldsymbol{x}$	State vector
$\hat{\boldsymbol{x}}$	State estimate vector
$\boldsymbol{z}$	Measurement vector

1 Introduction

To survive and cope with increasingly diverse and sophisticated threats, reaction times of modern military platforms, particularly warships, must be reduced in many ways. Particularly, reaction time is critical in Anti-Ship Missile Defense (ASMD). ASMD operations rely on hardkill and softkill defensive strategies. Hardkill strategies direct weapons to intercept the threat and actively destroy it through direct impact or explosive detonation in the proximity of the threat. Softkill defensive strategies use techniques to deceive or disorient the threat to cause it to destroy itself, or at least lose its fix on its intended target.

This report addresses the problem of hardkill target engagement in the context of ASMD in maritime Above Water Warfare (AWW). Constrained by short reaction time limitations, it aims at improving target engagement capabilities according to better Command and Control (C2) decisions. In hardkill ASMD strategies, threats must be engaged under a certain time in order to be intercepted. Thus, depending on the reaction time available to the C2 systems, a target may or may not be engageable. The process that evaluates whether a target is engageable or not is known as the engageability assessment process. The engageability of a target is defined as the opportunity/capabilitity to engage a target successfully. It acts as a filter and can be implemented as a Constraint Satisfaction Process [1, 2]. The constraint satisfaction process depends on the characteristics and capabilities of both the defensive and attacking parts.

The objective of the reported work is to define adaptive data fusion and resource management functionalities that facilitate target engageability in a ASMD context and that use the estimation of the search to lock-on time of the Fire-Control Radar (FCR). The naval C2 process is first described in Chapter 2, where the typical defensive battle management functions are presented along with shipboard weapons and FCR. The detect-to-engage sequence of hardkill target engagement is presented in Section 2.3. Section 2.4 discusses the concept of target engageability. Thereafter, an introduction to some adaptive data fusion and resource management concepts is given in Chapter 3. Chapter 4 then presents the target engageability improvement solution that uses the estimation of the search to lock-on time of the FCR and that rests on adaptive data fusion and resource management concepts. By making use of the search to lock-on time estimation of the FCR, the engageability of threatening targets directed toward a defending ship is improved. A practical example of the target engageability improvement application is presented in Chapter 5, where a quantitative evaluation of the approach is made. The evaluation is based on some selected target engagement scenarios that were executed on a simulated ASMD system. For some specific ASMD scenarios with short reaction time exigencies, it was shown that making use of the search to lock-on time estimation in the adaptive data fusion and resource management system leads to successful target engagements as opposed to failed engagements when the traditional engagement process is used. Finally, concluding remarks are made in Chapter 6.

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2 Naval command and control

The tactical naval Command and Control (C2) process can be decomposed into a set of generally accepted functions that must be executed within some reasonable delays to ensure mission success. A list that gives a very high-level description of those functions, related to defensive battle management, is given below.

1. Target detection - Highly dependent on the sensors performance, and may be based on data from a single sensor or a combination of several sensors.
2. Target tracking - uses the sensor data to optimally estimate the current kinematical properties of the target, and predict their future positions. It is generally based on data fusion techniques (filtering).
3. Target identification/classification - identity and class information of targets is established. This also results in the resolution of true targets from decoys or non-hostile objects.
4. Threat Evaluation - establishes the intent and the capability of the potential threat within the Volume Of Interest (VOI).
5. Weapons Assignment (Engagement) - In this process, decisions are made on how to deal with the identified threats. This process can be subdivided into several subproblems that include mainly
    (a) Response Planning - One or more weapons are assigned to engage each threat, including the assignment of supporting resources (as sensors, communications, etc.) required for each and every one-to-one engagement.
    (b) Response Execution - The process by which the planned response is executed in real-time.
    (c) Outcome Assessment - The process by which one evaluates the outcome (ownship damage or threat damage/kill) of the executed actions.

In order to defend itself, the ship relies on a set of tactical resources for the execution of all the above described operations. These consist mainly of weapons (that include hardkill, softkill and deterrence), sensors (for both surveillance and fire control), navigation, and communication systems. Among all the resources, the reported work is concerned with hardkill weapons and fire control radar, as described below.

2.1 Shipboard weapons

The Anti-Air Warfare (AAW) weapons for a typical frigate, such as the Canadian Halifax Class, include hardkill and softkill. While the hardkill weapons are directed to intercept the threat and actively destroy it through direct impact or explosive detonation in the proximity of the threat, the softkill weapons use techniques to deceive or disorient the threat to cause it to destroy itself, or at least lose its fix on its intended target, *e.g.*, the ownship or the High Value Unit (HVU). Hardkill weapons require FCR support and can be fired only after a FCR has locked on the target, while softkill are fired without the need of FCR. Hardkill weapons for a typical frigate include Surface to Air Missiles (SAM) that have the greatest range, an intermediate range Gun, and a Close-In Weapons System (CIWS) that is a short-range, rapid-fire gun. In this work, only SAM will be considered. The AAW softkill weapons for a typical frigate include decoys and jamming systems. The decoys can be used to screen the platform to protect, produce an alternate target on which a radar-guided threat can fix, or saturate the threats analysis capabilities. The jamming system uses electromagnetic emissions to confuse the threat's sensors to cause the threat to either lose its fix on its intended target, or to improperly assess the position of its target. Note that the effectiveness of the all different weapons depends on a variety of factors[1].

2.2 Fire control radar

Besides the above-mentioned weapons systems, the Combat Power (CP) of the Halifax Class Frigate comprises two FCR systems that are responsible for the control of the SAM fire channels and the pointing of the Gun. Note that the FCR system is mostly involved in the target engagement[2] phase of the maritime AAW operations.

2.3 Detect-to-engage sequence

The FCR system offer two concurrent fire channels for the hardkill weapons that provide high quality track data for fire control calculations during engagements. The decision of these engagements is based on a situation analysis process that starts with the detection and ends with a threat ranking. Figure 1 illustrates how the surveillance sensors, the tracking system, and the FCR systems interact in the completion of the detect-to-engage sequence.

2.3.1 Tracking

Tracking operations, as part of the situation analysis process, is aimed to provide accurate and timely kinematics, identification, and classification information about the entities within the VOI. This information is referred to as the compiled Tactical Picture (TP).

Upon detection by the 2D search and surveillance radars, the contact information is provided to the tracking system that maintains a more accurate estimation of the target position and infers about its identity and classification. In the sequel, only the target position will be considered. It is given by the state estimate

$$\hat{\boldsymbol{x}} = \left[\hat{x}, \hat{y}, \hat{\dot{x}}, \hat{\dot{y}} \right]^T \tag{1}$$

and the related covariance matrix $\hat{\boldsymbol{P}}$ that represents some measure of the TP positional quality. This quality of the TP may be affected by many factors that include, among

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[1] *e.g.*, the distance to the threat, the type of threat, the speed of the threat, the environment, etc.

[2] It may happen that the FCR be used in the surveillance and threat evaluation operation to obtain 3D information of a given target or to make the target uncover its actual indent.

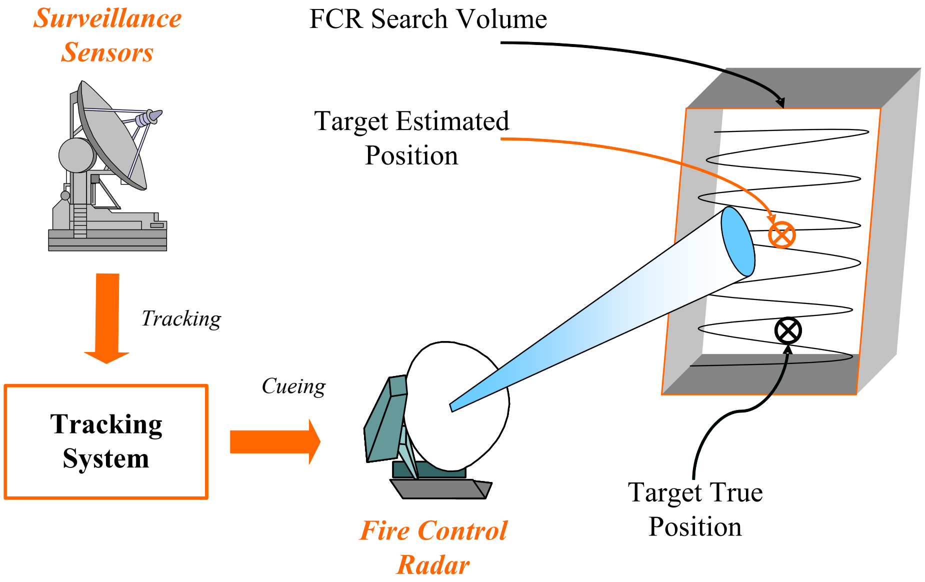

Figure 1: Fire Control cueing

others, the sensors accuracy, the tracking duration, and the type and tuning of the tracking algorithms. The effectiveness of most of the subsequent operations, in the detect-to-engage process, relies on this quality. These operations use this information to

1. help the decision maker gain and maintain situation awareness;
2. evaluate the threat level of the different objects within the VOI; and
3. provide the weapon systems with a good quality positional information whenever an engagement decision is made (*i.e.*, hand-over for fire control purposes).

From the tracking perspective, it is clear that the fire control operation is the most straightforwardly affected, through the hand-over, by the quality of the track information, since it does not require any human interpretation that introduces biases. The hand-over success and effectiveness depends heavily and almost exclusively on the quality of the track information.

2.3.2 FCR cue

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. This operation cannot be performed without a re-acquisition that involves a search to lock-on phase. This phase starts once the FCR is cued by the tracking system and begins its scan and ends when it locks on the target. 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 (as illustrated in Figure 1.

2.3.3 Search and lock-on

Target engagement using hardkill weapons cannot start without a target re-acquisition by the FCR. The FCR initiates its search within an area defined mostly by the 2D bearing-elevation information obtained from the Cartesian position $(\hat{\boldsymbol{x}}, \hat{\boldsymbol{P}})$ provided by the tracking system. Note here that search and lock-on also includes the designation phase[3]. Following a specific pattern, the FCR will scan the specific region of the 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 threat. During this threat re-acquisition[4] phase, the FCR has a search time that depends on several factors, such as: the ownship weapons properties, Command & Control System (CCS) performance, the operator skill/training, the attacking target characteristics, etc. The search to lock-on duration should be limited depending on the available reaction time.

The quality of the information handed-over to the FCR determines the volume the FCR 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 necessary to the ship survival. A poor quality tactical picture causes the FCR to search in a large volume, which should take more time to re-acquire the target and which may have grave consequences on the ownship reaction time.

An estimate $\hat{s}$ of the duration s of the search to lock-on phase can be calculated by taking into account both the target and the FCR characteristics. Track quality for the target to search for is also considered in the determination of the search volume. The estimation is an iteration over a number of probabilistic scans until the FCR re-acquires and locks on the target. The number of these scans must be limited to bind the search time. A track has a quality $\boldsymbol{Q}$ which is defined according to a function $\mathcal{Q}$ of the estimated error covariance matrix

$$\boldsymbol{Q} = \mathcal{Q}(\hat{\boldsymbol{P}}) \tag{2}$$

Similarly, the estimated duration of the search to lock-on phase can be expressed as a function $\mathcal{G}$ of the track quality

$$\hat{s} = \mathcal{G}(\boldsymbol{Q}) = \mathcal{G}(\mathcal{Q}(\hat{\boldsymbol{P}})) \tag{3}$$

A method for estimating the search to lock-on duration is given in [3].

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[3] Designation phase: From an initial position, the FCR must be directed to the general location of the target due to the FCR's narrower beamwidth than the surveillance radars.

[4] Also referred to as search to lock-on.

2.4 Target engageability

In order to improve the engageability of designated targets, a system must first be able to assess the engageability beforehand. Engageability assessment is described as a feasibility evaluation of the possible defensive strategies where one or more weapons are assigned to each threat. Generally, the evaluation should consider the states and characteristics of the threats as well as the characteristics of the defensive weapons and of their related resources (e.g. fire control radar). The evaluation should also be made in relation with the goals of the mission. Risk, effectiveness and cost constraints can also be derived in the engageability assessment.

Engageability assessment can contribute to reducing the problem complexity, saving reaction time and maximizing effectiveness, by discarding inconsistent candidate solutions and selecting the best compromise alternatives. 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 engagement: ammunitions are available; requested FCR is available; the threat to be engaged is within the range of the selected FCR; the interception will occur within the weapon envelope; and the threat is not in the blind zones of FCR and weapons.

Target engageability can be improved by tuning or modifying the naval C2 functions involved in target engagement. These functions relate to the detect-to-engage sequence described in Section 2.3. The engageability of a target is improved if the feasibility evaluation of some selected defensive strategies yields better results after tuning one or more functions involved in the detect-to-engage sequence.

In the reported work, engageability improvement involves target tracking, cue and search to lock-on of the FCR.

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3 Adaptive data fusion and resource management

As part of the naval C2 operations, a target engagement system is supported with two principal components that are data fusion and resource management. Data fusion and resource management act cooperatively in the target engagement operations. Concepts of data fusion and resource management are not to be discussed thoroughly in this report. The data fusion and resource management concepts used in this work are inspired from the JDL model [4] as well as from [5] and [6]. The resources involved in the target engagement application are the search and surveillance sensors, the fire control radar and the weapon system.

Generally speaking, a system is called adaptive if it can analyze its own performance and dynamically reconfigures itself to compensate for changes in its context. The changes might be from the environment it evolves in, its objectives and/or its requirements. Instead of being developed for a specific situation, adaptive systems are therefore able to handle a wide class of situations defined by a set of structural constraints on their context.

Since designers cannot foresee all the circumstances the systems will be used in, adaptation mechanisms aim at making those systems automatically adapt to unforeseen and changing contexts, by allowing to: i) change the system behavior and/or performance without the need to entirely redesign it; ii) do more on behalf of the human operator without a constant interaction; and iii) yield higher performance, lower costs, or both whenever it is possible.

An adaptive system needs therefore to perceive the environment it operates in (namely, its context) and uses this knowledge to produce appropriate actions to achieve its goals. The system must take into account the possible dynamic nature of the environment it interacts with to reach its goals throughout a wide range of situations, with the desired level of performance. Based on the newly available/inferred information, the adaptive system needs to modify its operational mode to cope with different performance criteria, variable contextual conditions, and changing status of resources.

Adaptive data fusion constitutes a step further compared to the purely open-loop data fusion [7, 8]. It allows obtaining increased quality with equal or less effort. More generally, adaptive data fusion systems can be seen as systems that meet adaptation requirements as described in [6] and as illustrated in Figure 2. These requirements should enable the system to automatically adapt to changing contexts, thus resulting in better responses.

High level measures of merits are required in an adaptive system to evaluate its behavior to be optimized with respect to high level and operational objectives. The results of such an evaluation set the low level objectives.

3.1 Adaptive target tracking

In military C^2 applications, target tracking are among the functionalities that use data fusion technology and have much to gain from the exploitation of the defined adaptation concepts. As mentioned in Subsection 2.3.1, target tracking is aimed at providing accurate

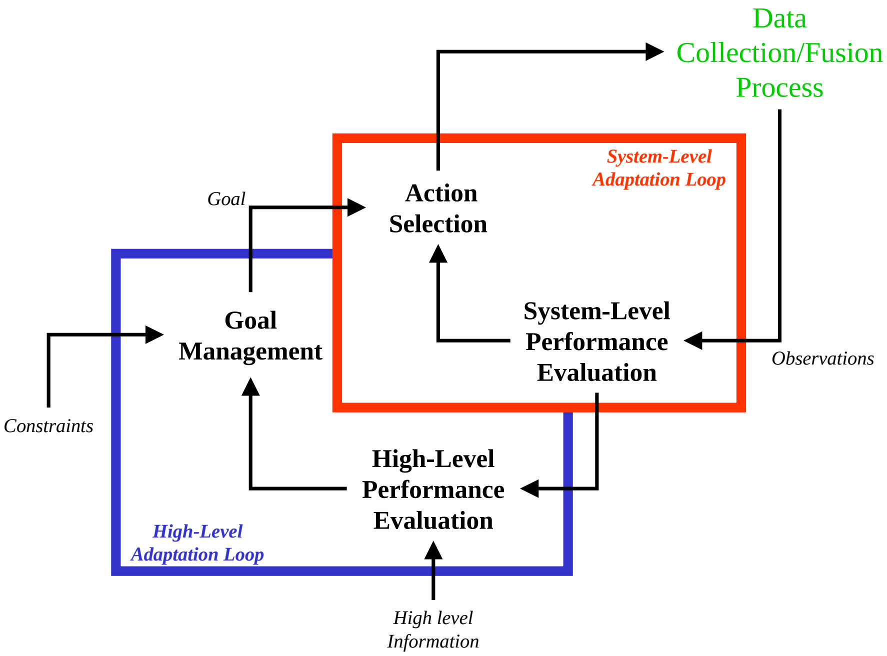

Figure 2: Adaptation requirements

and timely identification/classification and kinematics information about the entities within the VOI. Depending on the context, goals associated with target tracking may vary. Target tracking is adaptive in the cases where it can adjust to changes in the context of operation and to changes in objectives. Adaptation of tracking may be performed on various dimensions of the tracking system. Possible data fusion adaptation dimensions are parameter, function, reasoning-path and process [9, 6]. In this work, target tracking adaptation applies only to the process dimension since actions are taken on the tracking duration (time). Thus, the tracking algorithm, along with its parameters and its information sources, are pre-established and stay the same throughout the tracking operation.

3.1.1 Process dimension

In tracking, the process dimension considers the real-time aspect of the tracking process. It has to do with the determination of time intervals to achieve tracking in order to fulfill some particular tasks. Thus, adaptation on the process dimension is driven by time constraints. When there are no time constraints, optimal solutions can often be found. When time is an issue, sub-optimal solutions that satisfy time constraints are searched for and good trade-offs have to be found. When time constraints change, adaptation is required to maintain the performance within acceptable bounds without violating the constraints imposed.

4 Target engageability improvement through ADF/RM

The naval C2 system that supports target engagement divides into two principal parts: data fusion and resource management. To improve the target engagement operation, some feedback is needed on the data fusion and on the resource management processes. In this work, this feedback is achieved through the management of goals and constraints related to the FCR operation. The determination and the management of goals and constraints is a process that depends on the application at hand. In our target engagement application, goals and constraints management has to do with the scheduling of engagements and with the search to lock-on time of the FCR. Figure 3 illustrates how the data fusion process and the resource management process interact with the goals and constraints manager. The figure shows the following elements involved in the improvement of target engageability:

1. **Data fusion**
    - (a) Sensor level
    - (b) Target level
    - (c) Situation level
    - (d) Impact level
2. **Goal management**
    - (a) Constraints
    - (b) Group level goals
    - (c) Target level goals
    - (d) Performance evaluation
    - (e) Performance comparison
3. **Resource management**
    - (a) Resource response level

All of these elements will be detailed in Sections 4.1, 4.2 and 4.3. Note that some of the concepts of data fusion and resource management are based on the work reported in [5].

Target engageability is improved by tuning the functions involved in the target engagement process. One of the functions involved in target engagement is tracking, whose impact over the search to lock-on time was presented in Subsection 2.3.3. Because the search to lock-on time (s) depends on the quality of the tracks [3], the determination of goals and constraints on s can be translated into goals and constraints on the quality of the tracks. The goals and constraints must be respected in order to have target engageability assessment. From the adaptive tracking perspective, the tracking system is tuned in order to achieve the goals and respect the constraints. In this work, the adaptation has to do with the tracking time (t_s). It is said to be an adaptive process since t_s is adjusted in order to reach a state for which the constraints are respected.

From another perspective, the determination of the tracking time for the tracking system is equivalent to the determination of the cue time (s_t) of the FCR. The conceptualization of the solution is different, but the results are the same. When seen as the determination of the cue time, the target engageability improvement solution is simply referred to as a data fusion and resource management solution rather than an adaptive tracking process.

4.1 Data fusion

Each data fusion level will be described according to the target engagement context. Figure 3 shows how each data fusion level is involved in the target engageability improvement system. Table 1 shows inputs and outputs of each data fusion level.

Table 1: Inputs and outputs of each data fusion level for the target engageability improvement application.

Level	Inputs	Outputs
Sensor	Signal	Contact reports ($\boldsymbol{z}, R$)
Target	Contact reports ($\boldsymbol{z}, R$)	Tracks ($\hat{\boldsymbol{x}}, \boldsymbol{P}, \mathcal{T}$)
Situation	Tracks ($\hat{\boldsymbol{x}}, \boldsymbol{P}, \mathcal{T}$)	Number of targets (N_T) Track list ($\boldsymbol{X}$)
Impact	Track list ($\boldsymbol{X}$)	Capabilities ($\boldsymbol{C}$) Threat rank ($rank_T$) Engageability ($\boldsymbol{E}$)

4.1.1 Sensor level

Based on the received signal, the sensor level produces contact reports ($\boldsymbol{z}$) of the observed target states. The reports have error covariances that are expressed in a covariance matrix ($\boldsymbol{R}$). The contacts are in 2D Cartesian coordinates (z_x, z_y) and result from a polar to Cartesian conversion [3].

4.1.2 Target level

Target level data fusion involves the target tracking operations. It produces state estimates of the targets over time. The state estimate includes the estimate of the position and kinematics of a target ($\hat{\boldsymbol{x}}$) along with a corresponding error covariance matrix ($\boldsymbol{P}$), as well as type and identifier of the target.

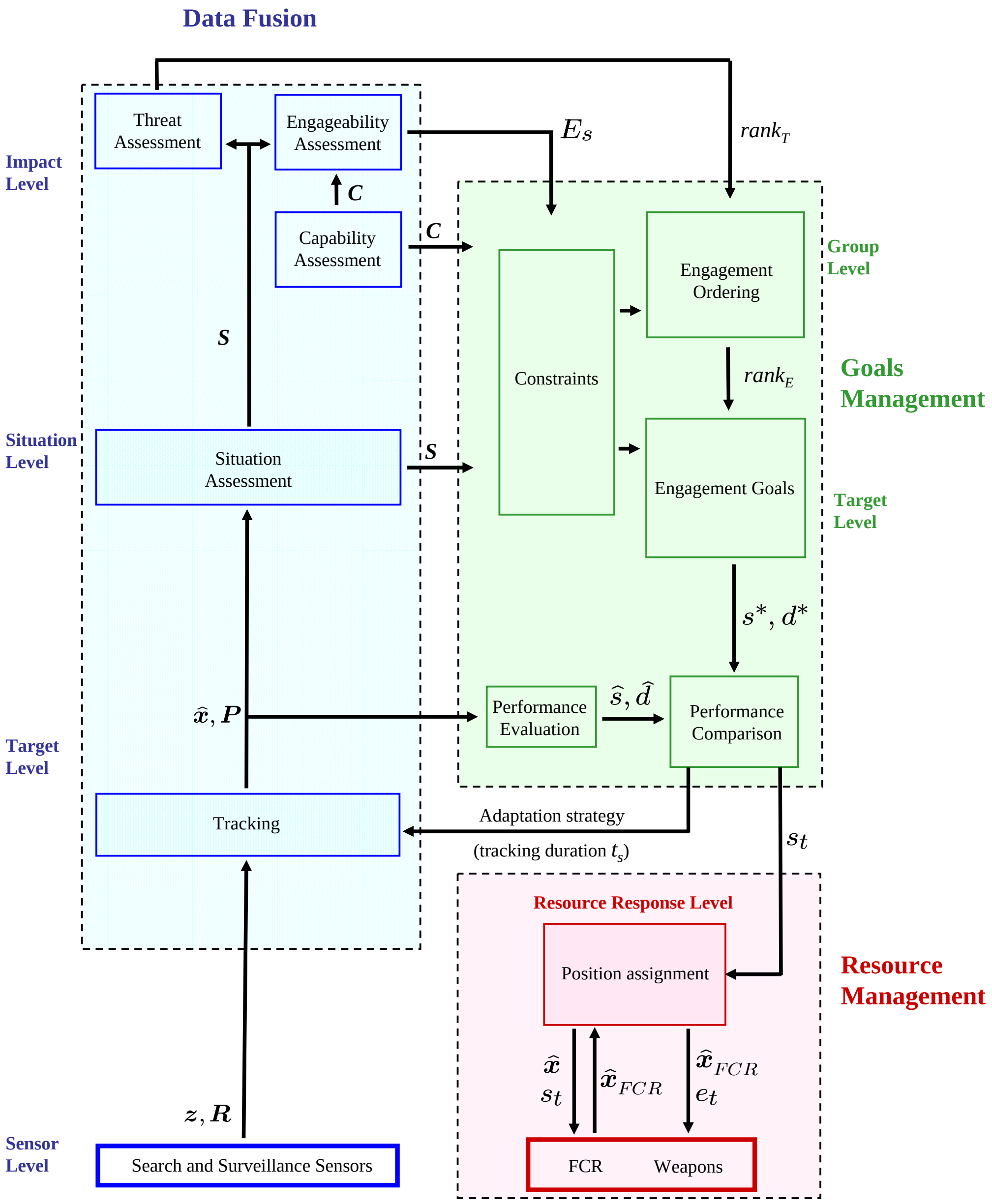

Figure 3: Target engageability improvement through search to lock-on time estimation

4.1.3 Situation level

The situation level provides a count of the targets observed within the VOI (N_T), as well as a track list ($\boldsymbol{X}$) that contains all the tracks of the different targets within the VOI, and the inter-object relationship.

$$\boldsymbol{X} = \{\boldsymbol{X}(1), \boldsymbol{X}(2), ..., \boldsymbol{X}(i), ..., \boldsymbol{X}(N_T)\} \tag{4}$$

where the track $\boldsymbol{X}(i)$ contains the latest state estimate $\hat{\boldsymbol{x}}_i$, the corresponding covariance matrix $\boldsymbol{P}_i$ and the target identifier $\mathcal{T}_i$.

$$\boldsymbol{X}(i) = \{\hat{\boldsymbol{x}}_i, \boldsymbol{P}_i, \mathcal{T}_i\} \tag{5}$$

The number of targets is used in the determination of constraints and goals (at the Group Level and at the Target Level) for the improvement of target engageability.

In this work, there are two different situations ($\boldsymbol{S}$) taken into consideration to improve target engageability:

$\boldsymbol{S}_1$ - Single target: Only one target is observed within the VOI.

$\boldsymbol{S}_2$ - Multiple targets: More than one target are observed within the VOI.

Different constraints and goals will be derived to improve target engageability whether a single target situation ($\boldsymbol{S}_1$) or a multiple target situation ($\boldsymbol{S}_2$) is observed.

4.1.4 Impact level

In the context of the target engageability improvement application, the impact level separates into three sub-levels:

Threat assessment – Based on the state estimates produced at the target level, the threat assessment process evaluates the threat level of each target observed within the VOI and produces a threat rank list. The threat rank list contains the threat rank of each target ($rank_T$) [10]. For example, $rank_T(\mathcal{T}_1, t) > rank_T(\mathcal{T}_2, t)$ means that target $\mathcal{T}_1$ is more threatening than target $\mathcal{T}_2$ at time t. Here the threat is evaluated on the basis of the target type and on the Closest Point of Approach (CPA)[5].

Capability assessment – A set of capabilities $\boldsymbol{C}$ is assessed for the defending ship. The ship is equipped with one or two FCRs and has a set of hardkill anti-missile weapons (SAMs). The capabilities comprise the number of available FCRs (N_{FCR}) and their specifications[6], as well as the number of available SAMs ($N_{\mathcal{W}}$) and their specifications. The specifications for the weapons are represented by their velocity ($\dot{w}$) and by their effective range ($[w^-, w^+]$).[7] The coverage zone of the FCR is $[f^-, f^+]$ (see Figure 4). It is also assumed that for hardkill engagements, the weapons cannot be launched until the FCR is locked on the target.

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[5] The CPA will also be used for target engagement scheduling.

[6] See [3, 11] for more specifications on the FCR.

[7] For simplicity, the weapon acceleration is not considered in this work. The weapon velocity is considered to be constant throughout its entire flight time.

Engageability assessment – Provided the engagement capabilities ($\boldsymbol{C}$) that are the properties of the weapons and of the FCRs, the engageability of each target is assessed individually. The engageability of the targets is expressed in the vector $\boldsymbol{E}(1)$ and can take values 0 or 1. The re-engageability of the targets is also taken into account. It is expressed in the vector $\boldsymbol{E}(2)$ and can take values 0 or 1 (not re-engageable, re-engageable). For example, a target $\mathcal{T}_i$ is said non-engageable ($E_{\mathcal{T}_i}(1) = 0$) if its time to closest point of approach is below a limit t_1 ($\text{TCPA}_{\mathcal{T}_i} < t_1$), and it is said engageable ($E_{\mathcal{T}_i}(1) = 1$) if its time to closest point of approach is beyond t_1 ($\text{TCPA}_{\mathcal{T}_i} > t_1$). Moreover, a target $\mathcal{T}_i$ is not re-engageable ($E_{\mathcal{T}_i}(2) = 0$) if its time to closest point of approach is below a limit t_2 ($\text{TCPA}_{\mathcal{T}_i} < t_2$), and it is said re-engageable ($E_{\mathcal{T}_i}(2) = 1$) if its time to closest point of approach is beyond t_2 ($\text{TCPA}_{\mathcal{T}_i} > t_2$). Note that at this point the engageability assessment is a preliminary one that is used by the goal management. Recall that the engageability issue constitutes the main problem addressed in this work. Then, a more in depth engageability assessment, that takes into account the estimated search to lock-on time of the FCR, is part of the overall target engageability improvement problem addressed by this report. Precisely, this more in depth engageability assessment is achieved by the performance comparison function described in Subsection 4.2.5.

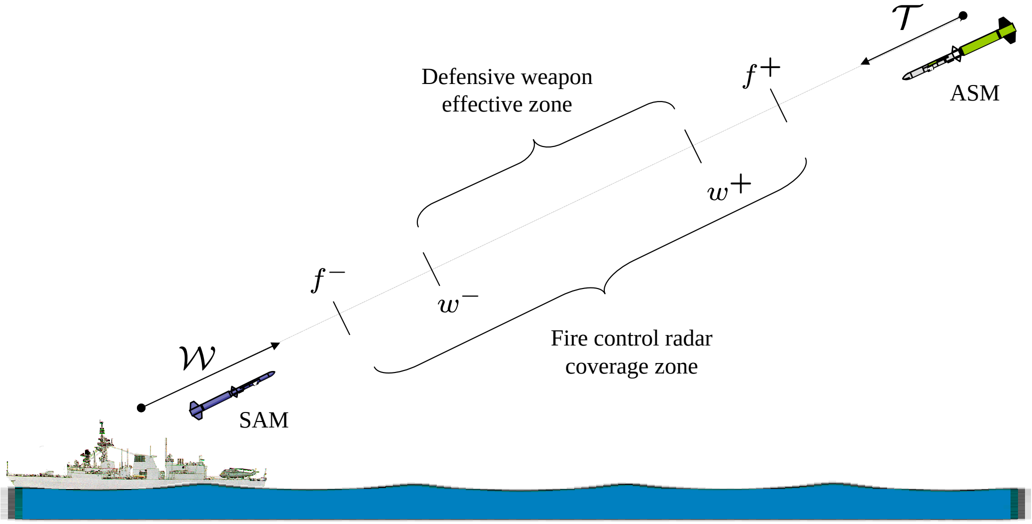


Figure 4: ASMD Scenario: Target $\mathcal{T}$ coming toward ownship equipped with weapons $\mathcal{W}$

4.2 Goal management

Goal management must do with the determination of goals and also the determination of constraints that enable the engageability of the targets under consideration. First, in Subsection 4.2.1 will be described the general constraints related to the assessment of engageability and that depend on the weapons' effective range. Thereafter, the determination of group level goals and target level goals will be discussed in Subsections 4.2.2 and 4.2.3, respectively. Comparison of goals with the actual system performance is also part of the engageability improvement process. Both performance evaluation and performance comparison functions are discussed in Subsections 4.2.4 and 4.2.5, respectively.

4.2.1 Constraints

Constraints related to target engageability are determined based on the assessed situation and impact. Precisely, the engageability of a specific target depends on the target kinematics as well as on the properties of the weapons and of the FCR. There is a minimum admissible range of interception i^- defined by both the properties of the weapons and of the FCR. The range of interception is function, among others, of the search to lock-on time of the FCR. Therefore constraints on the former impose constraints on the latter. For example, one constraint on s may be defined by the maximum duration s^+ that the FCR can afford in order to achieve target interception. Table 2 defines the symbols that will be used to demonstrate how the constraints are defined.

Table 2: Symbols used in Subsection 4.2.1.

Symbol	Definition
d	Detect-to-engage duration
d^+	Maximum admissible detect-to-engage time
e	Target range when it is engaged
e^-	Minimum admissible target range when it is engaged
h_o	FCR cueing delay[8]
i	Predicted interception range
i^-	Minimum admissible predicted interception range
l	Target range at lock-on time of the FCR
r	Target range when it is detected by the surveillance sensors
s	Search to lock-on duration of the FCR
s^+	Maximum admissible search to lock-on duration of the FCR
t_f	Tracking duration of the FCR
t_s	Tracking duration before FCR cueing
$\dot{\mathcal{T}}$	Target speed
$\dot{w}$	Weapon speed
$[w^-, w^+]$	Weapons effective range

The predicted threat intercept range i should always be such that it is greater or equal to the weapon's minimum effective range

$$i \geq i^- = w^- \tag{6}$$

where i is determined based on the threat velocity $\dot{\mathcal{T}}$, the threat range e at the beginning of the engagement, and the weapon velocity $\dot{w}$

$$i = \left[\frac{\dot{w}}{\dot{w} + \dot{\mathcal{T}}}\right] e \tag{7}$$

Given w^-, there is a minimum threat range e^-, at which the weapon must be fired to make interception happen within its effective range. If $\mathcal{W}$ is launched while the threat $\mathcal{T}$ has already passed e^-, it will be too late. The defensive weapon will not intercept its target, since the latter will be outside its effective zone, *i.e*, $i \notin [w^-, w^+]$. Therefore, the weapon $\mathcal{W}$ must be fired while the threat $\mathcal{T}$ is beyond e^-. To make this interception possible, the threat $\mathcal{T}$ must be re-acquired by the FCR at a range l such that

$$l \geq e \geq e^- \tag{8}$$

From Equation 7, it is clear that the intercept range i is dependent on e. Recall that e represents the range of the target at the end of the detect-to-engage sequence. This sequence is assumed to start with the threat detection and end with the weapon launch. The sequence includes detection, surveillance sensor tracking, FCR cue, FCR search and lock-on, FCR tracking, and finally weapon launch. The duration d of the whole sequence is a function of the different phases, as follows

$$d = t_s + s + t_f + \Gamma(dn, cu, w_l) \tag{9}$$

where the durations of detection (dn), FCR cue (cu), and weapon launch initialization (w_l) are assumed negligible (through the function Γ). t_s, s, and t_f designate respectively the durations of tracking (with the search and surveillance sensors), of search to lock-on of the FCR, and of FCR tracking. A limit d^+ on the detect-to-engage time d is set using the limit e^- defined by the minimum range beyond which the target must be engaged

$$d \leq d^+ = \frac{r - e^-}{\dot{\mathcal{T}}} \tag{10}$$

where r is the range at which the threat is detected by surveillance sensors, and e^- is given by

$$e \geq e^- = w^- \left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right] \tag{11}$$

Consequently, the detect-to-engage time d has an influence over the predicted intercept range i. Thus, any constraint on i can be reformulated into a constraint on d. Furthermore, the duration d is mainly determined by the length s of the search to lock-on phase of the FCR and by the duration t_s of the tracking phase. Therefore, the constraint on d can be re-expressed as a constraint on s

$$d = t_s + s + t_f \leq d^+ \Rightarrow s \leq s^+ \tag{12}$$

where

$$s^+ = d^+ - t_s - t_f \tag{13}$$

$$= \frac{r - e^-}{\dot{\mathcal{T}}} - t_s - t_f \tag{14}$$

$$= \frac{r - w^-}{\dot{\mathcal{T}}} - \frac{w^-}{\dot{w}} - t_s - t_f \tag{15}$$

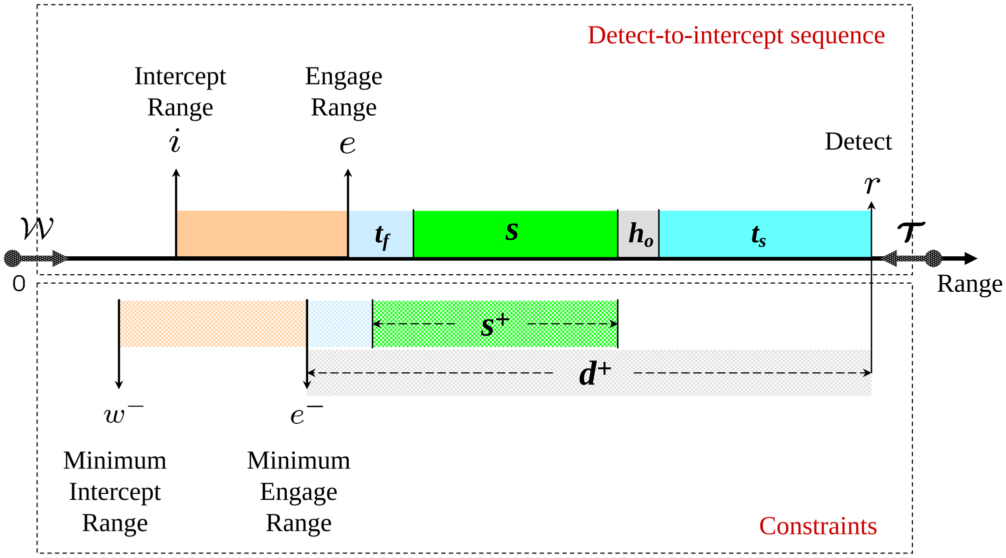


Figure 5: Detect to intercept constraints with target engageability assessment (Constraints are expressed in terms of range)

These engageability constraints on the different phases of the detect-to-intercept sequence are illustrated in Figure 5.

Moreover, note that since the duration of the search to lock-on phase of the FCR depends on the uncertainty related to the track of the target ($\boldsymbol{P}$), the established constraints on s can be re-expressed as constraints on $\boldsymbol{P}$.

Constraints expressed in the time dimension

The constraints described above can be re-expressed in terms of time instead of range. For example, instead of using the range r at which the target is detected, we will use the time r_t at which the target is detected. The conversion from range to time is dependent on the targets and weapons' velocities, $\dot{\mathcal{T}}$ and $\dot{w}$. The new expressions that will be used are:

r_t : The time at which the target is detected
e_t : The time at which the target is engaged
e_t^+ : Maximum time at which the target must be engaged to be intercepted.
i_t : The time of the predicted target interception
i_t^+ : Maximum admissible time at which the target must be intercepted

The time i_t of the predicted interception is

$$i_t = \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e}\right] + e_t \tag{16}$$

where e_t, the time at which the target is engaged, is given by

$$e_t = \frac{r - e}{\dot{\mathcal{T}}} \tag{17}$$

Similarly, the maximum admissible time i_t^+ at which the target must be intercepted is

$$i_t^+ = \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e^-}\right] + e_t^+ \tag{18}$$

where e_t^+, the maximum time at which the target must be engaged to be intercepted, is given by

$$e_t^+ = \frac{r - e^-}{\dot{\mathcal{T}}} \tag{19}$$

Thus the range constraints illustrated in Figure 5 have their time equivalents shown in Figure 6.

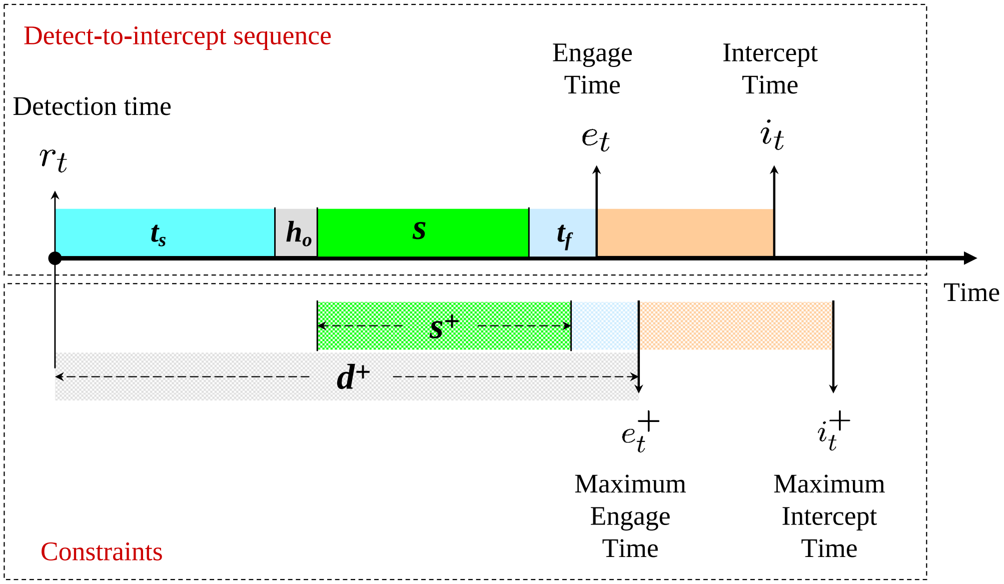


Figure 6: Constraints with target engageability assessment in relation with the detect-to-intercept sequence (Constraints are expressed in terms of time)

4.2.2 Group level goals

Given a threat list $(rank_T)$, the engageability value $\boldsymbol{E}$ for each target, some engagement capabilities $\boldsymbol{C}$ and a track list $\boldsymbol{X}$, an engagement schedule is determined:

$$rank_E = ES(rank_T, \boldsymbol{E}, \boldsymbol{C}, \boldsymbol{X}) \tag{20}$$

where ES is an engagement schedule algorithm and $rank_E$ is a ranked list of the targets to be engaged. For example, $rank_E(\mathcal{T}_1) < rank_E(\mathcal{T}_2)$ means that target $\mathcal{T}_1$ has been scheduled to be engaged before target $\mathcal{T}_2$. $rank_E$ will be used in the determination of constraints and goals at the target level.

Engagement scheduling can be very complex and may involve different strategies that depend on different target conditions. In order to restrain the engagement complexity in this work, it is supposed that the threat level ($\boldsymbol{T}$) of a target is given by the inverse of its TCPA:

$$\boldsymbol{T}(\mathcal{T}_i) = TCPA(\mathcal{T}_i)^{-1},\ \mathcal{T}_i \in \mathcal{T} \tag{21}$$

where $\mathcal{T}$ is the set of targets within the VOI. The threat rank is the ordered list of the threat level, where

$$rank_T(\mathcal{T}_i, t) < rank_T(\mathcal{T}_j, t), \tag{22}$$

if

$$\boldsymbol{T}(\mathcal{T}_i, t) > \boldsymbol{T}(\mathcal{T}_j, t),\ \mathcal{T}_i, \mathcal{T}_j \in \mathcal{T} \tag{23}$$

and where $\mathcal{T}_i$ is more threatening than $\mathcal{T}_j$.

According to this threat rank list, the following engagement scheduling algorithm is used, where the engagement rank of a target is simply its threat rank:

```
Algorithm $ES$ - A simple engagement scheduling method:
Inputs: $rank_T$, the threat list; $N_t$, the number of threats to be engaged; $N_{\mathcal{W}}$, the number of available SAMs.
Outputs: $rank_E$, a ranked list of the targets to be engaged.
$i = 1$
while ($i \leq N_T$ and $i \leq N_W$) do
$rank_E(\mathcal{T}_i) = rank_T(\mathcal{T}_i)$
$i \leftarrow i + 1$
end while
end
```

4.2.3 Target level goals

Given the engagement schedule $rank_E$, the engagement capabilities $\boldsymbol{C}$ and the tracks of the targets that are comprised in the engagement schedule, goals and constraints on the search to lock-on time of the FCR and on the detect-to-engage time are determined for each target under consideration.

Let a constraint express a limit on a value. The limit may be a minimum ($^-$) or a maximum ($^+$). For example, a constraint on the search to lock-on time may be that the duration must not exceed a maximum value s^+.

As opposed to a constraint, a goal does not necessarily refer to some explicit values. Instead, a goal expresses an intention to be accomplished. The level of specificity of the intention may vary. Possible intentions on some variables are the minimize (min) and maximize (max) intentions. According to our target engagement problem, the minimize and maximize intentions will define the goals related to the search to lock-on time and the detect-to-engage time. A goal is represented by a star (*). For example, $s^* = min(s)$ represents the goal that is the minimization of the search to lock-on time.

Again, note that from the adaptive data fusion perspective, the goals and the constraints on s and d can be translated into goals on the tracking time (t_s) before cueing the FCR. Table 3 presents inputs and outputs of each goal management level of function.

Table 3: Inputs and outputs of each goal management level of function for the target engageability improvement application (s^* and d^* represent the goals on the search to lock-on time and on the detect-to-engage time, respectively)

Level/Function	Inputs	Outputs
Group	Threat rank ($rank_T$) Engageability list ($\boldsymbol{E}$) Track list ($\boldsymbol{X}$) Capabilities ($\boldsymbol{C}$)	Engagement schedule ($rank_E$)
Target	Track list ($\boldsymbol{X}$) Engagement schedule ($rank_E$) Capabilities ($\boldsymbol{C}$)	Goals s^* and d^*
Performance evaluation	Tracks ($\hat{\boldsymbol{x}}, \boldsymbol{P}, \mathcal{T}$)	Estimates ($\hat{s}$ and $\hat{d}$)
Performance comparison	Goals (s^* and d^*) Estimates ($\hat{s}$ and $\hat{d}$)	Cueing time of the FCR (s_t) Tracking duration (t_s)

4.2.4 Performance evaluation

The Measures Of Performance (MOP) to be evaluated are selected on the basis of the particular application. In the case of our target engageability improvement application, the MOP is the estimated search to lock-on time $\hat{s}$ of the FCR. An estimated detect-to-engage time $\hat{d}$ can also be calculated according to $\hat{s}$. The complete method for estimating the search to lock-on time of the FCR is given in [3].

As mentioned earlier, the duration of the search to lock-on phase of the FCR is related to the tactical picture quality. The latter refers to the quality of the track that is cued to the FCR at the beginning of its search to lock-on phase. Based on the information contained in this track, *i.e.*, $\hat{\boldsymbol{x}}$ and $\boldsymbol{P}$, an estimate $\hat{s}$ of the duration s of the search to lock-on time can be computed. This estimate will form the basis of the performance evaluation and comparison functions, as follows.

$$\hat{s} = \mathcal{G}(\boldsymbol{P}) \leq s^+ \tag{24}$$

is a monotonic increasing function which can be re-expressed as

$$\begin{aligned} \boldsymbol{P} &= \mathcal{G}^{-1}(\hat{s}) && (25)\\ &\geq \mathcal{G}^{-1}(s^{+}) && (26)\\ &= \mathcal{G}^{-1}\big(\frac{r - w^{-}}{\dot{\mathcal{T}}} - \frac{w^{-}}{\dot{w}} - t_s - t_f\big) && (27) \end{aligned}$$

In the presence of a target within the VOI, an admissible track quality $\boldsymbol{Q}$ for hardkill engagements is established on the basis of admissible search to lock-on time s for the FCR. The latter is computed based on the admissible interception range i defined in Subsection 4.2.1 (or Section 4.4.1, 4.4.2 or 4.4.3, depending on the situation).

The constraint on $\boldsymbol{Q}$ prompts for some adaptation actions on the tracking system. The actions may take place over the different adaptation dimensions described in Section 3.1. In this work, the adaptation acts on the process dimension, more specifically on the tracking time (t_s). The constraint on $\boldsymbol{Q}$ is translated into a requirement on t_s. Moreover, let track quality be the inverse of track uncertainty. The track uncertainty $\boldsymbol{P}$ can be expressed in terms of t_s

$$\boldsymbol{P} = \mathcal{F}(t_s) \qquad (28)$$

Substituting Equation (28) into Equation (24) yields

$$\hat{s} = \mathcal{G}(\mathcal{F}(t_s)) \qquad (29)$$

Then, substituting Equation (29) into Equation (12), the estimated detect-to-engage time is then

$$\hat{d} = t_s + \mathcal{G}(\mathcal{F}(t_s)) + t_f \qquad (30)$$

Notwithstanding t_f ($t_f = 0$), Equation (30) shows that the detect-to-engage time d can be expressed as a function of t_s. This function is illustrated in Figure 7. Hence, an adaptive tracker can play on the duration t_s in order to respect the conditions presented in Equations (6) and (10), and such that the target be engageable. Taking the constraint d^{+} on the detect-to-engage time, three situations may occur and are shown in Figure 7:

(a) A short tracking time causes a low track quality, and therefore a long search to lock-on time. The target is engaged too late and cannot be intercepted.

(b) The tracking lasts long enough in order that the track cued to the FCR has good enough quality to expect locking on the target soon enough to engage the target in time.

(c) Tracking lasts too long before cueing over to the FCR. The FCR locks on the target too late to engage the target in time. The target cannot be intercepted.

An adaptive tracker should allow situation (b) to happen. Therefore, any goal d^{*} on the detect-to-engage time d should always be determined so that

$$d^{*} < d^{+} \qquad (31)$$

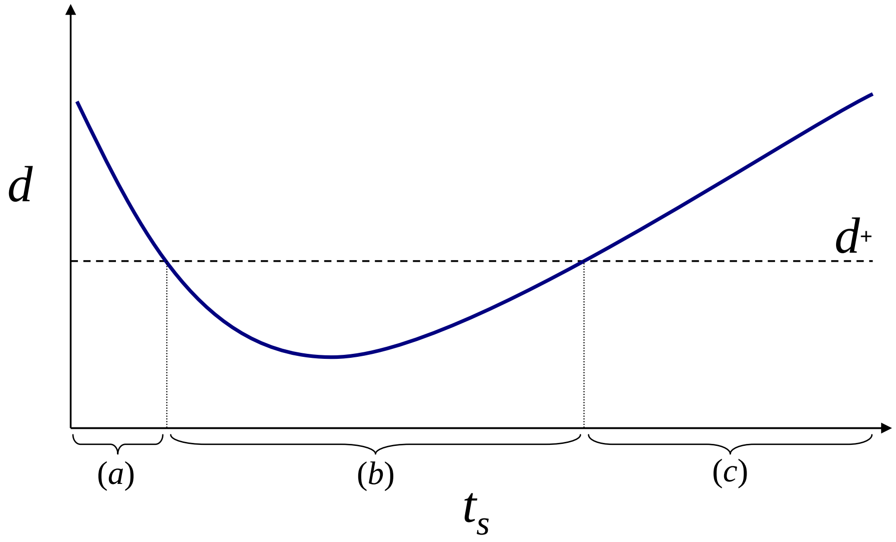


Figure 7: Detect-to-intercept sequence as a function of tracking time. (a),(c) - Target will not be intercepted in time, (b) - Target can be intercepted.

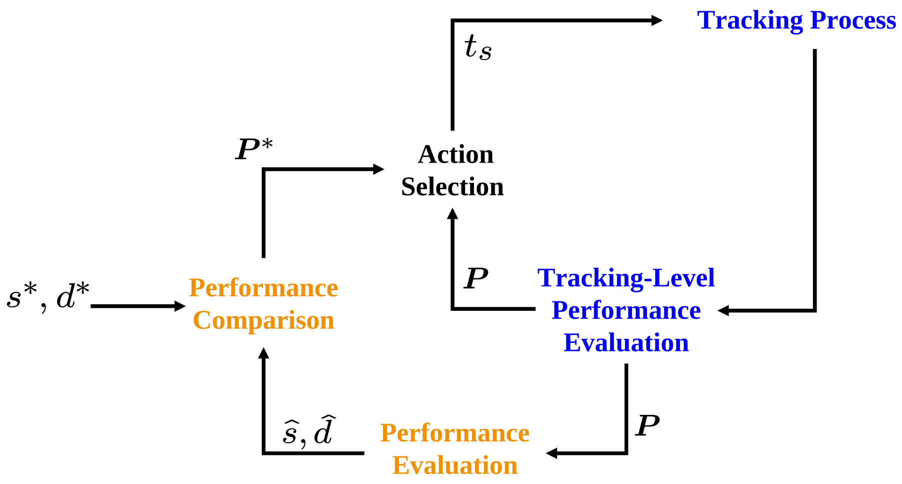
Practically, as time goes on and at some regular intervals, the adaptive tracking system will estimate the search to lock-on time based on the current track quality. Adding the current tracking time with the estimated search to lock-on time of Equation 29 $(t_s + \hat{s})$, the adaptive system gets an estimated detect-to-engage time $(\hat{d})$ which is compared with d^+. At any times where $\hat{d}$ is below d^+, the track can be cued to the FCR and thereafter the target should be intercepted beyond the minimum intercept range.

4.2.5 Performance comparison

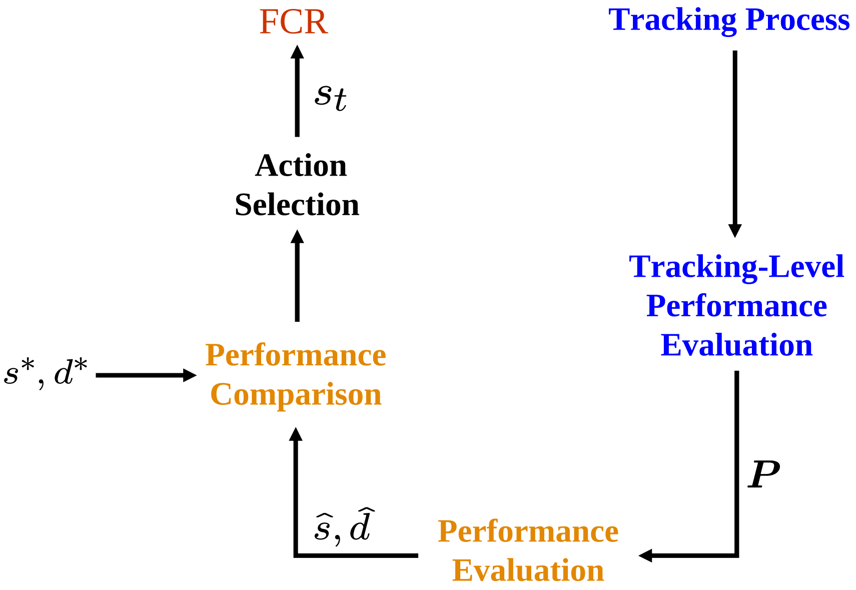
With respect to the selected MOPs, the evaluated performance must be compared with the desired goals. This comparison verifies whether goals are achieved or not. Actions are taken on the basis of the results of the comparison. The actions can be looked at to be on the data fusion process (adaptive data fusion perspective shown in Figure 8 (a)) or on the material resources (data fusion and resource management perspective shown in Figure 8 (b)). Both are equivalent. In the case of our target engageability improvement application, the comparison returns the cueing time of the FCR (s_t). The action is then about cueing the FCR at a particular time s_t. From the adaptive tracking perspective, this is equivalent to determining the tracking time t_s before cueing the FCR. In that case, the determination of the tracking time is an implicit action taken on the tracking system.

4.3 Resource management

In [5], resource management was described as a multi-level process that comprises resource signal management, resource response management, resource relationship management and



(a) Adaptive tracking, two-level closed-loop process



(b) Data fusion and resource management

Figure 8: Two equivalent representations of the target engageability improvement solution: Adaptive data fusion representation (a) and data fusion and resource management representation (b).

mission objective management. In the case of the target engageability improvement application, only the resource response level is involved. The resource response must do with the cueing of the FCR. It tasks the FCR for the target acquisition. Table 4 shows inputs and outputs of the resource manager.

Table 4: Inputs and outputs of resource management for the target engageability improvement application.

Level	Inputs	Outputs
Resource Response	Cueing time of the FCR (s_t) Track ($\hat{\boldsymbol{x}}, \boldsymbol{P}, \mathcal{T}$)	FCR track ($\hat{\boldsymbol{x}}_{FCR}, \boldsymbol{P}_{FCR}, \mathcal{T}$)

4.4 Target engagement scenarios

Three different target engagement scenarios are presented. Each of the three scenarios yields particular assessed impact and situation. As a consequence, different goals and constraints management strategies must be used.

The three scenarios are:

1. **Single target:** Only one target in the VOI needs to be engaged. Target re-engageability is not required.
2. **Single target with re-engageability requirement:** Only one target in the VOI needs to be engaged. It must be allowed to re-engage the target a second time in case of a missed interception at the first engagement.
3. **Multiple (two) targets:** Two targets in the VOI need to be engaged. It is assumed that the system is aware that a second target must be engaged before engaging the first one. There is no re-engageability requirement.

The scenarios are presented in Subsections 4.4.1, 4.4.2 and 4.4.3, respectively. It will be shown how goals and constraints are managed depending on the observed situations and the assessed impact.

4.4.1 Single target scenario

The single target scenario yields the following observed situation and assessed impact:

Number of targets ($S.N_T$) $=$ 1,
Number of available FCRs ($C.N_{FCR}$) $=$ 1,

Number of SAMs ($C.N_{\mathcal{W}}$) $>$ 1,
Threat rank list ($rank_T$) $=$ T_1,
Engageability list ($\boldsymbol{E}$)[9] $=$ E_1,

where

$$E_1(1) = 1, \tag{32}$$

$$E_1(2) = 0. \tag{33}$$

Thus, there is one target under consideration, with one available FCR and with more than one available missile (SAM). The threat list includes a single target. The target is assumed engageable but not re-engageable. Consider that with such data the goal (**G1**) is to have target interception as close as possible to the weapon's minimum intercept range and to minimize the search to lock-on time. This should maximize the probability of interception while minimizing the visibility of the ship[10].

G1: $\{\ \min(i) \cap \min(s)\ \}$ – Have target interception as close as possible to the weapons' minimum intercept range and minimize the search to lock-on time of the FCR.

Since we have

$$\min(i) = i^- \tag{34}$$

we can resolve the corresponding maximum detect-to-engage time (d^+) using (10) and (7). Then, a minimum search to lock-on time ($\min(s) = s^-$) that respects the limit d^+ on the detect-to-engage time is found. The determination of s^- according to d^+ is shown in Figure 9. Finally, **G1** can be expressed as

$$\mathbf{G1} : \{d^* \cap s^*\} = \{d^+ \cap s^-\} \tag{35}$$

As shown in Figure 9, in order to reach **G1**, an adaptive tracker will track for a duration $t_s^{\mathbf{G1}}$ before handing over to the FCR. The corresponding target engagement sequence is illustrated in Figure 10(a), where the resulting predicted intercept time (i_t) is equal to the maximum admissible intercept time (i_t^+). In the closed-loop, non-adaptive case, it may happen that t_s be set such that the target will not be engaged in time. Such a situation is shown in Figure 10(b).

4.4.2 Single target scenario with re-engageability requirement

The single target scenario yields the following observed situation and assessed impact:

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[9] Pre-assessment of engageability that does not take into account the search and lock-on time of the FCR.

[10] Minimizing the search to lock-on time of the FCR reduces its signal emission time, thus lowering the chances of being detected by an enemy.

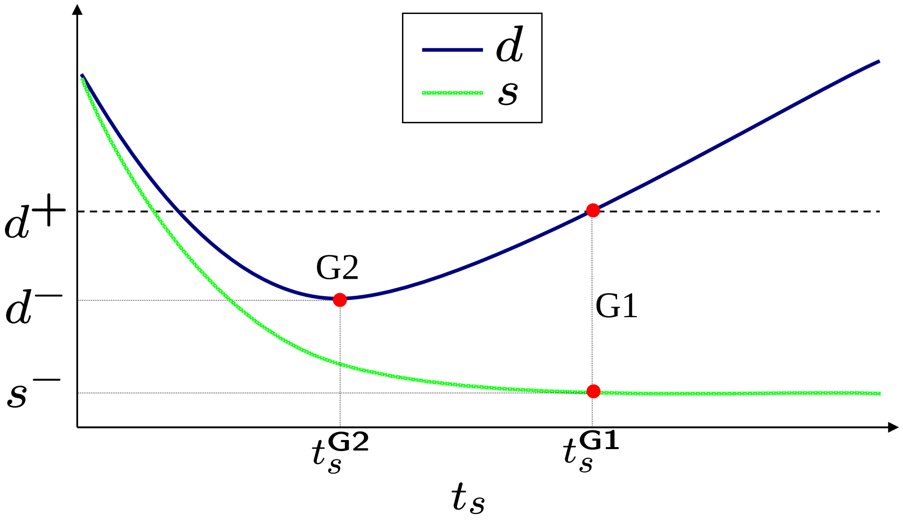

Figure 9: Detect-to-intercept sequence as a function of tracking time. There is a tracking time $t_s^{\mathbf{G1}}$ that results in a maximum detect-to-engage time d^{+} and a corresponding minimum search to lock-on time s^{-}. There is also a tracking time $t_s^{\mathbf{G2}}$ that yields the minimum detect-to-engage time d^{-}.

Number of targets $(S.N_T) = 1,$
Number of available FCRs $(C.N_{FCR}) = 1,$
Number of SAMs $(C.N_{\mathcal{W}}) > 1,$
Threat rank list $(rank_T) = T_1,$
Engageability list $(\boldsymbol{E})$ [11] $= E_1,$

where

$$E_1(1) = 1, \tag{36}$$

$$E_1(2) = 1. \tag{37}$$

The only difference with the single target scenario described in Subsection 4.4.1 is that target re-engageability is required in the present scenario. Simply, let us suppose that this re-engageability requirement is the result of the impact assessment process. To make re-engagements possible imposes some limit on the predicted target interception time. The predicted interception time is a parameter that may be of primary importance to the ship survival, and there are many reasons to limit it. One important reason is to make re-engagements possible, should a miss happen. Setting some new limit on the predicted target interception time sets new constraints on the detect-to-intercept sequence. These constraints are shown in Figures 11(a) and 11(b), where some range constraints and some time constraints are described, respectively.

In terms of range these new constraints are:

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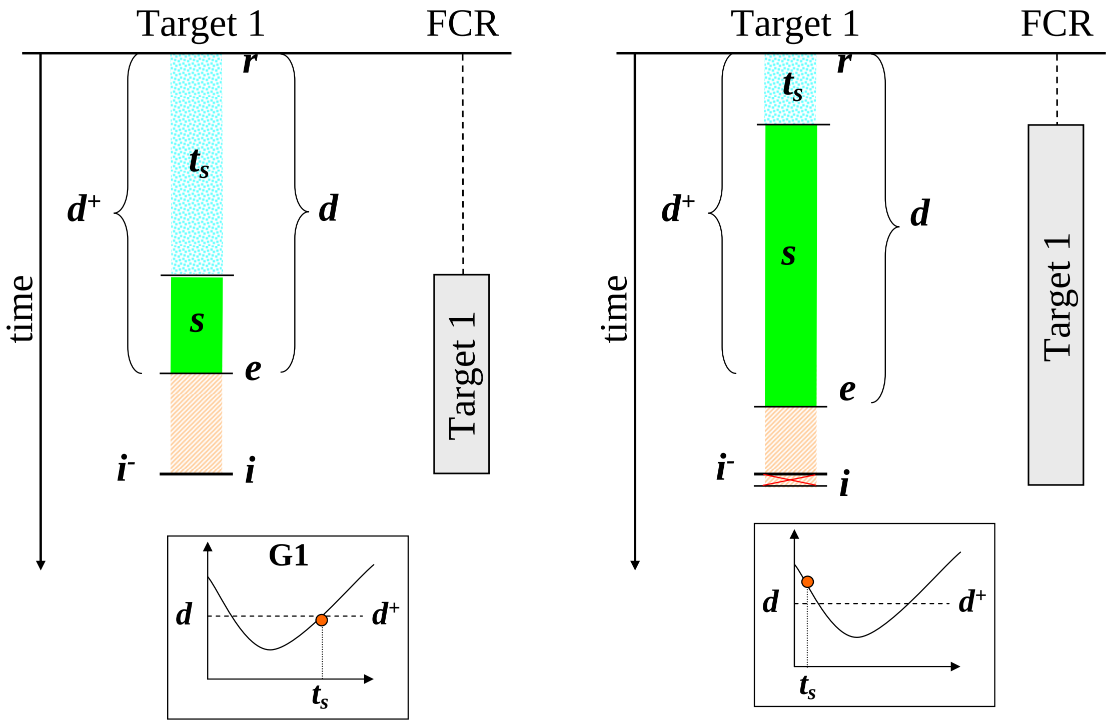
[11] Pre-assessment of engageability that does not take into account the search and lock-on time of the FCR.



(a) Engageability improvement through adaptive tracking. The effected tracking time (t_s) is the right one that minimizes the search to lock-on time while enabling target interception as close as possible to the weapon's minimum intercept range.

(b) Target engagement with an open-loop tracking system. The effected tracking time (t_s) is determined arbitrarily and the target is not engageable.

Figure 10: Single target engagement

$i^{-\prime}$: The minimum predicted intercept range of the first engagement
$e^{-\prime}$: The minimum target range at the first engagement
i^{-} : The minimum predicted intercept range of the second engagement
e^{-} : The minimum target range at the second engagement

where

$$i^{-} = w^{-}, \tag{38}$$

$$i^{-\prime} = e^{-}, \tag{39}$$

$$e^{-\prime} = w^{-}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right]^{2} \tag{40}$$

and where e^{-} is given by (11). Details for $e^{-\prime}$ are given in Annex A.

In terms of time the new constraints are

$i_t^{+\prime}$: The maximum admissible predicted intercept time of the first engagement
$e_t^{+\prime}$: The maximum admissible time of the first engagement
i_t^{+} : The maximum admissible predicted intercept time of the second engagement
e_t^{+} : The maximum admissible time of the second engagement

where

$$\begin{aligned} i_t^{+\prime} &= \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e^{-\prime}}\right] + e_t^{+\prime} && (41)\\ &= \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e^{-\prime}}\right] + \frac{r - e^{-\prime}}{\dot{\mathcal{T}}} && (42) \end{aligned}$$

with $e^{-\prime}$ given by (40). Also

$$\begin{aligned} i_t^{+} &= \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e^{-}}\right] + e_t^{+} && (43)\\ &= \left[\frac{\dot{w} + \dot{\mathcal{T}}}{e^{-}}\right] + \frac{r - e^{-}}{\dot{\mathcal{T}}} && (44) \end{aligned}$$

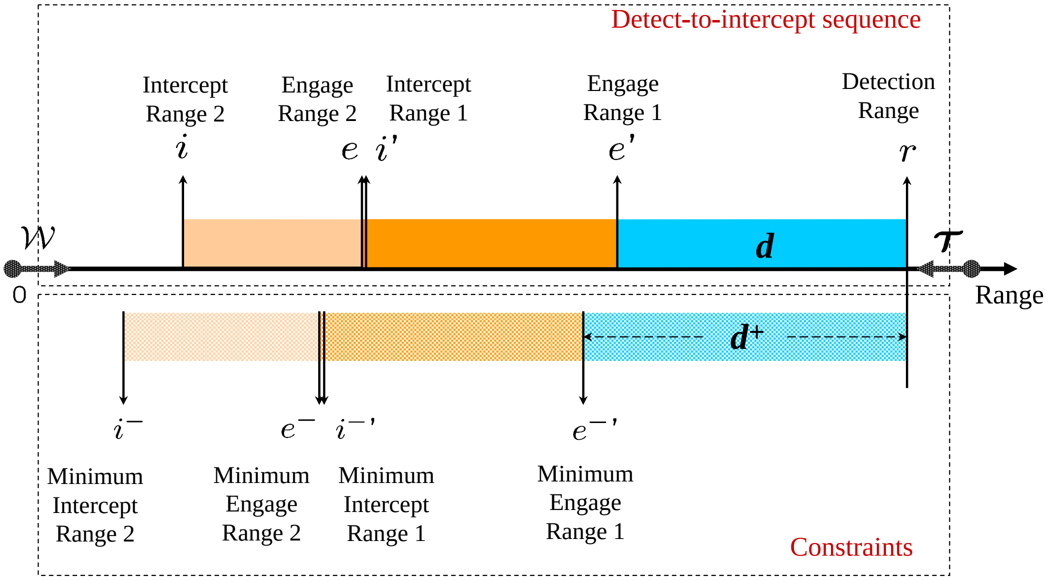
where e^{-} is given by (11).

The re-engageability requirement sets up the constraint d^{+} on the detect-to-engage time, in that the detection-to-engage duration must be lower than the maximum admissible time of the first engagement

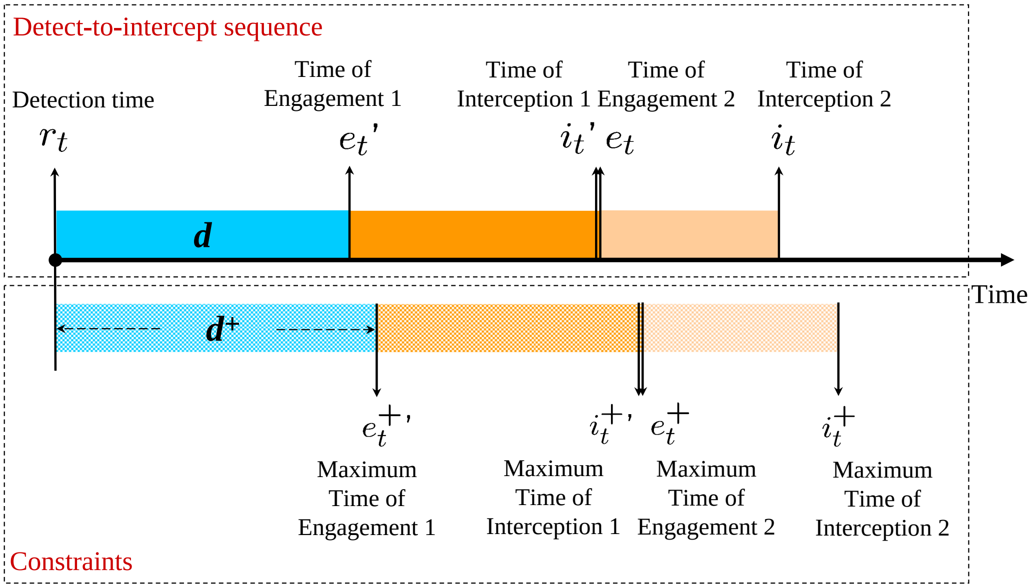
$$d \leq d^{+} = e_t^{+\prime}. \tag{45}$$

In order to respect this condition, the goal pursued is to minimize the detect-to-intercept duration so that the predicted threat interception be as early as possible after the detection time. This goal is noted **G2**.

G2: $\{ \min(i_t) \}$ – Minimize the predicted threat interception time i_t.



(a) Constraints for target re-engageability assessment in relation with the detect-to-intercept sequence. Constraints are expressed in terms of range.



(b) Constraints for target re-engageability assessment in relation with the detect-to-intercept sequence. Constraints are expressed in terms of time.

Figure 11: Single target re-engageability improvement

Recall that minimizing the predicted threat interception time is equivalent to minimizing the detect-to-intercept duration, which is also equivalent to minimizing the detect-to-engage time.

$$\mathbf{G2} : \{d^*\} = \{d^-\} \tag{46}$$

As shown in Figure 9, in order to minimize the detect-to-engage time, an adaptive tracker will track for a duration $t_s^{\mathbf{G2}}$ before cueing the FCR.

Practically, **G2** can be achieved by having t_s such that

$$\hat{d}_{t_s-2} > \hat{d}_{t_s-1} \text{ and } \hat{d}_{t_s-1} < \hat{d}_{t_s} \tag{47}$$

where t_s is the current tracking time that corresponds to the last track update. $t_s - 1$ and $t_s - 2$ are the tracking times that correspond to the second and third track updates, respectively.

Figure 12 illustrates the different times for the single target engagement where the target is missed at the first engagement.

4.4.3 Multiple target scenario

The multiple target scenario considers two targets that need to be engaged. Re-engageability is not required for any target. This scenario yields the following system awareness:

Number of targets ($S.NT$) = 2,
Number of available FCRs ($C.N_{FCR}$) = 1,
Number of SAMs ($C.N_{\mathcal{W}}$) > 1,
Threat rank list ($rank_T$) = $[T_1, T_2]$,
Engageability list ($\boldsymbol{E}$)[12] = $[E_1, E_2]$,

where

$$E_1(1) = 1, \tag{48}$$
$$E_2(1) = 1, \tag{49}$$
$$E_1(2) = 0, \tag{50}$$
$$E_2(2) = 0. \tag{51}$$

In such a multiple target engagement scenario, the satisfaction of the constraints expressed in Subsection 4.2.1 for each target individually may not be sufficient, considering the limited accessibility of the FCR. Engaging multiple targets necessitates time-sharing of the FCR among the targets to be engaged.[13] For that reason, group level constraints and goals that take into consideration the capabilities of the FCR and of the defending system need to be determined. In this example, group level goals are expressed in terms of a target engagement schedule. The engagement schedule specifies the order in which the targets must be engaged

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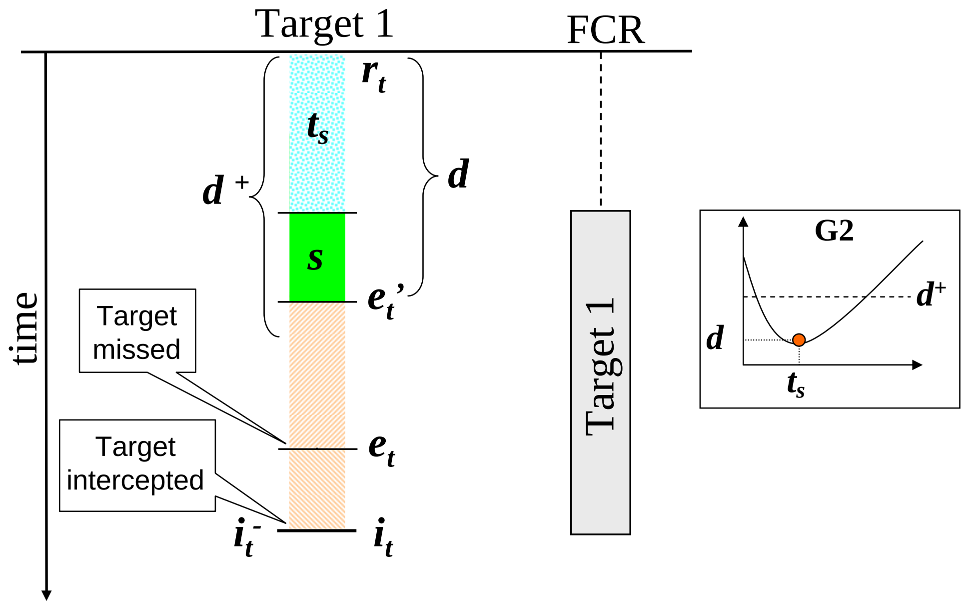
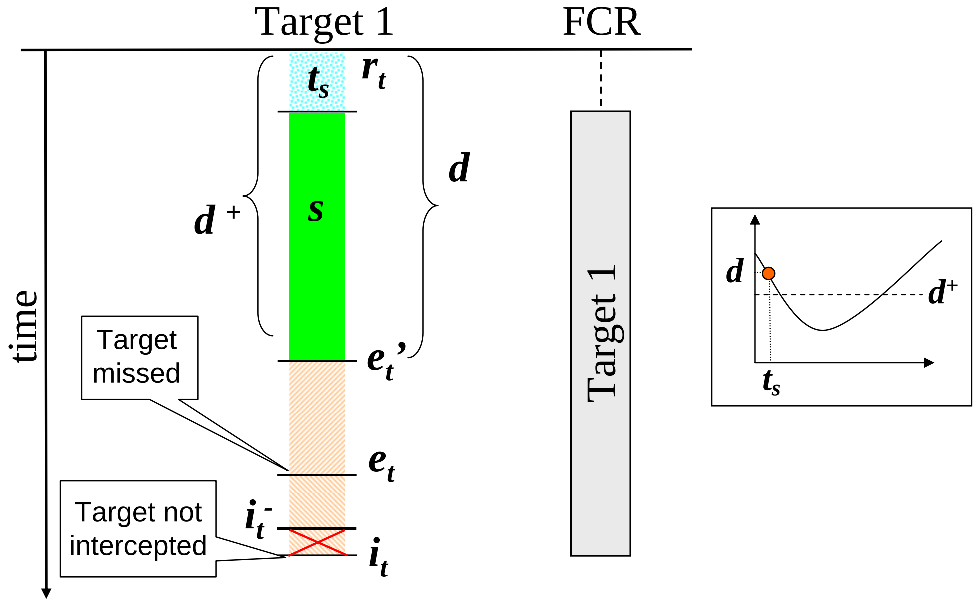
[12] Pre-assessment of engageability that does not take into account the search and lock-on time of the FCR.

[13] It is supposed that the FCR is assigned to one target at a time for the whole engagement sequence.



(a) Adaptive tracking system. The effected tracking times (t_s) enables the target to be re-engaged in time.



(b) Open-loop tracking system. The effected tracking times (t_s) is determined arbitrarily and will result in a late first engagement, thus the target cannot be re-engaged in time.

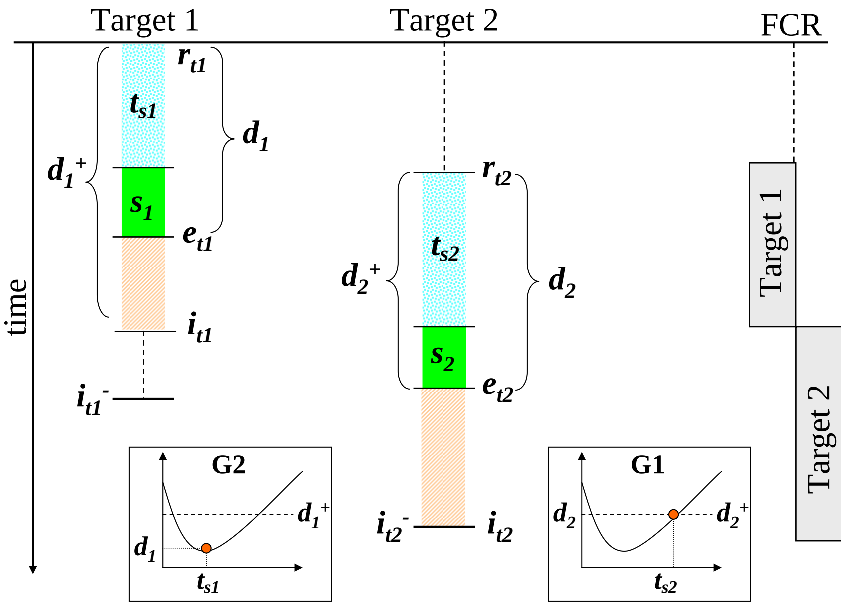
Figure 12: Single target engagement with a miss during the first engagement

(represented by $rank_E$ in Figure 3). This is done by considering the observed situation **S** and the observed impact **I**. The observed impact comprises threat assessment, engageability assessment and capabilities assessment. A simple engagement schedule is created according to **Algorithm** ES, that is given in Subsection 4.2.2.

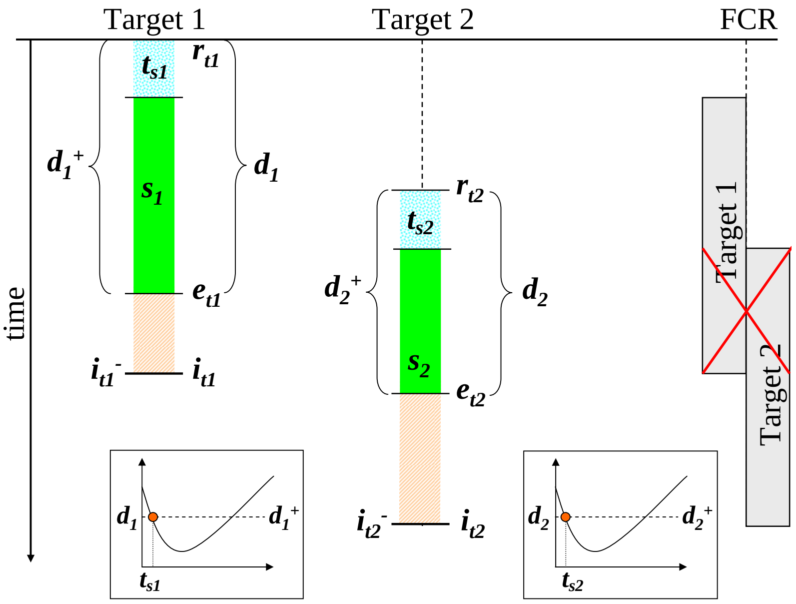
Given the engagement schedule, target level goals can be made. Let us consider the two target scenario. Ideally, both targets should be intercepted as close as possible to the weapon's minimum intercept range. This is goal **G1** defined in Subsection 4.4.1. But to achieve **G1** for both targets may be impossible in the cases where the targets follow one another closely in time. In such cases, goal **G1** will be designated to the target whose maximum intercept time i_t^+ is the longest. This is the target scheduled to be engaged last. The remaining target, scheduled as the first target to be engaged, has to be engaged and intercepted early enough in time so that the FCR be available soon enough to engage the other target. To maximize the chances that the FCR be available soon enough to engage the second target, the first target to be engaged must be intercepted as early as possible. Equivalently, it must have a detect-to-engage time as short as possible. Hence, the goal with the first target is to minimize its detect-to-engage time. This is goal **G2** described in Subsection 4.4.2.

Figure 13(a) shows the adaptive tracking case where **G1** and **G2** are associated with Target 2 and Target 1 respectively, while Figure 13(b) shows a closed-loop, non-adaptive case. In the closed-loop case, although the constraints d_1^+ and d_2^+ are respected for each target individually, there is a FCR sharing conflict between Target 1 and Target 2.

In order to resolve the conflict in the closed-loop system, the cueing of the FCR on Target 2 will be delayed until Target 1 is intercepted and until the FCR is freed. Such a delay will cause the FCR to lock on Target 2 too late for an interception. This problem is shown in Figure 14.



(a) Adaptive tracking system. The effected tracking times (t_s) on both targets enables them to be engaged.



(b) Open-loop tracking system. A FCR sharing conflict occurs.

Figure 13: Multiple target engagement

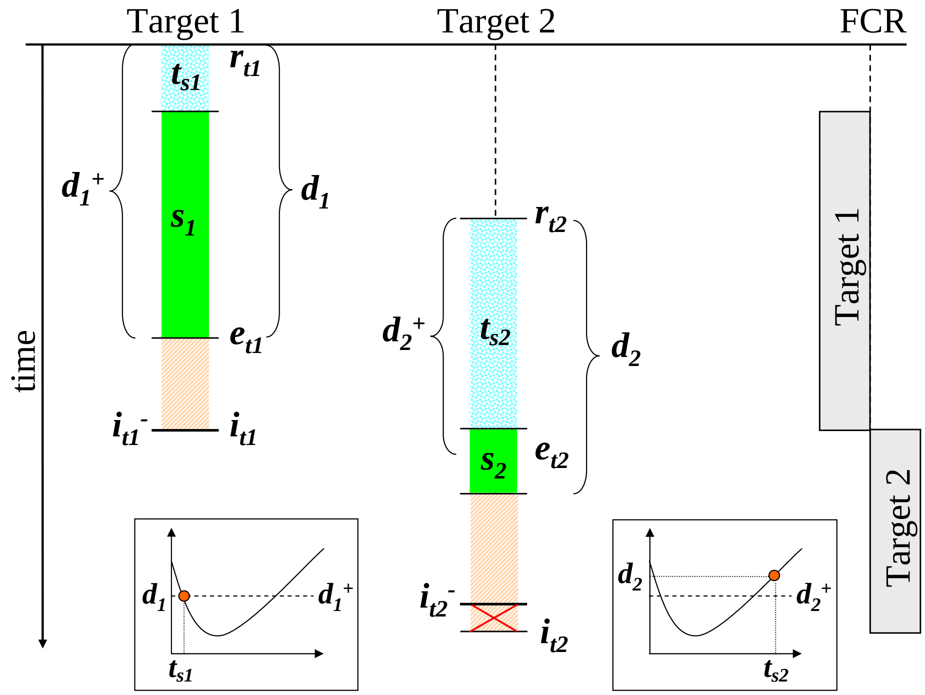


Figure 14: Multiple target engagement with a open-loop tracking system. Delaying FCR cue on Target 2 causes it to be engaged too late for an interception.

5 Simulation and results

A quantitative evaluation of the proposed target engageability improvement approach was performed using a combination of the SEATS test-bed [12], SADM simulator [13] and CASE_ATTI test-bed [14]. The demonstration uses the search & lock-on time estimator presented in [3].

Two scenarios, featuring a warship that is attacked respectively by one or two supersonic ASMs, are presented. The scenarios were defined so 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.

The ship is assumed to be equipped with Surface-to-Air Missiles (SAMs) as primary hardkill weapons. The SAM minimum intercept range is assumed 1000 m. Any interception below this range is considered to be highly unlikely successful. In the case, the defending ship would be hit by the ASM. Also, it is assumed that the ship has only one FCR available[14]. Figures 15 and 16 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, that is with and without the proposed target engageability improvement method. Without improvement, the FCR is cued as soon as the ASM is detected and a confirmed track is established. This corresponds to the standard tactic that most navies use. Although more sophisticated hardkill and softkill coordination strategies exist [15, 16, 17, 18], in this simulation softkill combat power resources are used as second resorts in cases where hardkill engagements are deemed not feasible.

It should be noted that the FCR model used in the demonstration is one that strictly relies on an estimation of the search to lock-on time, as described in [3]. This model was evaluated and compared with SADM's model in [11]. It was chosen as a first step that enables demonstrating the developed techniques with moderate resources. A step further, could make use of more realistic models that simulate the target acquisitions.[15] This would then allow for statistical evaluations and analysis.

5.1 Single target scenario

The first scenario (Figure 15) considers a closing single ASM with a zero CPA relative to the ownship. This scenario provides the ship with conditions for re-engagement should a miss occur. In that case, a second SAM could be launched shortly after the miss assessment.

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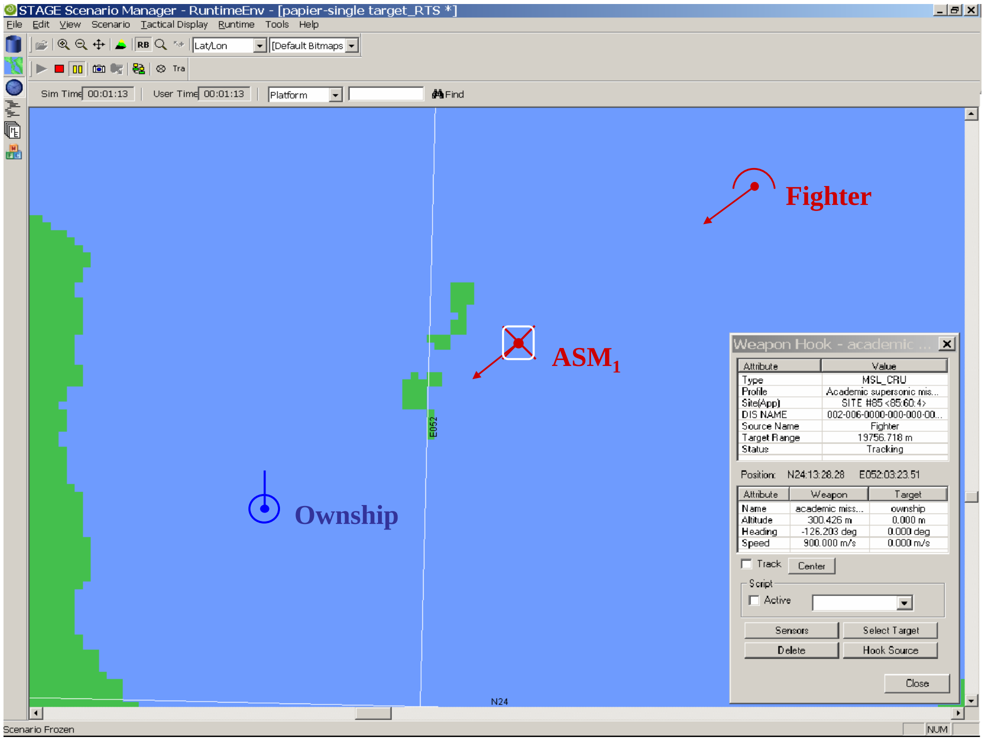
[14] Note that Canadian Frigates of Class Halifax have two FCRs.

[15] Although SADM's FCR model does simulate the target acquisitions, it was not suitable for our study.[11]

The scenario starts at $t = 0.0$ s with the detection of the ASM by the surveillance system at the initial range of 26000 m, the initial altitude of 300 m and the speed of 900 m/s. Under these conditions, the threat time-to-go (or time on flight) is about 29 s.



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

Figure 15: Single target scenario in STAGE (within SEATS test-bed)

5.1.1 Engagement without engageability improvement

Without target engageability improvement, 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 26.5 s. A second SAM could then be fired at 27.5 s, but it would be too late. The warship is hit by the target at 28.9 s, unless a softkill is used as a backup strategy.

5.1.2 Engagement with engageability improvement

Using target engageability improvement, the FCR is not cued as soon as a confirmed track is obtained. Instead, an optimal cueing time is computed (*i.e.*, at 9.9 s). The FCR locks on the target at 15.4 s, offering a gain of 5.9 s even if cueing started 7.0 s later compared to the previous case. A first SAM is fired at 16.4 s and misses the target at 24.4 s. This offers the opportunity for a re-engagement. A second SAM is fired at 25.4 s and hits the target at 27.7 s, at 1112 m from the warship. Table 5 summarizes the results.

Table 5: Results of the conventional engagement and the engageability improvement method for the single target scenario

Without engageability improvement		
Function	Time (s)	ASM range (m)
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

5.2 Two-target scenario

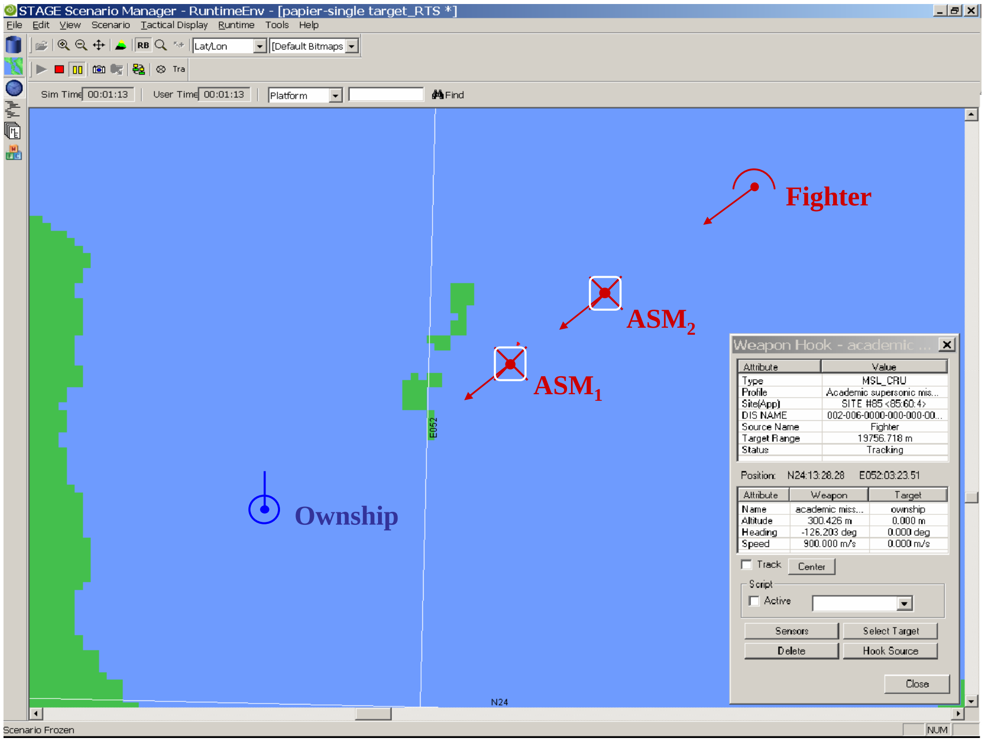
This second scenario (Figure 16) illustrates the engagement of two closing supersonic ASMs, again with zero CPA relative to the defending ship. $\mathbf{ASM}_1$ has an initial range of 19000 m, an altitude of 300 m and its speed is 900 m/s. $\mathbf{ASM}_2$ has an initial range of 23000 m, an altitude of 300 m and its speed is 900 m/s as well. $\mathbf{ASM}_1$ pops up at 0.0 s, while $\mathbf{ASM}_2$ pops up at 2.0 s. It is assumed that the defending ship is aware that an attack by more than one ASM is potentially high.

5.2.1 Without engageability improvement

Without target engageability improvement, $\mathbf{ASM}_1$ is missed in a similar way to the previous scenario. $\mathbf{ASM}_2$ is detected by the surveillance radar at 2.0 s. At that time, the FCR is busy on the first target until freed after the $\mathbf{ASM}_1$ miss assessment. The cueing of the FCR toward $\mathbf{ASM}_2$ starts 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 $\mathbf{ASM}_2$ from hitting the ship (at 27.56 s). Based on all this information and since $\mathbf{ASM}_2$ is not engageable with hardkill, softkill strategy could be recommended from the beginning.

5.2.2 Engageability improvement

With target engageability improvement, the FCR is cued toward the first detected target ($\mathbf{ASM}_1$) at 9.9 s, that is 7.0 s after track confirmation. The FCR locks on the threat at



Sim Time 00:01:13

User Time 00:01:13

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

Figure 16: Two-target scenario in STAGE (within SEATS test-bed)

14.9 s. Thereon, a SAM is 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 freed by the kill assessment for **ASM**$_1$. According to that, the FCR is cued toward **ASM**$_2$ at 20.25 s. It locks on it at 23.25 s. A second SAM is then fired at 24.25 s and **ASM**$_2$ is intercepted at 26.38 s. Table 6 summarizes the results.

Table 6: Results of the conventional engagement and the engageability improvement method for the two-target scenario

Without engageability improvement			
Target	Function	Time (s)	ASM range (m)
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 27.56s	

With engageability improvement			
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 Conclusions

This report addressed the problem of hardkill target engagement in the context of ASMD in maritime AWW. It was demonstrated that using the relation between time, track quality and search to lock-on time of the FCR can be useful in improving target engageability. For some specific Anti-Ship Missile Defence scenarios with short reaction time exigencies, it was shown that making use of this relation leads to successful target engagements as opposed to failed engagements when the traditional engagement process was used. The engageability of targets is improved thanks to the adaptation of the data fusion and resource management process. The adaptation is achieved through the management of goals and performance related to the application. Depending on the situation, the two main goals to be pursued are minimization of the detection to engage duration or minimization of the search to lock-on time.

The target engageability improvement method that was demonstrated involved taking actions on the tracking duration before cueing the FCR. Other ways to improve target engageability could have been considered. On the data fusion side, adaptation could have taken place on other adaptation dimensions such as parameter or function. These remain to be done and have yet to prove that it can be valuable candidate solutions to improve target engageability. Also, other issues of the naval C2 could also be looked at to improve target engageability. These include target detection, target identification/classification, threat evaluation and weapons assignment. Finally, future work could also integrate more complex ASMD techniques such as hardkill/softkill coordination strategies [15, 18], for example. Also, the simulated ASMD could be upgraded by refining our FCR model or allowing different FCR models to be tested, as well as using more realistic FCR parameters.

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List of acronyms

AAW	Anti-Air Warfare
AWW	Above Water Warfare
ASM	Air Surface Missile
ASMD	Anti-Ship Missile Defence
CASE_ATTI	Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification
C2	Command and Control
CCS	Command and Control Systems
CIWS	Close-In Weapons System
CP	Combat Power
CPA	Closest Point of Approach
DRDC	Defence Research & Development Canada
DSS	Decision Support Systems
FCR	Fire Control Radar
HVU	High Value Unit
MOP	Measure Of Performance
PIP	Predicted Intercept Point
PWGSC	Public Works and Government Services Canada
RDDC	Recherche et développement pour la défense du Canada
SADM	Ship Air Defence Model
SAM	Surface to Air Missiles
SEATS	Simulation Environment for the Analysis of the Tactical Situation
TCPA	Time to Closest Point of Approach
TEI	Target Engageability Improvement
TEWA	Threat Evaluation and Weapons Assignment
TP	Tactical Picture
VOI	Volume Of Interest
WA	Weapons Assignment

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Annex A: Minimum target range at the first engagement

The time $t_{i^{-\prime}}$ taken by weapon $\mathcal{W}$ to reach i^{-}’ (or e^{-}) is:

$$\frac{e^{-}}{\dot{w}} = \frac{w^{-}}{\dot{w}}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right] \tag{A.1}$$

The distance $D_{t_{i^{-\prime}}}$ traveled by the target during time $t_{i^{-\prime}}$ is:

$$D_{t_{i^{-\prime}}} = \frac{e^{-}}{\dot{w}}\dot{\mathcal{T}} = \frac{w^{-}}{\dot{w}}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right]\dot{\mathcal{T}} \tag{A.2}$$

Thus, the minimum target range at the first engagement is

$$e^{-\prime} = \frac{w^{-}}{\dot{w}}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right]\dot{\mathcal{T}} + e^{-} \tag{A.3}$$

$$= w^{-}\left[1 + \frac{\dot{\mathcal{T}}}{\dot{w}}\right]^{2} \tag{A.4}$$

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Annex B: Parameters

Here is a description of the parameters that were set in the demonstration:

Process noise spectral density (the process noise power spectral density in the prediction model)	4 m^2/s^3
SlantRangeSTDMeters (the standard deviation of the slant range for the surveillance radar)	18.75 m
BearingSTDRad (the standard deviation error in bearing for the surveillance radar)	0.01309 rad
ScanRate (the scan rate of the surveillance radar)	60 rpm
AlphaR (the accepted probability of not locating a target for a single FCR scan)	0.07
FCRBeamWidthInRad (the beam width of the FCR)	0.0348 rad
FCRElevationMaxInRad (the maximum elevation of the FCR)	0.698 rad
FCRElevationMinInRad (the minimum elevation of the FCR)	0 rad
FCRRangeMaxInMeters (the maximum range of the FCR)	80000 m
FCRRangeMinInMeters (the minimum range of the FCR)	0 m
FCRMaxNbOfScans (the maximum number of scans during the search of the FCR)	3
FCRBearingBeamSpeedInRadPerSec (the bearing beam speed of the FCR)	0.3 rad/s
FCRElevationBeamSpeedInRadPerSec (the elevation beam speed of the FCR)	0.3 rad/s
FCRMaxBearingDisplacementInRad (the maximum bearing displacement of the FCR)	2π rad

FCRCumulativeDetectionProbabilityThreshold (the cumulative detection probability threshold of the FCR)	1
Sensor2DNominalDetectionProbability (the nominal detection probability of the surveillance radar)	1
FCRNbOfScansConsidered (the number of scans considered during the search of the FCR)	1

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The Decision Support Systems Section (DSS) at Defence Research & Development Canada(DRDC) – Valcartier is conducting research activities aiming at developing and demonstrating advanced adaptive data fusion and resource management concepts. A typical application that can benefit from these concepts is the military naval Command and Control (C2). Military naval C2 systems are faced with an evermore increasing pace of the modern warfare, where increased threat sophistication and mobility demand shorter reaction time of the defending ship. Particularly, reaction time is of prime importance in Anti-Ship Missile
Defense (ASMD) operations. When hardkill strategies are used to counter the threat, the latter must be engaged under a certain time in order to be intercepted. This work presents a practical example of an adaptive data fusion and resource management system that aims at improving the engageability of targets threatening a defending ship. Target engageability is improved by making use of the search to lock-on time estimation of the Fire Control Radar (FCR). A quantitative evaluation of the approach is presented using the SEATS-SADM-CASE ATTI test-bed environment. For some specific Anti-Ship Missile Defense scenarios with short reaction time exigencies, it was shown that making use of the search to lock-on time estimation in the adaptive data fusion and resource management system leads to successful target engagements as opposed to failed engagements when the traditional engagement process was used.

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