Threat Assessment for Missions in Hostile Territory – From the Aircraft Perspective

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Abstract—A fighter pilot flying an air mission within hostile territory is exposed to the risk of getting hit by enemy weapons. This paper presents a survivability model that can be used for calculating this risk and assessing the threat to the mission. The model consists of two components; a tracking model and a fire model. The tracking model calculates the probabilities that the enemy is tracking the aircraft and has identified it as hostile. The enemy’s decision to fire a weapon depends on this probability but also on the enemy’s intentions to hit the aircraft. The fire model estimates the aircraft’s threat value, which describes the enemy intensions and capabilities [1]. Roy et al. [2, p. 329] has defined the term threat as “an expression of intention to inflict evil, injury or damage”. For a fighter aircraft, the enemy’s intentions are typically less complete than e.g., physical models used in target tracking. On the other hand, by assuming that the assets are valuable for the enemy, it is reasonable to assume that the enemy’s goal is to protect them. The enemy’s actions will therefore depend on how dangerous the aircraft is to the assets. The process of assessing how much threat an object poses against a valuable asset is known as threat evaluation [2]. The result of this process is a threat value which can be used for e.g., to prioritize the objects [4], [5]. Even though the concepts of threat assessment and threat evaluation are closely related, there is an important distinction between them. Threat evaluation focuses on the threat posed by a single object and threat assessment considers an entire view has been studied in e.g., [4], [6], [7] and this literature offers valuable insights in the process.

The threat value describes the enemy’s intentions, but the enemy’s capabilities and opportunities also affect the threat assessment of the mission. The enemy must detect and track the aircraft in order to fire a weapon and the probability that the weapon hits the aircraft depends on the relative geometry between the aircraft and the weapon launch position. Bossé et al. [8] have argued that the goal of information fusion is to reduce uncertainty. Hence, by combining information regarding the enemy’s capabilities and intentions, it is possible to predict the enemy’s behavior and assess the threat to the mission.

A. Related Work

The literature regarding route planning for fighter aircraft or unmanned aerial vehicles includes a few suggestions of

Keywords: threat assessment, fighter aircraft, survivability, Markov model.

I. INTRODUCTION

A fighter pilot flying a mission is exposed to the risk of getting hit by enemy fire. Consider a reconnaissance mission with the aim to gather information about some assets located inside hostile territory. These assets are for instance troops, infrastructure or weapon factories. The enemy is most likely interested in protecting these assets and therefore positions air defense systems close to them. It is valuable for the fighter pilot to analyze the situation and predict the enemy’s actions in order to assess the risk associated with the mission. This assessment can be used for planning the mission in such a way that the goals can be accomplished without exposing the aircraft to unnecessary risk and for triggering re-planning of the mission if the risk is considered too high.

The assessment of the risk of getting hit by enemy fire is closely connected to the assessment of threat that the enemy poses against the aircraft. Threat assessment is an analysis of enemy intentions and capabilities [1]. Roy et al. [2, p. 329] has defined the term threat as “an expression of intention to inflict evil, injury or damage”. For a fighter aircraft, the enemy’s intentions and opportunities to inflict damage depends to a high degree on the aircraft’s actions, for instance which route the aircraft flies. It is therefore interesting to perform threat assessment of a mission in order to determine how dangerous it is to fly that particular mission route. Threat assessment for a mission is far from trivial and requires that information regarding the enemy’s capabilities and intentions are fused. This information is typically held secret and the assessment will therefore be uncertain. Furthermore, according to Steinberg [3], threat assessment is complicated due to weak spatio-temporal and ontological constraints on relevant evidence as well as weakly-modeled causality. For instance, models of the enemy’s intentions are typically less complete than e.g., physical models used in target tracking. On the other hand, by assuming that the assets are valuable for the enemy, it is reasonable to assume that the enemy’s goal is to protect them. The enemy’s actions will therefore depend on how dangerous the aircraft is to the assets. The process of assessing how much threat an object poses against a valuable asset is known as threat evaluation [2]. The result of this process is a threat value which can be used for e.g., to prioritize the objects [4], [5]. Even though the concepts of threat assessment and threat evaluation are closely related, there is an important distinction between them. Threat evaluation focuses on the threat posed by a single object and threat assessment considers an entire situation. In this paper, the term threat evaluation is used for describing the enemy’s process of evaluating the aircraft. Threat assessment is used for describing how dangerous the mission is to fly with respect to all hostile objects that the enemy possesses. Hence, in order to assess the threat to the mission, it is useful to estimate the threat values assigned by the enemy. Threat evaluation from the air defense point of view has been studied in e.g., [4], [6], [7] and this literature offers valuable insights in the process.

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models describing the danger associated with flying inside hostile territory. The most basic model is to use so called no-fly zones and minimize the time inside these zones, see e.g., [9]. Another possibility is to consider the enemy’s radar stations and to describe the danger with flying a (short) segment of the route as \( K/R^4 \), where \( R \) is the shortest distance between the segment and the position of the radar and \( K \) is a constant for describing the radar system, see [10], [11]. This is motivated by the \( 1/R^4 \)-component in the radar equation. However, Dogan [12] argued that a probabilistic approach is suitable for mission planning, since it accounts for the non-deterministic nature of the problem. It was suggested to describe the danger of a position with the probability density function that the aircraft would get disabled at that position. However, directions of how such a function should be specified were not given. Erlandsson et al. [13] suggested a survivability model, where survivability for a mission route refers to the probability that the aircraft can fly the entire route unharmed. The danger of each position was described with an intensity function and it was suggested that the intensity should be described by a combination of the probability of the enemy detecting and tracking the aircraft, the probability per time unit that the enemy launches a weapon and the probability that a fired weapon hits the aircraft.

However, it can be argued that the relationship between the enemy’s ability to track and hit the aircraft is more complex than that, since the enemy is not lacking a memory. This implies that the enemy might have good knowledge regarding the aircraft’s position even though it is currently outside the sensor ranges, since the enemy is able to predict the movements of the aircraft. As soon as the aircraft flies within the range of a sensor, the enemy can quickly track and identify it. On the other hand, if the enemy did not earlier have knowledge regarding the aircraft, it will take some time before the enemy is tracking it and is able to identify it as hostile. This identification is often a necessary condition for firing a weapon due to the rules of engagement. An extension to the survivability model was therefore suggested in [14], which explicitly described the enemy’s capability of tracking and hitting the aircraft as well as the relation between these abilities. The components in the model as well as its intended usages were discussed with domain experts, which resulted in clarifications of the model and also suggestions for further development, see [15]. The risk that the enemy fires a weapon that hits the aircraft was modeled as an intensity describing the rate of fire. In practice, the enemy’s decision to fire a weapon depends on many factors such as the threat value and whether or not a weapon has already been fired. Furthermore, the probability that the weapon hits the aircraft depends on the aircraft’s velocity vector in relation to the weapons launch position. It is difficult to incorporate all these parameters in a single intensity function.

B. Contributions

This work advances the survivability models in [13], [14] in order to represent the enemy in a more realistic way and more in accordance with the domain expert’s way of describing the air defense. In practice this means that the sensory part and the weaponry part of the enemy are described differently. The sensors work in a continuous manner and constantly search for targets and track the ones that are detected. Weapons, on the other hand, are not constantly fired. The decision to fire a weapon can rather be seen as a discrete event, which depends on the enemy’s knowledge of the aircraft, the threat evaluation and the capabilities of the weapons. Furthermore, the model also includes a more realistic way of describing the weapons capabilities in relation to the geometry between the aircraft and the weapon launch position. A reconnaissance mission is used for illustrating the model and to show that the model enables a deeper analysis of the mission than previous suggested models.

II. Survivability Model

The purpose of the survivability model is to assess the threat to a mission and the risk of getting hit by enemy fire. However, uncertainties regarding the enemy’s capabilities and intentions affect this assessment. Due to these uncertainties, we consider the survival for the route as a stochastic process, since the route is extended in time and the survival for one part of the route depends on what has happened earlier in the route. Markov models are common for describing stochastic processes and are used in many applications, e.g., reliability theory [16] and medical decision making [17], [18]. The survivability model is therefore based on Markov models.

The survivability for a mission route describes the probability that the aircraft can fly the route unharmed, i.e., that the aircraft can fly the entire mission route without getting hit by a weapon fired by the enemy. The enemy’s decision process regarding weapon launch depends on many factors including the military doctrine of the enemy as well as the level of conflict. The aim of this work is to suggest a survivability model that is fairly generic and enables different enemy behaviors to be described. However, the parameters and numerical values should be considered as illustrative examples and are not intended to describe any particular doctrine.

There are a number of conditions that should be fulfilled before the enemy can fire a weapon:

- The aircraft should be tracked with sufficiently good quality to guide a weapon.
- The aircraft should have been identified as hostile, i.e., the enemy must make sure that the aircraft is not civilian or belonging to the own forces in order to avoid collateral damage and fratricide.
- The aircraft should be within the enemy’s weapon range.
- The enemy should consider the aircraft to be an important target, i.e., the aircraft should pose a threat against one or several of the enemy’s valuable assets.

The survivability model consists of two Markov models, which are connected, see Fig. 1. The tracking model is a continuous Markov model that describes the enemy’s knowledge regarding the aircraft. This part of the model describes the first two conditions in the bullet list above. The fire model is a discrete Markov model and describes whether or not the enemy has fired a weapon that hit the aircraft. The submodels are connected, since the decision to fire a weapon depends on the enemy’s knowledge regarding the aircraft.

Consider the scenario depicted in Fig. 2, which will be used for illustrating the model. The mission is a reconnaissance
mission and the task is to gather information about the two assets marked with stars. The enemy has positioned sensors and weapons in order to protect the assets. The dashed circles illustrate the sensor areas within which the aircraft can get detected and tracked by the enemy. The solid circles illustrate the weapon systems, where a larger circle indicates a larger weapon range. However, the weapons’ abilities to hit the aircraft depend on the aircraft’s velocity and are more complex than indicated in the figure, see Section IV-A.

III. TRACKING MODEL

The tracking model has four states: Undetected, Detected, Tracked and Identified. The enemy’s knowledge regarding the aircraft is considered as a stochastic process, which is in one of these states. The possible transitions between the states depend on whether the aircraft is inside or outside the sensor areas. When the aircraft enters a sensor area, it will first get detected, i.e., the enemy detects that the aircraft is present. After a while, the enemy is able to track the aircraft with sufficiently good quality in order to fire a weapon against it. Finally, before the aircraft is a valid target it must be identified as hostile. Hence, when the aircraft stays within a sensor area, the process can transit towards the states to the right in Fig. 1. On the other hand, if the aircraft leaves the sensor area, the enemy will lose track of the aircraft after a while and have to predict its movements. Eventually, the aircraft is forgotten, i.e., once again undetected. Hence, when the aircraft is outside the sensor areas, the process only transits to states to the left in Fig. 1.

The transition from state $i$ to $j$ is described with the intensity $\lambda_{ij}$, that is the rate of the conditional probability that a transition occurs to state $j$ given that the process is in state $i$. Transitions that are not possible have intensity $\lambda_{ij} = 0$, for instance transition from Identified to Undetected. The Markov model is closely related to the Poisson process and the intensities can be interpreted as the inverse of the expected time before transition [20]. Instead of specifying the intensities for the transitions, it is therefore possible to specify the expected time in each state before transition, $\tau_{ij}$.

For Markov models with finite state space, the rate matrix $\Lambda$ is defined as a matrix with the $i, j$th entry:

$$\Lambda_{ij} = \begin{cases} \lambda_{ij} = \frac{1}{\tau_{ij}}, & i \neq j \\ -\sum_{k \neq i} \lambda_{ik}, & i = j, \end{cases}$$

where $\lambda_{ij} = 0$ if the transition is not possible. The rate matrix for the tracking model is piece-wise constant and changes at the time points where the route crosses a border of a sensor area. Hence,

$$\Lambda(t) = \begin{cases} \Lambda_0, & t_0 \leq t < t_1 \\ \Lambda_1, & t_1 \leq t < t_2 \\ \Lambda_2, & t_2 \leq t < t_3 \\ \vdots \end{cases}$$

Let $p_{TM}$ be a vector that describes the state probabilities for the tracking model. For a time point $t_n$ on the route, $p_{TM}(t_n)$ is calculated recursively as:

$$p_{TM}^T(t_n) = p_{TM}^T(t_{n-1})e^{\Lambda(t_{n-1})(t_n-t_{n-1})}.$$

The sensor areas are usually not well separated but may overlap, since the enemy wants to ensure that the area is covered. By assuming that the sensors detect and track the aircraft independently of each other, the intensities for an area that is covered by multiple sensors is given as the sum of the individual intensities. For two sensors with the same $\tau_{ij}$, this implies that:

$$\frac{1}{\tau_{ij}^{\text{tot}}} = \frac{1}{\tau_{ij}} + \frac{1}{\tau_{ij}} = \frac{2}{\tau_{ij}}.$$

Hence, the expected time before transition is half of the time for the individual sensors.

A. Simulation

In order to illustrate the tracking model, the scenario in Fig. 2 has been simulated. For simplifying the analysis, all sensors were simulated with the same expected transition times according to Table I. In practice, knowledge regarding the different sensor systems that the enemy possesses can be incorporated in the model by using different values for different sensor areas.
The transitions in the fire model are described with probabilities instead of intensities as in the tracking model, since the fire model is a discrete-time Markov model. The transition matrix has the following appearance:

$$P(t_k) = \begin{pmatrix} 1 - p_{\text{fire}}(t_k) & p_{\text{fire}}(t_k) & 0 & 0 \\ 0 & 0 & 1 - p_{\text{kill}}(t_k) & p_{\text{kill}}(t_k) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The state probability vector for the fire model, $p_{FM}$, is calculated recursively as:

$$p_{FM}(t_k) = p_{FM}(t_{k-1}) P(t_k).$$

Furthermore, when the aircraft leaves a weapon range, all probability mass in the states Fire and Miss are transferred to state Unharmed.

The probability of fire, $p_{\text{fire}}$, depends on several parameters as indicated in the bullet list in the beginning of Section II. There are many possible ways to combine these parameters and in this work the following is suggested as a first approach:

$$p_{\text{fire}} = \begin{cases} p_I \cdot TV, & \text{if aircraft is inside weapon range} \\ 0, & \text{otherwise}. \end{cases}$$

$p_I$ is the state probability for state Identified and is calculated by the tracking model. The calculations of threat value, $TV$, and the weapon ranges are described below.

### A. Calculation of Weapon Range

The ability for a weapon to hit the aircraft depends on the relative geometry between the aircraft and the launching station. The probability that the weapon can hit the aircraft is higher if the aircraft approaches the launch station than if the aircraft is flying away and the weapon has to follow the aircraft [15]. The weapons are valuable resources and the enemy is not likely to fire if the probability of hit is too low. The weapon range can therefore be considered as the area where a weapon system has sufficiently high probability of hitting the aircraft. This area is sometimes referred to as the weapon engagement zone. A simple model of this area is an ellipse where the major axis is aligned with the aircraft’s velocity vector and the center point is located in front of the weapons launch position along the major axis. Fig. 4 shows the weapon areas for the scenario, when the aircraft is flying between WP1 and WP2. It can be seen that WP2 is located in such a way that the aircraft will fly inside the weapon range. However, the weapon area could easily be avoided by moving WP2 a little bit to the left. Hence, this more realistic model of the weapon areas is more useful for planning the route than the circular weapon areas depicted in Fig. 2.

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**TABLE I. EXPECTED TIME BEFORE TRANSITION.**

<table>
<thead>
<tr>
<th>Outside sensor range</th>
<th>$\tau_{DU} : 5$</th>
<th>$\tau_{FD} : 5$</th>
<th>$\tau_{F} : 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within sensor range</td>
<td>$\tau_{ID} : 2.5$</td>
<td>$\tau_{FD} : 3.3$</td>
<td>$\tau_{F} : 5$</td>
</tr>
</tbody>
</table>

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1There are situations where the enemy might fire multiple weapons against the aircraft, for instance if it is very important to hit the aircraft and $p_{\text{kill}}$ for each weapon is low. However, these situations are not considered in this paper.
avoid assumptions of the enemy’s threat evaluation process.

TV

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evaluation can be found in e.g., [4], [6], [7]. On the other
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Hence, if a mission is considered to be too risky, one can in-
creases the survivability by flying further away from the assets.
Secondly, to assess the other parameter’s influence to the threat
value is difficult. It requires that the enemy’s assessment of the
aircraft’s capability and intentions is estimated. The aircraft’s
capability and the pilot’s intentions are of course known, but
the enemy’s knowledge about these parameters is not known
and need to be estimated. Furthermore, in order to estimate
the threat value, assumptions regarding how these assessments
affect the threat value are required. Even though it is not trivial
to predict how the proximity influences the threat value, it is
reasonable to assume that the aircraft will be assigned a higher
threat value if it is close to an asset than if it is far away.

The estimations of threat values used here is inspired by
the Bayesian network for threat evaluation presented in [4].
One of the inputs in that network is the distance between
the aircraft and the asset, which is described by five levels. We
therefore estimate the threat value based on the distance to the
closest asset according to:

\[ TV = \begin{cases} 
1, & \text{very close} \\
0.9, & \text{close} \\
0.7, & \text{medium} \\
0.5, & \text{far} \\
0, & \text{very far}. 
\end{cases} \]

Inspiration for constructing more complex models for threat
evaluation can be found in e.g., [4], [6], [7]. On the other
hand, it is also possible to assign \( TV = 1 \), if one wants to
avoid assumptions of the enemy’s threat evaluation process.

B. Estimation of Threat Value, TV

The enemy’s threat evaluation process will typically assign
a threat value to the aircraft. The survivability model includes
an estimate of this threat value. Even though the process is
typically secret, the literature regarding threat evaluation for
identified three classes of parameters typically used: proximity, capability and intent. This work only considers proximity to
the valuable assets. The reason is twofold. First of all, this kind
of parameters can be changed by re-planning the mission route.
Hence, if a mission is considered to be too risky, one can in-
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The survivability model

WP1 WP2 WP3 WP4 WP5 WP6 WP7

Fire state probabilities over time

WP1 WP2 WP3 WP4 WP5 WP6 WP7

Survivability model

V. Threat Assessment for the Mission

The aim of the survivability model is to assess the threat to the mission and to identify the critical parts. The survivability, i.e., $1 - p_{Hit}$, is displayed in Fig. 7 together with three parameters that influence it. The goal for the first part of the mission is to gather information regarding the first asset and this task can be considered accomplished when the aircraft reaches WP3. The figure shows that the survivability is almost 100% at WP3 and this part of the mission is only associated with a small risk. Hence, the first part of the mission, between WP1 and WP3, is not as dangerous as indicated in Fig. 2. First of all, the aircraft only has to fly inside the range of the first weapon system, but avoids the second one. When the aircraft enters the first weapon area it also enters the first sensor area and the state probability for Identified is low. $p_{fire}$ is therefore low during this part of the route and is hardly visible in Fig. 7.

The second part of the route is more dangerous. The aircraft enters a weapon area after passing WP4 and the survivability decreases. However, the state probability for Identified is fairly low since the aircraft has been outside the sensor ranges for a long period of time. The survivability therefore only decreases slightly. On the other hand, when the aircraft enters the next weapon area, between WP5 and WP6, the survivability significantly decreases. The state probability for Identified is high and the threat value is also fairly high. This results in high values for $p_{fire}$. Furthermore, the aircraft is within the weapon range for a long period of time and the enemy has a lot of time to make the decision to fire. Thus, the risk is high that a weapon is fired when the aircraft is within its range. The survivability therefore decreases with almost 50%, which equals $p_{kill}$, i.e., the probability that a fired weapon hits the aircraft.

The simulations have shown that the most critical part of the route is the leg between WP5 and WP6. Even though this result is not surprising, the simulations have increased the knowledge of the mission. For instance, the first part of the mission is less dangerous than it appears in Fig. 2. Furthermore, the parameters that influence the survivability have been identified and there are several possibilities to increase the survivability for the mission. For instance, moving WP5 and WP6 a little bit further away from the asset would decrease the time inside weapon range and might also decrease the threat value. Another possibility would be to move WP4 in order to decrease the time inside the sensor range and consequently decrease the probability that the aircraft gets tracked and identified. It is of course also possible to consider the second part of the mission too risky and return to the air base after accomplishing the first part. This indicates that the model can be useful for simulating the route before it is flown to identify its critical parts and re-plan the route if necessary.

VI. Conclusions and Future Work

Fighter pilot flying missions inside hostile territory are exposed to the risk of getting hit by enemy fire from ground-based air defense systems. Ideally, the fighter pilots should fly outside the enemy’s weapon ranges at all times. However, the goals of the missions often require that the aircraft fly close to some assets, for instance with the purpose of gathering information as in the reconnaissance mission discussed in this paper. The enemy wants to protect these assets and therefore positions its air defense system in order to hinder the aircraft. It is therefore not possible to both stay outside the weapon ranges and accomplish the goals of the mission. We have here proposed a survivability model which could aid pilots in such situations. By assessing the threat to the mission, the pilot can plan where to fly and how to act in order to minimize the risk of getting hit.

Contrary to previous work, the survivability model presented here describes the enemy’s sensors and weapons separately due to their different natures. The enemy must track and identify the aircraft as hostile before firing a weapon against it and the model describes this relation between sensors and weapons. The model also enables the description of weapon ranges that depend on the relative geometry between the aircraft and the weapon launch position. Furthermore, the model mirrors the threat evaluation process performed by the enemy and estimates the threat value for the aircraft. The threat value affects the probability that the enemy will fire a weapon. The simulations illustrated how the model can be used for threat assessment of a reconnaissance mission to identify the critical parts of the mission as well as identify how the mission
route can be modified in order to increase the survivability. This indicates that the model can be useful for planning the mission by simulating the route before flight and re-plan the route if necessary.

Information regarding the enemy’s locations, capabilities and intentions is typically uncertain, mainly since the enemy aims to keep this information secret. The threat assessment of the mission will include some uncertainty and the pilot needs to be aware of this. Model transparency is therefore of great importance. On the other hand, too simple models, such as declaring the entire hostile area as a no fly zone, will not aid the pilot when planning how to penetrate the area. The development of the survivability model has aimed to balance these two objectives and to present a model that is both transparent and useful. This implies that the parameters in the model should be intuitive and easy to comprehend. The sensors are therefore described with ranges and expected time within the states, the weapons systems are described with \( P_{\text{kill}} \) and weapon ranges and the assets are associated with distances connected with threat values. The model is modular and enables other descriptions of the weapon ranges and threat evaluation processes to be incorporated in order to describe different doctrines or to increase the realism in the model if necessary. Future work includes discussing the model with domain experts to assess their opinions of its usefulness as well as its transparency. The model should also be analyzed further, for instance regarding its sensitivity to uncertainty regarding the locations of the enemy’s assets, sensors and weapons.

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