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Automatic evaluation of air mission routes with respect to combat survival

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ABSTRACT

Aircraft flying in hostile environments are exposed to ground-based air defense systems. It is not always possible to both accomplish the mission and fly outside the range of the enemy's weapon systems, especially if the positions of the enemy's systems are not perfectly known. Automatic evaluation of mission routes from a combat survival perspective could therefore aid the pilots to plan their missions. When updated information regarding the positions and capabilities of the enemy's systems is received during flight, the route could be re-evaluated and the mission could be re-planed or aborted if it is assessed to be too dangerous.

The survivability model presented here describes the relation between the aircraft and the enemy's defense systems. It calculates the probabilities that the aircraft is in certain modes along the route, e.g., undetected, tracked or hit. Contrary to previous work, the model is able to capture that the enemy's systems can communicate and that the enemy must track the aircraft before firing a weapon. The survivability model is used to calculate an expected cost for the mission route. The expected cost has the attractive properties of summarizing the route into a single value and is able to take the pilot's risk attitude for the mission into account. The evaluation of the route is influenced by uncertainty regarding the locations of the enemy's sensors and weapons. Monte Carlo simulations are used to capture this uncertainty by calculating the mean and standard deviation for the expected cost. These two parameters give the pilots an assessment of the danger associated with the route as well as the reliability of this assessment. The paper concludes that evaluating routes with the survivability model and the expected cost could aid the pilots to plan and execute their missions.

1. Introduction

A fighter pilot flying a mission inside hostile territory is exposed to the enemy's ground-based air defense systems. The best way of surviving the mission is to fly outside the enemy's weapon ranges. However, this is not always possible. First of all, the enemy locates weapons to protect their valuable assets and hinder the fighter aircraft to reach them. The pilot therefore needs to balance the objectives of flying the aircraft in a safe way, accomplishing the mission and combat survival, i.e., flying the route unharmed [1]. Secondly, information regarding the enemy's sensors and weapons is often uncertain, since the enemy camouflages its systems and relocates them frequently. Even though the pilot plans the route with the best available intelligence information, the situation might have changed when the mission is flown. The pilot therefore needs to analyze the situation when new information is received and re-plan or abort the mission if the situation is too dangerous [2]. The purpose of this work is to suggest a method for automatic evaluation of mission routes from a combat survival perspective. This can be used for planning the mission by comparing several possible routes and selecting the least dangerous one. During flight, it could aid the pilot to re-evaluate the route when updated information regarding the enemy systems is received.

The enemy's air defense systems consist of both sensors and weapons system [3], which are potential threats to the aircraft and should be avoided if possible. The danger posed by the enemy's defense systems depends on the enemy's capabilities and intentions to harm the aircraft. Furthermore, the enemy's opportunities to detect and hit the aircraft depend on the aircraft's position as well as the previous part of the route. For instance, if the aircraft has flown inside the range of the enemy's sensors for a long period of time when it enters a weapon area, the risk that the enemy fires a weapon against it is high. On the other hand, if the aircraft can enter the weapon area undetected, the survivability, i.e., the probability of flying the mission unharmed, is higher. The evaluation of the route is further complicated by the fact that information regarding the enemy's capabilities, positions and intentions are

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typically held secret and therefore needs to be estimated based on intelligence information and sensor data. This information is therefore uncertain and the evaluation of the routes needs to take this uncertainty into account. Hence, for assessing the survivability for a mission, information regarding the enemy's capabilities and positions should be fused with information regarding the history as well as the future of the mission route. This corresponds to Level 3, Threat Assessment, in the JDL model, since the aim is to predict the enemy's intentions, capabilities and future opportunities to harm the aircraft [4,5].

1.1. Related work

Models for describing the risk or danger associated with flying a route have been suggested in the literature regarding decision support for fighter pilots and operators of unmanned aerial vehicles (UAVs) as well as in the literature for route planning in hostile environment. The most straightforward approach is to consider the enemy's defense systems as no-fly zones that should be avoided [6,7] or to minimize the time inside these zones [8]. However, when the mission requires that the aircraft flies near the enemy's systems, there is a need for more complex models for determining where to fly. More advanced approaches focus on how the aircraft can use the terrain to hide and describe the time the aircraft is visible for enemy sensors [2,9]. Inspired by the radar equation, the danger associated with a part of the route passing near a radar station has been described as proportional to $\frac{1}{d^4}$, where d is the distance to the radar, see e.g., [10–13].

The approaches above all used deterministic descriptions of the relation between the aircraft and the enemy's systems. However, the information regarding the enemy's intentions and capabilities are typically uncertain and several probabilistic modeling approaches have therefore been suggested. Berger et al. [14] calculated the probability of flying a route unharmed and Pfeiffer et al. [15] calculated the probability that a UAV could fly a route undetected or detected at most k times. Detection could either be interpreted as a fatal attack, in which case no detection is desirable, or as detection by enemy sensors, in which case $k > 1$ can be acceptable. Kim and Hespanha [16] presented a similar model, which described the probability that a group of UAVs could fly a route undetected given their use of radar jamming. Kabamba et al. [17] argued that the UAV must be tracked by radar for some time before a weapon can be fired and also during the time it takes for the missile to reach the UAV. They therefore modeled the probability that the enemy radar is able to continuously track a UAV during a sufficiently long period of time. Other references have focused on the enemy's weapons and the risk of getting hit. Dogan [18] utilized a probability density function for describing the probability that the aircraft would get hit at a position. Randleff [19] suggested a similar approach where each position was associated with a threat lethality affected by the pilot's use of countermeasures. More detailed models have also been proposed. Ögren and Winstrand [20] used simulations with surface-to-air missile models. Theunissen et al. [2] suggested a weapon state diagram for calculating the probability that a weapon hits the aircraft by identifying the underlying events and their probabilities.

The enemy possesses both sensors and weapons and they are all potential threats to the aircraft and affect its chances of flying the mission unharmed. It is therefore suitable with models that consider both the probability of detection and the probability of getting hit. Xinzeng et al. [21]and Besada-Portas et al. [22] suggested probabilistic models for radar and weapon systems, but handled these threats as independent. On the other hand, several references have described the risk at a position as the combination of the probability that the aircraft is tracked and the conditional probability that the aircraft gets hit if it is tracked, see [23–25]. It is assumed that these probabilities at one position are independent of where the aircraft has previously flown. This approach can be suitable if each sensor is co-located with a weapon and the different sensors are assumed to work independently. However, in an integrated air defense system, several sensors are searching the airspace and share information with each other and with the weapon systems, which not necessarily have the same range as the sensors. Furthermore, as commented above, the aircraft must be tracked by radar for some time before a weapon can be fired. The probability that the aircraft will get hit inside the range of the weapon therefore depends on how long time it has previously flown within the range of the sensors. The references identified in the literature review are not able to capture this dependency, but the model suggested in this paper has been developed to allow for this.

The literature reveals different approaches for handling uncertainty regarding the positions of the enemy's systems. A straight forward approach is to ignore the uncertainty and assume that the position are known, see e.g., [17,22]. Another approach is to construct a probability map, where each position on the map is associated with the probability that an enemy system occurs at that position. The probability map can either be assumed to be known, see e.g., [14,19] or constructed based on surveillance information see e.g., [24,25]. Yet another approach was used in [23], where the threats' positions were regarded as random variables with known distributions. These distributions were used for calculating the corresponding distribution of the survivability of the route. This latter approach will be utilized also in this paper, since it has the nice property of separating the uncertainty that is associated with the capability and intents of the enemy and the uncertainty that stems from the locations.

1.2. Problem formulation and contributions

Automatic evaluation of routes from a combat survival perspective requires a model of how the enemy's systems affect the aircraft opportunities to fly the route unharmed. Discussions with domain experts reported in [26] resulted in the following assumptions regarding the enemy's systems.

- The enemy has access to both sensors and weapons, which are not necessarily co-located.
- The enemy's system can share information.
- The aircraft must be tracked during some time before a weapon can be fired.
- The aircraft is much faster than the enemy's systems and these can therefore be modeled as stationary.

Contrary to the models identified in the literature review, the survivability model presented here incorporates all these assumptions. It explicitly describes both the probability of getting tracked by the enemy's sensors and the probability of getting hit by the enemy's weapon as well as the relation between these events. An initial implementation of the model was presented in [27,28]. This paper extends the model and the analysis of its usage by:

- Extending the model to handle the case when the sensor and weapon system are located such that their ranges overlap, see Section 2.
- Introducing and analyzing a method for evaluating routes based on the survivability model, see Section 3.1.
- Analyzing and incorporating the influence of position uncertainty regarding the enemy's systems in the evaluation of the route, see Section 3.2.