Limitations of Subliminal Control in Air Traffic Management

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***Abstract*—An air traffic control concept under the name of *Subliminal Control* has been introduced. In this approach, an automated system, commanding minor speed adjustments imperceptible by the Air Traffic Controller, tries to keep the Air Traffic Controller's risk perception low, emulating a "lucky traffic". In this paper, we investigate the limits of this air traffic control approach. We test a proposed subliminal controller against several encounter geometries for level flights. A stochastic environment using wind forecast uncertainties is used for this purpose. The results demonstrate the cases where subliminal control can potentially reduce the workload of the ATC.**

I. INTRODUCTION

The current Air Traffic Management (ATM) system is to a large extent based on a rigidly structured airspace and a mostly human-operated system architecture [1], [2]. For the separation assurance between aircraft, Air Traffic Controllers (ATC) have to make decisions under a highly uncertain and complex environment. To do so, they have to estimate the future positions of aircraft and intervene whenever they perceive a high risk of loss of separation. It is obvious that the projected traffic increase [3], [4] demands an increase in the number of aircraft per sector. This will result in more stress on the ATC. To alleviate some of this workload, several potential solutions have been proposed, including conflict detection and resolution algorithms (for a thorough overview and classification of the literature, the reader is referred to [5]).

An alternative solution was proposed in [6] under the name *Subliminal Control*. The premise is that minor speed adjustments, commanded by an automated system running in parallel with the ATC, can convert a potentially conflicting situation into a "lucky traffic" for the ATC, in the sense, that the trajectories turn out to ensure safe separation at an early stage, reducing the ATC's monitoring workload. These speed adjustments have to be as small as possible in order to remain imperceptible by the ATC. In this approach the human is still kept in the loop, and automation is introduced in a user-friendly way. Crück and Lygeros in [7] presented a mathematical framework for subliminal control, while in [8], a hybrid dynamical game is proposed in which the control has to minimize a cost representing the risk perceived by air-traffic controllers despite the uncertainty of trajectory prediction.

In this paper, we investigate the limits of subliminal control method for Air Traffic Control. Subliminal control is tested against several conflict encounters under stochastic environment, due to the presence of wind forecast uncertainty.

The paper is organized as follows: Section II briefly introduces the subliminal control concept, Section III describes the modeling of the risk perception of the ATC, Section IV discusses the flight simulation model, Section V presents the simulations results of this study and Section VI states the conclusions of this work.

II. SUBLIMINAL CONTROL

The main idea of subliminal control is to turn ATC's uncertainty about traffic evolution into an advantage. It has been shown that small adjustments of speeds commanded early enough can prevent a large percentage of conflicts [9]. Here we consider speed resets small enough to be within the uncertainty margin of the ATC (and hence, in principle, imperceptible). Results from the experiments of the European project ERASMUS [10] indicate that speed variations up to 12% may go unnoticed by the ATC.

For the subliminal control concept, instead of detecting conflicts and then resolving them, the problem considered is:

1) Predict the risk the ATC will perceive in the near future, when faced with a given traffic situation.
2) Reduce (if necessary) the risk perception by applying unnoticeable speed changes.

The function we use to compute the risk perception is described in Section III. Given this function, we assume that the automated system can predict the traffic with sufficient accuracy for a time horizon significantly longer than the ATC's "prediction horizon", i.e. the time ahead the ATC can foresee a dangerous situation. Then the task of the system will be to minimize the risk perception along all possible set of aircraft trajectories.

It should be emphasized here, that in our subliminal control setting, the system consists of two separate models: the model of the ATC, representing the risk perception at each time step and the aircraft/environment model, which is used for an accurate trajectory prediction. Thus, the model of the ATC's risk perception is used for the computation of the cost and the

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aircraft/environment model for computing the control commands. Furthermore, the ATC's model introduces additional constraints for the maximum (in number and magnitude) speed change commands.

The system operates in a dynamic environment. Aircraft may enter or leave the sector of interest, deviate from their expected trajectory, etc. Due to the high uncertainties involved, it would be unrealistic to compute an optimal control valid for a very long time. Instead, we employ a receding horizon control approach, solving at each time step a finite horizon optimal control problem and re-compute a new optimal control law at each time step (or possibly whenever an event takes place, e.g. a probability of high risk perception is high).

III. RISK PERCEPTION OF THE ATC

The risk perception model we use is along the lines of the one proposed in [8]. The risk function for a given traffic situation is defined as:

$$V_{\text{ATC},n} : X_1 \times X_2 \times \cdots \times X_n \longrightarrow [0,7],$$

where X_i denotes the state of aircraft i and n is the total number of aircraft in the traffic situation. The range of values $[0,7]$ has been set in reference to the experimental setting in [11].

In the general situation of n aircraft, if a pair of them generates a high risk, then the whole situation will be perceived as a high risk situation. Of course, as the number of aircraft increases, the situation becomes more complex, influencing the risk perception of the ATC. Thus, we set for the risk function:

$$V_{\text{ATC},n}(X_1,\ldots,X_n) = \lambda(n) \max_{i,j,i\neq j} V_{\text{ATC},2}(X_i,X_j),$$

where $\lambda(n)$ is a complexity coefficient associated with a n-aircraft situation. Since there is very few relevant data available to validate this approach, we do not pursue this aspect any further and concentrate on pairwise risk perception $V_{\text{ATC},2}(X_i,X_j)$.

The risk function for 2 aircraft is defined for the planar case as follows [8]:

$$V_{\text{ATC},2}(X_1,X_2) = \frac{b}{\max\{\text{Sep}(X_1,X_2) + cT_{go}(X_1,X_2), d\Delta\}},$$

where $\text{Sep}(X_1,X_2)$ is the minimum separation between the aircraft that the ATC expects to happen in the worst case inside his prediction horizon. T_{go} is the time at which this minimum separation occurs, Δ is the minimum prescribed separation (for the situation to remain conflict free) and b,c,d are design parameters.

Since ATC do not have a very good perception of the speeds of the aircraft, we assume they extrapolate trajectories using constant estimated speeds $\hat{V}_1,\hat{V}_2$ and an uncertainty margin α. The model that we use to represent their trajectory prediction process is

$$(S_{\text{ATC}}) \qquad \begin{cases} \dot{x}_1(t) & \in & (1+[-\alpha,\alpha])\hat{V}_1 \\ \dot{x}_2(t) & \in & (1+[-\alpha,\alpha])\hat{V}_2 \end{cases} \tag{1}$$

with initial conditions $x_1(0), x_2(0)$ (the current aircraft positions).

IV. AIRCRAFT/FLIGHT ENVIRONMENT MODEL

We use the model developed in [12] to perform the simulations. This model allows one to capture multiple flights taking place at the same time. Each flight has an associated flight plan, aircraft dynamics and a Flight Management System (FMS). The evolution of flights is affected by the wind speed. The wind speed is modeled as a sum of a nominal and a stochastic part. The stochastic component is assumed to be correlated in time and space, i.e.the wind experienced by each aircraft at a given time is correlated to the wind experienced by all other aircraft at the same time and the wind experienced by all aircraft at earlier times [13]. The authors have shown in [14] that ignoring this correlation structure can result in high conflict probability estimation errors, when simulating more than one aircraft. Therefore, the evolutions of different flights are coupled to one another through the wind model.

The model is stochastic (because of the wind uncertainty) and hybrid, since it comprises both continuous and discrete dynamics; the former arise from the aircraft's physical motion, while the latter from the flight plans and the FMS.

A. Aircraft dynamics

The aircraft is modeled using a Point Mass Model (PMM), based on the Base of Aircraft Data (BADA) database [15]. The continuous dynamics for the aircraft motion are extensively described in [12]. Apart from the continuous dynamics, discrete dynamics also arise in our model, mainly because of the FMS and the flight plan.

The flight plan consists of a sequence of way-points $\{O(i)\}_{i=0}^{M}$, in three dimensions, $O(i) \in \mathbb{R}^3$. The sequence of the way-points defines a sequence of straight lines joining each way-point to the next. In our experiments, Requested Time of Arrival (RTA) for each way point is not implemented. As a result, the aircraft only corrects cross track deviations from the reference path, while along track errors are ignored. This assumption reflects what is known as a 3D FMS, which is is currently the standard for most commercial aircraft.

The FMS can be thought of as a controller, which, by measuring the state and using it together with the flight plan, determines the values for the inputs. The control is to some extent continuous, but some parameters and set points of the controllers depend on the discrete dynamics of the FMS [12].

B. Stochastic environment

The stochasticity of our model arises because of uncertainty about the wind velocity. The wind velocity is modeled as a sum of two terms: a deterministic (nominal) component, representing the meteorological predictions available to ATC and a stochastic component, representing inaccuracy and uncertainty in these predictions. Since the meteorological predictions are known and available to the ATC before a flight takes place, the flight plans are adjusted taking them into consideration. Thus, the way the nominal wind affects aircraft trajectories is deterministic and known a priori. For simplicity reasons, we set the deterministic part of the wind to zero.

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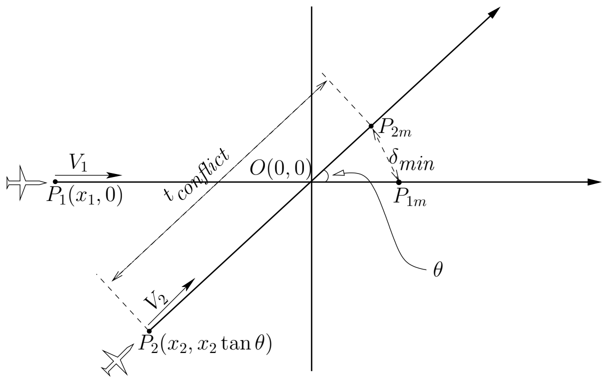

Fig. 1. Conflict scenario

The stochastic wind component is modeled as a random field $w : \mathbb{R} \times \mathbb{R}^3 \to \mathbb{R}^3$, where $w(t, P)$ represents the wind at point $P \in \mathbb{R}^3$ and at time $t \in \mathbb{R}$. We assume that $w(t, P)$ is a Gaussian random variable with zero mean. Recall that the wind experienced by each aircraft at a given time is correlated to the wind experienced by all other aircraft at the same time and the wind experienced by all aircraft at earlier times [13]. As discussed in [14], [16], this correlation structure cannot be ignored for accuracy reasons when simulating more than one aircraft. A detailed procedure for extracting wind samples with given spatio-temporal correlation can be found in [12].

V. SIMULATION RESULTS

Since subliminal control involves only speed alterations for the conflicting aircraft, it is reasonable to restrict ourselves in level flight scenarios. We consider two aircraft flying level at the same altitude, in straight lines, at constant airspeeds (see Fig. 1) without applying subliminal control. In the absence of a wind field, the minimum distance the two aircraft approach each other is denoted δ_{min} and the time this event occurs $t_{conflict}$ (time to minimum separation).

We construct flight plans to code this encounter geometry that intersect at $O(0, 0)$. $P_1(t) = (x_1(t), 0)$ and $P_2(t) = (x_2(t), x_2(t) \tan\theta)$ denote the positions of the aircraft at time t. For the simulation purposes, we use the nominal speed for an Airbus 321 cruising at 33000ft, which is 454knots [15].

We use four different values for the minimum separation δ_{min}: 0nm (where a mid-air collision would happen), 5nm, 10nm and 15nm. Three different crossing angles $\theta = (45°, 90°, 135°)$ and 25 different values for nominal time to minimum separation $t_{conflict} = (1, 2, \ldots, 25 \text{ minutes})$ are considered. Even though nominally the aircraft would follow exactly their flight plans, uncertainty in aircraft motion forces them to a different minimum separation at a different time.

Concerning the risk perception model, we use $\alpha = 0.1$, $b = 49$, $c = 0$, $d = 1.4$ and $\Delta = 5$nm. All distances are expresses in nautical miles. For prediction horizon, we assume that the ATC can predict up to 8 minutes ahead. We then say we have a *high risk* situation if $V_{\text{ATC},2}(X_1, X_2) = 7$, a *medium risk* situation if $3.5 \leq V_{\text{ATC},2}(X_1, X_2) < 7$, and a *low risk* situation otherwise.

To investigate the limits of the subliminal control, in all simulations, we apply the maximum speed change not perceived by the ATC (i.e. -12% or +6%) as early as possible (i.e. in the beginning of the simulation). Thus, we will try to determine how soon before an incident a speed change command has to be sent to the FMS of the aircraft. The aircraft FMS is assumed to immediately accept and implement the command. Since our system is stochastic, we perform Monte Carlo simulations to estimate the risk perceived by the ATC and the conflict probability of the aircraft by performing 1000 simulations and computing the fraction of them that enters conflict. By the term conflict we define a situation where two aircraft violate required minimum separation standards, in our case 5nm.

A. Simulations for $\delta_{min} = 0$nm

Simulation results are shown in Figures 2-5. Figure 2 shows the probability of conflict for the three different crossing angles as a function of the time to minimum separation $t_{conflict}$. Solid lines correspond to $\theta = 45°$, dotted lines to $\theta = 90°$ and dashed lines to $\theta = 135°$. The simulations where no speed changes are sent to the aircraft are plotted with blue color, while red color corresponds to speed change sent to only one aircraft and the simulations with speed clearances sent to both aircraft are plotted in green. One can observe that subliminal control is a good technique to solve potential conflicts up to 15 minutes before the time they would appear, sending speed clearances to both aircraft.

Figures 3-5 show the levels of the perceived risk of the ATC for the three crossing angles. Solid lines correspond to a high risk perception by the ATC (i.e. cases when the ATC would issue a conflict resolution command), dotted lines correspond to a medium risk perception (i.e. cases when the ATC would monitor the situation closely, waiting to see if it evolves into a high risk or a low risk situation) and dashed lines correspond to low risk situations (i.e. cases when the ATC would not expect the situation to evolve into an unsafe one). We observe that even though no conflict actually occurs, the risk perception of the ATC is low only in the case of $\theta = 45°$ and if the the subliminal controller issues speed clearance commands to both aircraft 25 minutes ahead of the expected time of the conflict. In all other cases, ATC's risk perception cannot be kept low applying subliminal control.

B. Simulations for $\delta_{min} = 5$nm

Figures 6-9 illustrate the results for the simulations. This time, the conflict resolution can be easily handled by the subliminal controller, as changing the speed of only one aircraft is enough to resolve any conflict, even if the speed command is issued as late as only a minute before the conflict. The algorithm though is unable to keep the ATC confident that the traffic will not evolve into a conflict, unless the speed change command is issued (to both aircraft) no later than 23 minutes before the expected time of minimum separation. Thus, no flexibility for optimization between different possible solutions of the subliminal controller is left, since the controller has to

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command the largest speed changes that are allowed to both aircraft.

C. Simulations for $\delta_{min} = 10$nm

This case is quite different from the previous ones, since the nominal minimum distance between the aircraft is adequate to almost ensure that no conflict will occur except for the case when aircraft are very far away and the remaining uncertainty is big (Figure 10). As expected, subliminal control guarantees in this case, too, no conflict between the aircraft. Figures 11-13 show that if a speed adjustment is sent to both aircraft at least 17 minutes before the expected occurrence of the minimum separation, the ATC will not perceive the situation as potentially dangerous. It is still required for both aircraft to adjust their speeds accordingly to avoid a medium risk situation, that would keep the ATC busy monitoring the situation, but on the other hand, an early enough decision can leave a small window for optimization depending on each aircraft's priorities (i.e. small speed adjustment vs. late speed adjustment).

D. Simulations for $\delta_{min} = 15$nm

As in the previous case, conflict avoidance is ensured in all cases, even when no speed control is applied to the aircraft (see Figure 14). This is not the case for the risk perception of the ATC though (see Figures 15-17), since a high risk perception is only avoided when the expected time to minimum separation is 5 minutes or less, which reduces the ATC uncertainty window. The risk perception can be kept low however, even by applying only one speed change, provided that it is applied around 17 minutes ahead of the expected time of the minimum separation. If both aircraft adjust their speeds, the commands can be issued just 8 minutes before the expected time of the minimum separation, leaving a big margin for an optimization depending on the aircraft's priorities.

VI. CONCLUSIONS

We have investigated the potential of the use of subliminal control to alleviate ATC's workload and monitoring of some potentially dangerous encounters. The results clearly indicate that, depending on the geometry, subliminal control can reduce the workload of the ATCs monitoring situations. Those can instead be solved early enough with minor speed adjustments, keeping the risk perception low. In all cases, care needs to be taken to ensure maneuvers remain subliminal. The accuracy of the trajectory prediction tools is also important, since more accurate tools would allow the application of subliminal control over longer horizons. As envisioned by the ERASMUS concept [10], a potential solution for this could be air-based trajectory prediction tool, that avoids radar measurement errors, and down-links the information to the ATC.

ACKNOWLEDGMENTS

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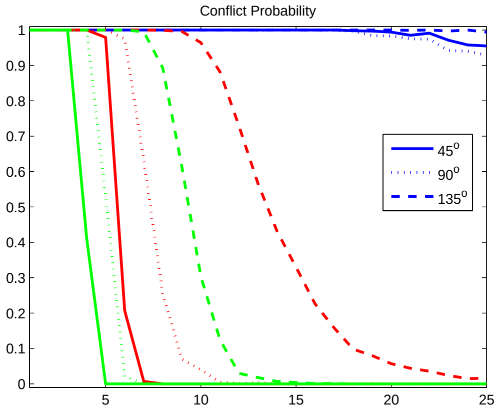

Fig. 2. Conflict Probability for $\delta_{min} = 0$nm

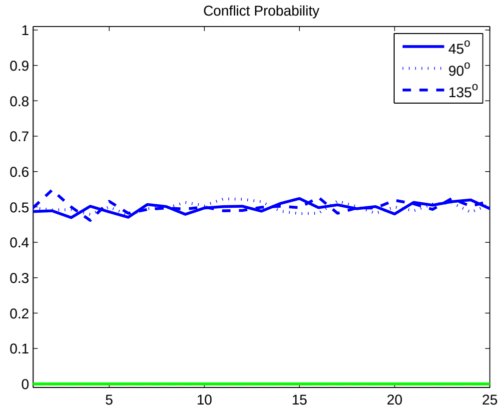

Fig. 6. Conflict Probability for $\delta_{min} = 5$nm

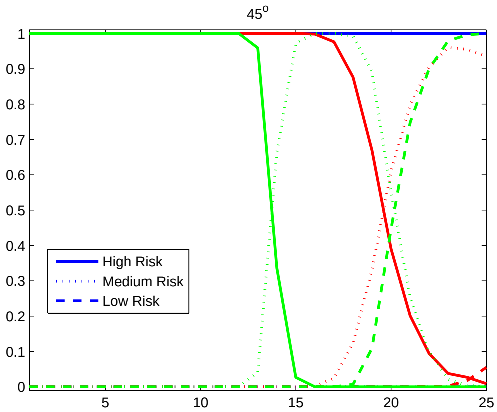

Fig. 3. Risk perceived by the ATC for $\theta = 45°$

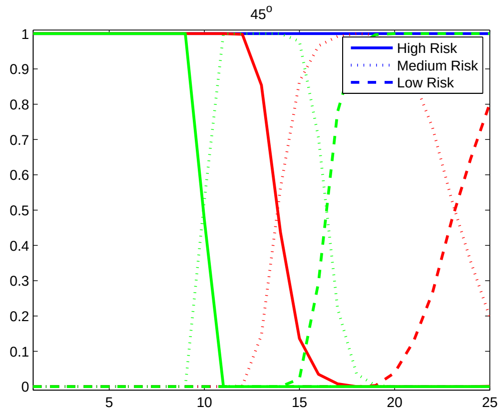

Fig. 7. Risk perceived by the ATC for $\theta = 45°$

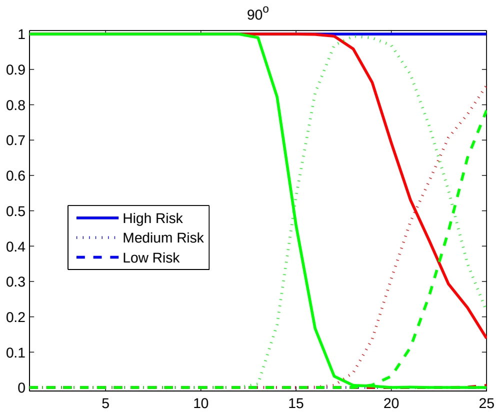

Fig. 4. Risk perceived by the ATC for $\theta = 90°$

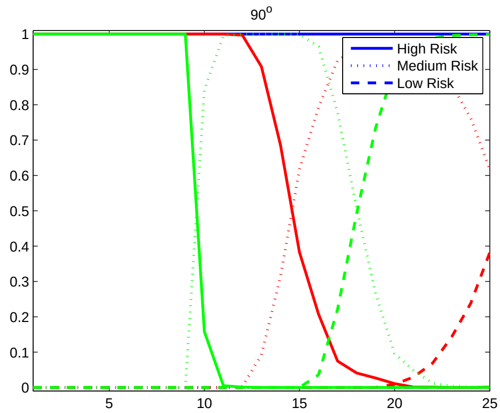

Fig. 8. Risk perceived by the ATC for $\theta = 90°$

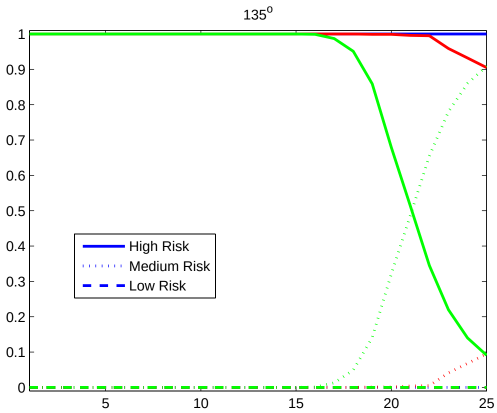

Fig. 5. Risk perceived by the ATC for $\theta = 135°$

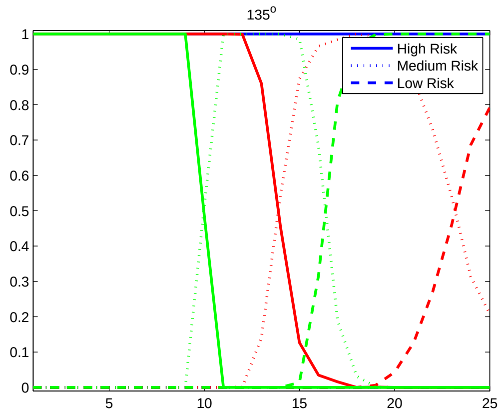

Fig. 9. Risk perceived by the ATC for $\theta = 135°$

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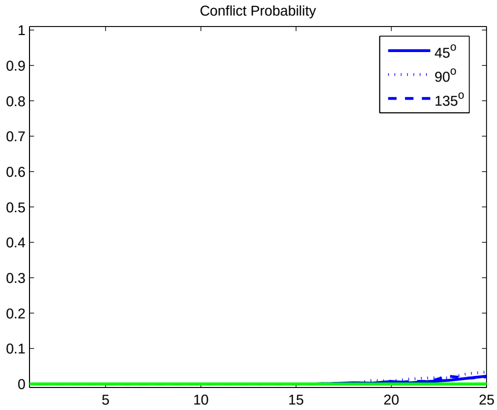

Fig. 10. Conflict Probability for $\delta_{min} = 10$nm

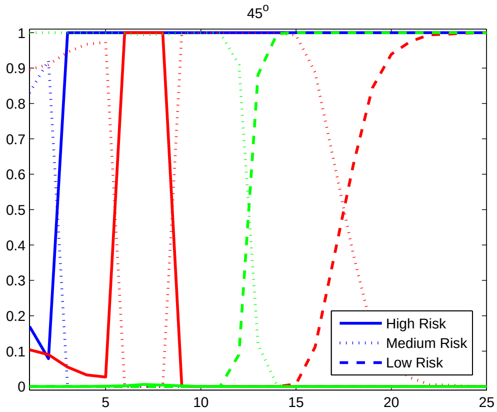

Fig. 11. Risk perceived by the ATC for $\theta = 45°$

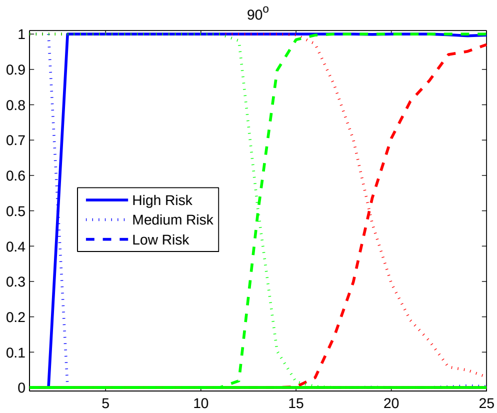

Fig. 12. Risk perceived by the ATC for $\theta = 90°$

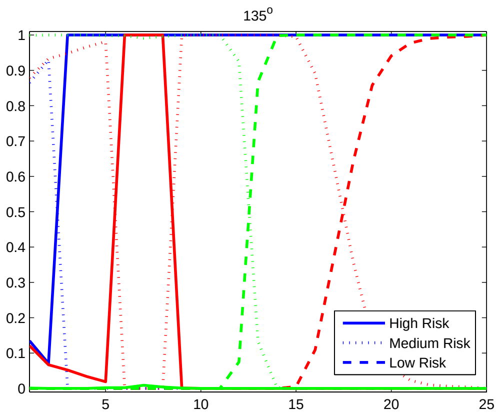

Fig. 13. Risk perceived by the ATC for $\theta = 135°$

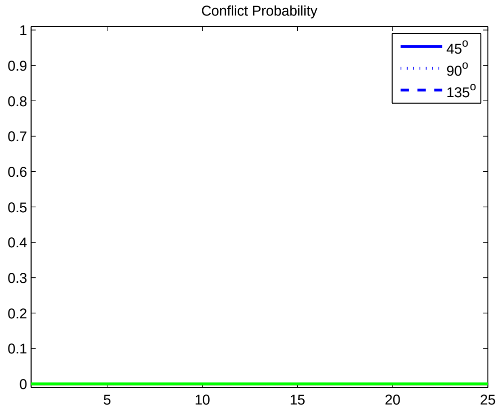

Fig. 14. Conflict Probability for $\delta_{min} = 15$nm

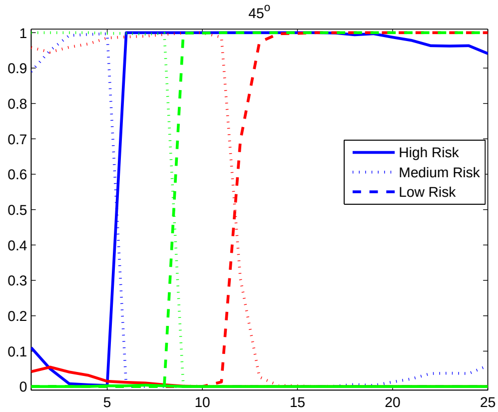

Fig. 15. Risk perceived by the ATC for $\theta = 45°$

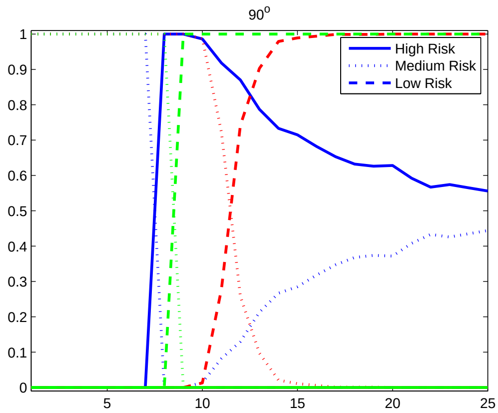

Fig. 16. Risk perceived by the ATC for $\theta = 90°$

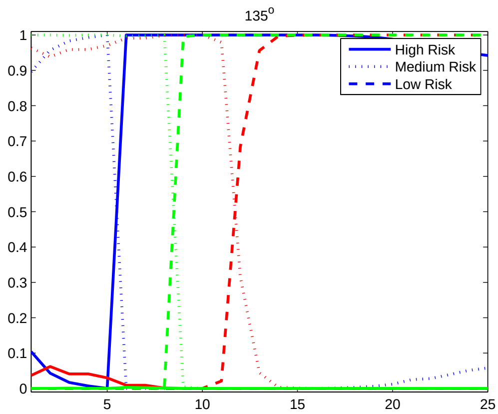

Fig. 17. Risk perceived by the ATC for $\theta = 135°$

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