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On maximizing safety in stochastic aircraft trajectory planning with uncertain thunderstorm development

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ABSTRACT

Dealing with meteorological uncertainty poses a major challenge in air traffic management (ATM). Convective weather (commonly referred to as storms or thunderstorms) in particular represents a significant safety hazard that is responsible for one quarter of weather-related ATM delays in the US. With commercial air traffic on the rise and the risk of potentially critical capacity bottlenecks looming, it is vital that future trajectory planning tools are able to account for meteorological uncertainty. We propose an approach to model the uncertainty inherent to forecasts of convective weather regions using statistical analysis of state-of-the-art forecast data. The developed stochastic storm model is tailored for use in an optimal control algorithm that maximizes the probability of reaching a waypoint while avoiding hazardous storm regions. Both the aircraft and the thunderstorms are modeled stochastically. The performance of the approach is illustrated and validated through simulated case studies based on recent nowcast data and storm observations.

1. Introduction

A challenging aspect of tactical aircraft trajectory planning[1] is the avoidance of hazardous convective weather regions, more commonly referred to as storms or thunderstorms.[2] The inherently uncertain nature of thunderstorms causes major safety risks. Strong conflicting up- and downdrafts lead to heavy turbulence. Hail, severe icing and lightning can also inflict significant damage to aircraft equipment and windshields. In addition to increased safety risks, thunderstorms are also a leading cause of reduced time [16] and cost [15] efficiencies. From 2008 to 2013, inclement weather caused 69% of system-impacting delays (delays greater than 15 minutes), as recorded in the *OPSNET Standard "Delay by Cause" Reports*.[3] Within those weather delays, thunderstorms emerging from atmospheric instabilities were responsible for around 25%, turning them into the leading cause of flight delays in the US airspace.

Today, commonly used approaches to plan trajectories in the presence of thunderstorms are suboptimal and prone to human error. Thunderstorms are typically detected by satellite images or weather radar signals, which are processed into graphical images. The identified *thunderstorm cells* are then classified according to severity. Regions of airspace that are considered to pose a significant safety hazard are recommended as unsafe-to-fly regions to air traffic controllers (ATCO) and pilots [10].

In many cases these regions are avoided by manual trajectory modifications. This involves increased workload and potential loss of situational awareness for both ATCOs and pilots, jeopardizing safety and air traffic capacity.

One of the key concepts of future Air Traffic Management (ATM) systems is the so-called *trajectory-based operations* (TBO) described in the SESAR [3] or NextGen [6] ATM master plans. The TBO concept will give aircraft the autonomy to update their trajectories to satisfy business needs, such as fuel or flight time savings, or to avoid potential conflicts or hazardous weather regions. Robust planning that accounts for the uncertainty associated to aircraft motion and thunderstorm development is paramount for a successful transition to TBO.

In [13], the authors reported two years of operational testing of a tool coined *Dynamic Weather Routes* at American Airlines. The tool is a ground-based real-time trajectory automation system that continuously analyzes en-route aircraft. It computes simple correc-

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[1] By *tactical* we refer to 10 minutes to 1 hour prior to the potential hazard encounter.

[2] Throughout this paper we will use the more general term *thunderstorm* to describe convective weather regions.

[3] NextGen Weather – Weather Delays https://www.faa.gov/nextgen/programs/weather/faq/.

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tions to flight plans to avoid thunderstorms while ensuring conflict avoidance, respecting airspace constraints and minimizing delay. However, the tool neither accounts for weather uncertainty, nor does it use advanced control and optimization algorithms, thus leaving room for improvement in the system's efficiency, safety, and capacity.

The lack of probabilistic forecast data is one of the main bottlenecks in the development and full-scale deployment of automated trajectory planning tools that account for thunderstorm uncertainty. Today's state-of-the-art meteorological forecast products include current observations of the thunderstorm cells as well as predictions for their locations at discrete forecast horizons. A commonly used approach relies on deterministic short term forecasts, so-called nowcasts. They provide information on thunderstorm cell positions for up to a few hours ahead [22]. Examples for such nowcast systems include the satellite data-based cloud tracker Cb-TRAM (Cumulonimbus Tracking and Monitoring) [24]; and the radar-based Rad-TRAM (Radar Tracking and Monitoring), developed by Kober and Tafferner [9]. Nevertheless, these forecast products do not provide any uncertainty quantification.

The integration of stochastic information in meteorological forecast products has indeed proven difficult, mainly due to the short lifespan of convective phenomena (around 30 minutes) and an imperfect knowledge of the atmosphere at macroscopic scale. Recent efforts in this direction include, e.g., [14,18]. The former presented two statistical learning approaches that incorporate numerical weather prediction (NWP) input within satellite images to produce probabilistic forecasts. Osinski and Bouttier [18] presented an experimental product developed by Meteo-France. It combines the numerical weather prediction model AROME-NWC with simulated radar images and post-processing. An ensemble of time-lagged forecasts with thunderstorm development information is then produced. Besides these efforts in combining data-driven methods and NWP, pure data-driven methods can be also used to model uncertainties in forecast products through comparison of actual instances of thunderstorms and their predictions.

The authors in [19] investigated statistical properties of thunderstorm cells' growth and decay, as well as their scale dependence and predictability. They concluded that forecast accuracy of deterministic, radar-based nowcasts can be improved by the extrapolation of growth and decay for a few hours. In [20], the authors analyzed the error of radar-based nowcasts and their increasing uncertainty with time by determining spatial deviations of the nowcast predictions compared to the observed thunderstorm realizations. The authors argued that thunderstorm cells could be enlarged by an uncertainty margin that is dependent on the desired probability of avoiding the respective thunderstorm cell. In [1,23], the authors introduced a probabilistic analysis of weather forecasting. The analysis is based on ensemble weather forecasting data provided by the Center for Analysis and Prediction of Storm (CAPS) [7]. Additionally, Zhang et al. [23] presented a path planning algorithm to avoid the stochastic hazard, including a mission risk analysis. Nevertheless, additional efforts are needed in stochastic thunderstorm modeling and aircraft trajectory planning, e.g., considering the additional uncertainty introduced by the aircraft dynamic system.

Several methods to address aircraft path planning subject to uncertainties in system dynamics and obstacles (such as unsafe-to-fly regions) have been proposed. The problem of routing an aircraft to a target while avoiding uncertain hazardous weather zones in the presence of wind disturbance can be cast as the optimal control of a stochastic dynamic system through probabilistic obstacles, such as unsafe-to-fly regions. The following challenges arise: First, both the aircraft dynamics and the thunderstorm cells are nonlinear and non-convex. Second, the use of stochastic models is required, resulting in a theoretically and computationally challenging *stochastic optimal control* problem.

A possible approach is to bound the uncertain obstacles with deterministic sets. The authors in [11] presented a receding horizon control strategy for aircraft trajectory planning in environments with unknown but bounded disturbances. The authors in [8] proposed a receding horizon framework for designing safe aircraft trajectories. They took into account a dynamic weather forecast product to determine deterministic bounds for the thunderstorm regions to be avoided. While this set-bounded approach offers a high degree of safety, the solutions often degrade overall performance due to high conservatism arising from the protection against low probability uncertainty outliers. More importantly, the optimization problem can quickly become infeasible, for example in a scenario featuring a high number of obstacles. Such scenarios call for a solution that minimizes the risk of failure, instead of trying to eliminate it entirely. In [12], a stochastic optimal control framework for mid-air conflict resolution was presented that could incorporate uncertainties in both aircraft and wind dynamics. However, in the studied aircraft-weather conflict, the weather hazard was considered deterministic. In [17], the authors addressed the problem of generating aircraft trajectories using a Markov decision problem where the evolution of the thunderstorms was modeled as a Markov chain. The transition probabilities were extracted from historical data using maximum-likelihood estimators. However, these probabilities were assumed stationary. Moreover, delay was used as the objective to be minimized. Given the uncertainties in thunderstorm development, an important objective is to minimize the probability of intersecting a hazardous weather region.

A suitable approach to generate trajectories that reach a target set while minimizing the probability of intersecting probabilistic unsafe-to-fly regions is to formulate a *stochastic reach-avoid problem*. The authors in [21] considered a stochastic reach-avoid problem with a time-varying stochastic obstacle set. The problem was reformulated as a finite horizon stochastic optimal control problem and solved with Bellman's Dynamic Programming principle. We proposed this method as a feasible approach to aircraft trajectory planning in the presence of a single hypothetical thunderstorm, modeled by a stochastic ellipse [4]. However, in this preliminary study, we assumed a priori knowledge of the stochastic unsafe-to-fly regions. No forecast data was incorporated to define stochastic unsafe-to-fly regions. Furthermore, the approach did not address trajectory planning in the presence of multiple thunderstorm regions.

The contribution of the paper is twofold: First, we propose a method for modeling thunderstorm in a stochastic manner. The method accounts for uncertainty in both the movement and, crucially, in the growth or decay of the thunderstorm cells. It is based on statistical analysis of historical nowcast data and its comparison with actual thunderstorm observations. Second, we combine the developed stochastic thunderstorm model with an optimal trajectory planning algorithm based on the stochastic reach-avoid methodology by Summers et al. [21]. The resulting aircraft trajectories maximize the probability of reaching a given waypoint while avoiding multiple thunderstorms, taking into account uncertainties in both the system dynamics (due to wind disturbance) and the unsafe-to-fly regions (due to uncertainties in nowcast data on thunderstorms). The resulting trajectories are validated against actual realizations of thunderstorms.

The paper is structured as follows: The proposed stochastic thunderstorm model derived from nowcast data is presented in Section 2. The stochastic reach-avoid framework, in which the aircraft trajectory generation is cast as a stochastic optimal control problem, is presented in Section 3. The trajectory planner, resulting from the integration of the stochastic thunderstorm model and

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