Dynamic Airspace Control via Spatial Network Morphing

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Abstract. In the coming years, a plethora of new and autonomous aircraft will fill the airspace, approaching a density similar to the ground traffic below. At the same time, human pilots that use the prevailing navigational tools and decision processes will continue to fly along flexible trajectories, now contending with inflexible non-human agents. As the density of the airspace increases, the number of potential conflicts also rises, leading to a possibly disastrous cascade effect that can fail even the most advanced tactical see-and-avoid algorithms. Any engineered solution that maintains safety in the airspace must satisfy both the computational requirements for effective airspace management as well as the political issue that human-pilots should maintain priority in the airspace. To this end, the research presented here expands on a concept of air traffic management called the *Lane-Based Approach* and describes a method for morphing the underlying spatial network to effectively deal with multiple potential conflicts. The spatial-network, which represents a model of the airspace occupied by autonomous aircraft, is mutated with respect to extrapolated human-piloted trajectories, leading to a real-world execution that modifies the trajectories of multiple vehicles at once. This reduces the number of pairwise deconfliction operations that must occur to maintain safe separation and reduces the possibility of a cascade effect. An experiment using real Automatic Dependent Surveillance–Broadcast (ADS-B) data, representing human-piloted aircraft trajectories, and simulated autonomous aircraft will demonstrate the proposed method.

Keywords: UAS Traffic Management · Tactical Deconfliction · DDDAS · Lane-Based Approach

1 Introduction

The problem of tactically deconflicting multiple flights and automating air traffic management fundamentally requires a dynamic data driven application system (DDDAS). Human air traffic controllers must fuse multiple data sources into a running model of the airspace before making critical decisions. What the Federal Aviation Administration's air traffic controller manual often refers to as "common sense" is actually a complex feedback loop involving multiple cyber-physical systems and sensors. This paper presents the case for this in terms of the fundamental problem of motion planning for multiple agents, which can quickly become intractable for both humans and machines. The experimental section will demonstrate how the proposed DDDAS system can cope with at least hundreds of conflicts, whereas the prevailing commercial tactical collision avoidance system has sparse evidence that it can deal with more than seven.

2 Background

The airspace represents an environment where multiple agents execute trajectories according to their mission goals and constraints. It is a dynamic and uncertain environment: with respect to any individual agent, other agents are essentially moving obstacles, and the perceived state-space is subject to a host of possible errors. Planning conflict-free trajectories for agents, represented as point objects (i.e., in configuration space) with constraints on its velocity, is provably NP-hard even when the moving obstacles are convex polygons with constant linear velocity [4, 8]. By including uncertainty in controls and perception, the motion-planning problem becomes non-deterministic exponential time hard [4]. In practical terms, the problem of generating a conflict-free trajectory has a worst-case time complexity that is at least exponential in the degrees-of-freedom (the union of all agent's degrees-of-freedom), and can easily become intractable for both humans and machines. For tactical deconfliction, generating new trajectories in response to unplanned conflicts during the execution of a mission, dynamic constraints add to an already non-holonomic system and increase the base of the exponential in the worst-case time complexity. The prevailing method for dealing with this complexity is by limiting the number of aircraft that have the potential for conflicts in a given area, either by requiring minimum separation of aircraft or maximum sector capacities [1]. Both methods functionally reduce the density of vehicles in the airspace and therefore reduce conflict probabilities. As the density of the airspace increases, the number of potential conflicts also increases and could lead to a cascading effect where the conflict resolution procedure produces further conflicts [6]. Other methods for reducing this complexity involve decomposing the problem into sub-problems that can then be distributed among agents, for example sequencing aircraft into a single corridor for landing and launching. This reduces the degrees of freedom that both air traffic controllers and pilots must consider individually, however without a complete structuring of, and sequencing throughout the airspace, cascading conflicts are still possible.

The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and the International Civil Aviation Organization (ICAO) have all advocated for the concept of *Strategic Deconfliction* for the next generation of air traffic control. The new paradigm assumes the density of the airspace will continue to increase, and with the introduction of Advanced Air Mobility (AAM) and autonomous vehicles of all sizes, the density could eventually rival that of ground-traffic. Among the strategies encompassed by strategic deconfliction, two methods include structuring the airspace, and/or requiring that all planned trajectories are deconflicted prior to executing a mission. The latter strategy removes or reduces the dynamic constraints associated with tactical deconfliction, however it does not guarantee that cascading conflicts are impossible because contending operations must still resolve conflicts in a virtual airspace. In previous works, the authors have described a *Lane-Based Approach* for an unmanned aircraft systems (UAS) traffic management system (UTM), whereby the airspace is structured as a spatial network, coupled with a simple and efficient deconfliction algorithm [9] (see [10] for a comparison of this approach with that currently proposed by the FAA and NASA). However, there will likely always be aircraft (human-piloted or otherwise) not subject to this kind of standardization, and therefore, tactical scenarios must still be considered.

The prevailing tactical deconfliction system required on all large passenger and cargo aircraft worldwide is the Traffic Alert and Collision Avoidance System (TCAS), and its forthcoming successor is the Airborne Collision Avoidance System X (ACAS X). TCAS receives telemetry from nearby aircraft once-per-second, tracking their slant range, altitude, and bearing to calculate the closest point of approach (CPA) and issue alerts to the pilot should they become a threat. Resolution advisories (RA) from TCAS recommend altitude adjustments to the flight trajectory, increasing the vertical separation between aircraft while minimizing the effect on the current trajectory [2]. Data describing scenarios where more than seven aircraft are in conflict at a time is sparse for (TCAS) [3], stemming from the fact that the airspace density has remained relatively low. Additionally, TCAS was designed for human-piloted aircraft that are assumed to be capable of achieving climb and descend rates of 1500ft/min and 2500ft/min respectively [7]. While TCAS has been considered for UAS given it's long track record (in particular, for the Global Hawk UAS [2]), the inflexibility of it's algorithms to adapt to aircraft with more limited climb and descend rates, or provide heading and airspeed guidance, limit it's applicability. ACAS X, on the other hand, is designed to be more flexible with support for global positioning system (GPS) data, small aircraft, and new sensor modalities [7]. ACAS X applies dynamic programming to a model of the airspace and collision problem formulated as a partially observable Markov decision process (POMDP) [7]. However, this formulation may still suffer from combinatorial explosions of possible trajectory states if multiple aircraft are involved. Many methods for planning multiple conflict-free trajectories exist, for example the two-phase decoupled approach [12] which first computes a path for each robot individually, then applies operations to the resulting path set to avoid collisions. The advantage of this approach is that the "search space explored by the decoupled planner has lower dimensionality than the joint configuration space explored by the centralized planner" [12]. However, the cascade effect is still prevalent since the local planners do not consider the global configuration of vehicles. Structuring the airspace can help mitigate this potential by reducing the dimensionality of the configuration space. In other words, agents can make assumptions about the probable trajectories of all aircraft.

3 Structured Airspace and Aircraft Trajectories

The Lane-Based approach reduces the dimensionality of the motion planning problem for individual agents by predefining all the possible trajectories through the airspace. It is then the agent's responsibility to select the "lanes" it must traverse to accomplish its mission, and reserve a time/space slot in those lanes. The lane vertexes represent waypoints, or control points, for a vehicle's actual trajectory. The vertical and lateral separation constraints between aircraft are managed by the lane network, while the longitudinal separation between aircraft (termed *headway*) is the responsibility of the individual agents. The cascade potential is reduced because a tactical resolution procedure need only consider the predefined paths of the lane system (effectively encapsulating multiple agents as a single "lane system") and perhaps a few aircraft that are unable or unwilling to follow the structure. The encapsulation is intended to enable system designers and regulators to control which aircraft are allowed to fly where, given their instrumentation and performance capabilities. To model the interaction between aircraft both inside and outside the structured airspace, we consider a generalized trajectory model formed from the interpolation of waypoints and time-of-arrivals (TOAs). The trajectories within the structured airspace are encapsulated by the lane-system, and can be treated as a single object with a reduced number of degrees-of-freedom. As conflicts arise between aircraft inside and outside of the lane-network, the conflict resolution procedure can effectively control multiple aircraft without the combinatorial explosion or cascading conflicts that would result in the same system without any airspace structure.

The generalized trajectory model considered here is a shape-preserving piecewise cubic interpolation of waypoints and time-of-arrivals. This type of interpolation uses a polynomial $P(x)$ with the following properties (from [13]):

- Each subinterval, $x_k \leq x \leq x_{k+1}$, is a cubic Hermite interpolating polynomial for the given waypoints and specified derivatives at the interpolation points.
- $P(x)$ interpolates the waypoints y such that $P(x_j) = y_j$, and the first derivative $\frac{dP}{dx}$ is continuous. The derivative may not be continuous at the control points.
- The slopes at the x_j are chosen in such a way that $P(x)$ preserves the shape of the data and respects monotonicity.

Figure 1 shows an example of this type of interpolation for a single aircraft traversing a lane system. This trajectory model was selected because there are readily available software implementations (e.g., the *waypointTrajectory* object in MATLAB) and its behavior under a range of constraints is appealing. Additionally, the homotopy equivalence class containing these trajectories enables many different constructions, for example, using wavefront and optimal control algorithms (see a survey of mathematical models for aircraft trajectories in [5]).

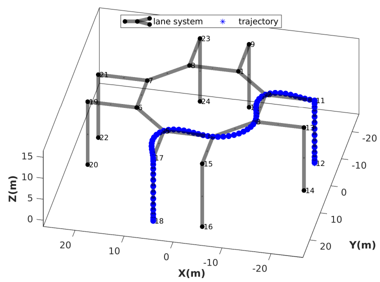

Fig. 1. Example trajectory interpolation performed over lane system vertexes.

4 A DDDAS Approach to Multiple Aircraft Deconfliction

A challenge for the automated air traffic management system proposed here is to efficiently address tactical conflicts (those that occur during the execution of missions) between aircraft using the structured lane-based airspace and those that are not. Tactical conflict resolution between aircraft within the lane system is described in [11]. To handle tactical conflicts, the proposed system vertically displaces the lane vertexes, analogous to the human-pilots vertical displacements initiated by TCAS advisories. To determine the required vertical displacement and climb/descend rates, sensor data (e.g., telemetry or radar) that describes the state of the airspace is fed into a simulated model of the airspace. The simulation has the capability of testing multiple scenarios before deciding on a control for the vertical displacement of the structured airspace. A diagram for the overarching dynamic data-driven application system (DDDAS) is shown in Figure 2.

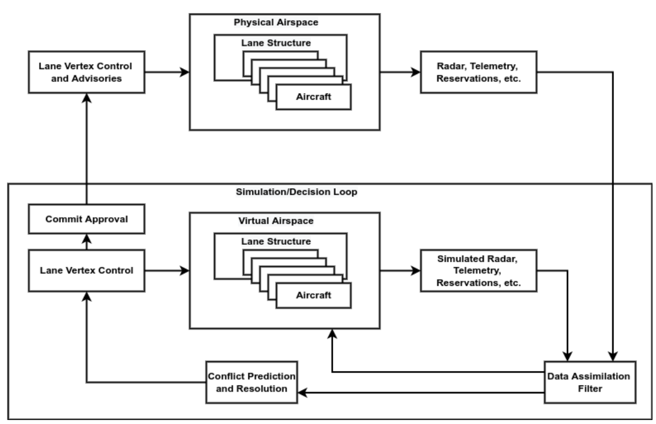

Fig. 2. Dynamic data driven application system with a feedback loop for lane vertex control.

5 Experiments

The foundation of the proposed DDDAS system is computational; many publications exploring the automation of air traffic management neglect the computational complexity of the motion planning problem and often begin with modeling vehicles or software architectures. This research instead begins with the problem of intractability and builds upon it an architecture that supports efficient deconfliction. However, the physical limitations of the agents are important to consider and therefore the experiment described here is designed to explore how those constraints can be considered within the framework proposed. To this end, a dataset was collected using an Automatic Dependent Surveillance–Broadcast (ADS-B) receiver placed atop one of the authors roofs in Salt Lake City, Utah, USA.

The particular implementation chosen here assumes a discrete proportional controller for the lane vertexes with a single parameter K and a sample rate of one second. A low-flying trajectory from the ADSB data was chosen as an example non-structured airspace flight for generating the conflict, shown in Figure 3 and in relation to the experimental lane system in Figure 4. Within the

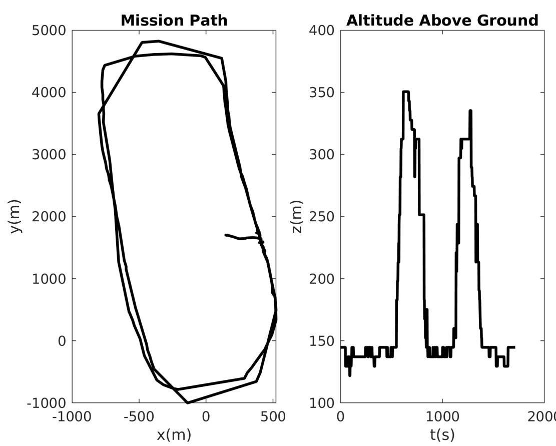

Fig. 3. Selected ADSB trajectory, translated to experiment position.

lane system 300 aircraft were scheduled using lane-based strategic deconfliction. Once the vehicles have begun executing their trajectories, they must traverse a spatial network that is morphing to direct traffic away from the threat posed by the intruder aircraft. The ADSB telemetry is used to create a shape-preserving piecewise cubic interpolation, and an estimate of the closest point of approach is used to inform a vertical displacement control input. Figure 5 shows a plot of the calculated closest-point-of-approach between the initial lane system (only a single node is chosen in this case) and the ADSB trajectory interpolation. The vehicles within the lane system recalculate their trajectories at each time-step

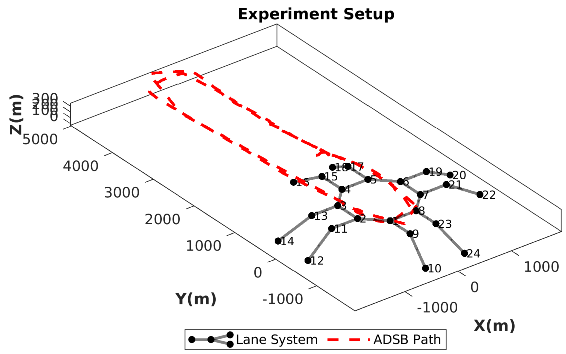

Fig. 4. Experiment setup showing conflict between lane system and ADSB path.

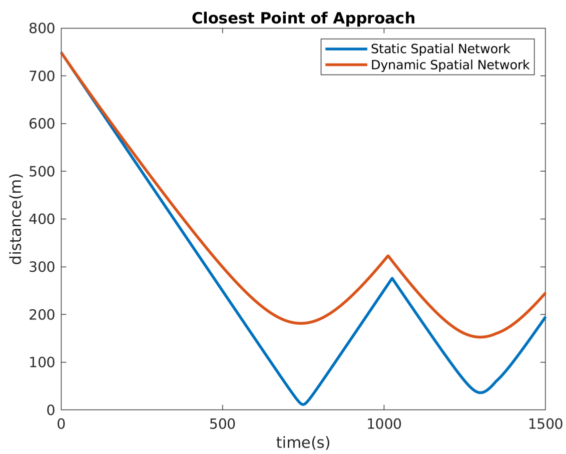

Fig. 5. Closest point of approach between lane system and ADSB trajectory (K=0.01).

when any of their trajectory waypoints is updated by the morphing process. These tactical updates result in changes to the originally planned climb/descent rates, which is a critical parameter to consider before applying the control to the physical system. Table 1 shows the maximum climb and minimum descent rate for each simulation trial.

Table 1. Climb rates for tested proportional control constants.

K	Max Climb Rate (ft/min)	Min Descend Rate (ft/min)
no control	374.253	-374.914
0.0001	374.253	-99.1532
0.001	374.253	-157.1
0.004	374.253	-216.575
0.01	374.253	-114.992
0.1	374.253	-88.4352

6 Conclusion

The computational complexity of coordinating multiple vehicles is one of the major reasons why air traffic control has yet to be automated. The proposed DDDAS system presented here provides a standardized way to resolve multiple conflicts by morphing the underlying spatial network of a lane-based system, and by simulating controls prior to execution in a physical system. Future research should continue to build on the structured airspace approach, adding more complexity to the physical models of aircraft and validating decisions before applying them.

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