A DDDAS Protocol for Real-Time Large-Scale UAS Flight Coordination

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Abstract. NASA engineers have published a number of system requirements in an effort to enable dense operations of unmanned aircraft systems (UAS) in urban environments [7, 8]. These requirements describe a free-flight model, where operators are afforded the maximum flexibility to design individually optimal trajectories, with the caveat that all operations must be strategically deconflicted prior to flight. Strategic deconfliction reduces the probability of having to perform tactical deconflicton using onboard sensors and real-time algorithms to avoid conflicts. Such approaches require a common protocol to guarantee that UAS do not collide, but do not scale well. Thus, UAS Service Suppliers (USS) must deconflict their planned trajectories pairwise prior to flight in order to achieve strategic deconfliction. We propose a communication-based protocol to coordinate airspace during flight. We present a dynamic distributed protocol for reactive conflict management that serves a similar purpose, albeit functioning at a time-horizon in between strategic deconfliction and sensor-based conflict management. This DDDAS inspired approach obviates the need for any centralized control by having each UAS maintain a model of its environment, and exploiting sensing and communication resources as dictated by the lane-based model.

Keywords: UAS Traffic Management · Tactical Deconfliction · DDDAS

1 Introduction

In a seminal article describing the purpose and scope of dynamic data-driven applications systems (DDDAS), Darema describes a motivating example where injecting experimental data into a long-running computation (informing oil exploration decisions) could be performed in an online manner to produce better results [3]. An *online* program in the DDDAS paradigm accepts data whenever it is available and could also inform the measurement process to improve system efficiency. The computational effort required to produce good decisions is also a motivating factor for the development of a DDDAS approach to traffic management described in this paper.

NASA and the FAA are making a concerted effort to develop an Unmanned Aircraft System (UAS) Traffic Management (UTM) system to enable large-scale

UAS exploitation in urban environments. The UTM is organized in terms of UAS operators who manage their flights through UAS Service Suppliers (USS). These service suppliers must declare the geographic region of their flights (in terms of 4D trajectories of space-time), and moreover, must strategically deconflict their flights pairwise with all other UAS flights in the region (we call this method *FAA-NASA Strategic Deconfliction* or FNSD). This can easily lead to quite complex path planning and coordination problems, and also requires USS to share data which would best be kept private. We have introduced a lane-based organizational structure for a UTM in which a set of lanes are defined (much like a ground road network), and then a USS simply reserves a sequence of lanes from takeoff site to destination site [5, 11]. In that work, we demonstrated a lane reservation system that efficiently guarantees strategic deconfliction, however that only applies to flights that have yet to be active in the airspace. Active flights experience a more dynamic situation, where contingencies (possible future events, usually causing problems or making further plans necessary) can occur.

Contingencies are communicated to agents in an online fashion, either by tactical avoidance sensors such as radar and sonar, or as information from authorities and other agents. Both sources can result in undesirable system responses, for example cascading effects due to high-density operations [6] and unstable control response due to the structure of the information flow [4]. We describe here the Lane Strategic Deconfliction algorithm (called LSD), and show that it has very low complexity, and allows for quite acceptable lane stream properties. Overall, contingencies that lead to a violation of safe separation represent the most critical element to consider in the design of a large-scale traffic management system. Safe separation requires agents to plan collision-free paths, which in the most general case of multiple-agent planning is PSPACE-hard. Even the more narrow problem of tuning velocity profiles is NP-hard [1].

In this paper we consider a lane-based airspace model that enables the propagation of contingency information in a well-defined manner. UAS plan locally in real-time within lanes, broadcasting contingencies (as deceleration events) to neighboring lanes that are likely to be effected. Unlike car-following models [9], information from a contingency can reach multiple agents at the same, yet enabling agents to react in a similarly predictable way. The theoretical contribution of this paper provides an efficient real-time algorithm for strategic deconfliction and applies a solution in terms of ground-delay (delaying access to the airspace network) or air-delay. The experimental section of this paper demonstrates the ability to resolve conflicts within a simulated environment.

1.1 Lane-Based UTM

A central issue concerning the DDDAS paradigm is the choice of model, and how information is represented, distributed, and consumed. The lane-based airspace structure is a model for the configuration of UAS in space and time and contrasts with other proposed models, such as the grid-based structure proposed by NASA. For example, in a grid model UAS share position information (through a USS as a proxy) within cells of a grid, and it is incumbent on USS to determine whether changes to trajectories could impact operations in neighboring cells. In other words, the flow of information between cells is not explicit in the model and represents a major point of uncertainty in the system. This contrasts to the lane-based approach, where impacts of trajectory changes (the dynamic data in this system) within a lane propagate in a well-defined manner throughout the lane network. The lane-based approach imposes a clear downstream and upstream direction to the information flow because lanes form a graph structure that mirrors the possible paths by UAS. The representation of trajectories in the lane-based approach is simple, as described below, and limits the amount of information that must be shared between aircraft to ensure safe separation. Finally, utilities can be defined in a straightforward way for both the UTM and UAS; e.g., the distance between all flights is important for the UTM, while maintaining desired speed and distance to destination characterize the utility of a configuration for a UAS.

Given a set of ground launch and land sites, a set of one-way lanes is defined which provides a path from any launch to any land site. A lane is a directed 3D vector with its tail as the entry point to the lane and its head as the exit point. A flight path is a sequence of lanes starting with a vertical launch lane and ending with a vertical land lane. A crucial constraint on lanes is that every vertex (entry or exit point) has either in-degree 1 or out-degree 1; this allows the deconfliction of flights by considering lanes as opposed to nodes in the network.

In order for two UAS to be safe, they must at no time be closer than some minimal Euclidean distance, called d_S. We assume that lanes are defined so that no two lanes have points closer than d_S unless the two lanes share an endpoint. Figure 1 shows the simple lane layout used in the set of experiments described below. There are 51 lanes, along with 10 launch lanes and 10 land lanes.

1.2 Contingencies

Both approaches (FNSD and LSD) are subject to the problem of contingencies when a UAS flight departs from its nominal plan (e.g., slows down, goes off course, etc.). Due to the complexity of the UTM system, predicting the effects of contingencies is a major impediment to the wide-spread integration of UAS into the urban airspace. The currently published protocol for mitigating many contingencies requires the UAS to try to return directly to its launch site [2]. However, this trajectory may not be strategically deconflicted and requires obstacle detection and avoidance along the way.

The lane-based model, together with the coordination protocol proposed in this paper, offer methods to mitigate such a contingency and also provides techniques to analyze the possible outcomes of different contingencies. The well-defined structure of lanes suggest that only a restricted set of contingency trajectories need to be considered, those that follow the lane structure and those that do not. For example, addressing contingencies where UAS must exit a lane could include designating emergency side lanes where a UAS can wait, or dynamic landing lane creation to go to the nearest safe landing site. In the case

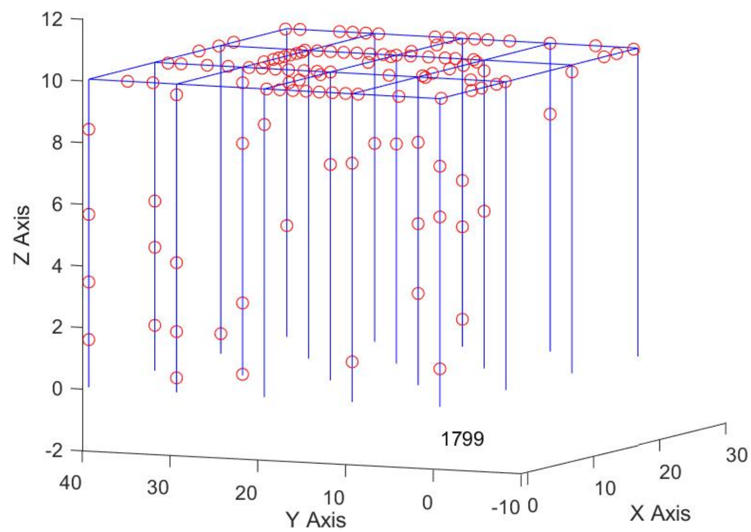

Fig. 1: Set of UAS on Airways during Discrete Event Simulation. Red dots represent UAS in Flight; blue lanes are launch lanes.

that the UAS can still follow lanes, the simulations demonstrated in the experimental section of this paper offer a method to understand the possible outcomes. In [11] an analysis of the impact of lane density on the delay of a requested lane reservation was shown to be an instance of a process of random space filling, sometimes referred to as Renyi's parking problem [10]. The lane-based structure imposes constraints on the network that make this analysis possible and could inform what a safe operating density for the UTM should be.

The proposed real-time tactical deconfliction method described in this paper simply modifies UAS speeds throughout the network in such a way as to avoid conflict. This method effectively absorbs contingencies when the UAS agent is still capable of following lanes. In the event of a contingency where a UAS cannot still follow lanes, the impact is minimized because non-contingent operations remain within the lane structure.

2 Real-Time Tactical Deconfliction

Each lane has a set of neighboring lanes with which it shares an endpoint. A flight in a given lane is tactically deconflicted if there is no point in its trajectory along the lane such that it is within distance d_S of any flight in a neighboring lane. This can be efficiently checked using the Closest Point of Approach (CPA) algorithm as follows. Let two lanes, $\mathcal{L}_1$ and $\mathcal{L}_2$, be defined by vectors $\bar{S}_1$ and

$\bar{S}_2$, where $\bar{S}_1 \equiv \overrightarrow{\bar{P}_1\bar{P}_2}$ and $\bar{S}_2 \equiv \overrightarrow{\bar{Q}_1\bar{Q}_2}$. The trajectories of flights f_1 and f_2 in lane $\mathcal{L}_1$ and $\mathcal{L}_2$, with velocities $\bar{v}$ and $\bar{w}$, are defined as $\bar{P}(t) = \bar{P}_1 + t\bar{v}$ and $\bar{Q}(t) = \bar{Q}_1 + t\bar{w}$. Since the velocities are $\bar{v} = \frac{s_1(\bar{P}_2 - \bar{P}_1)}{|\bar{P}_2 - \bar{P}_1|}$ and $\bar{w} = \frac{s_2(\bar{Q}_2 - \bar{Q}_1)}{|\bar{Q}_2 - \bar{Q}_1|}$, where s_1 and s_2 are the respective speeds of f_1 and f_2, then the time, t_{min}, when the two flights are closest in their trajectories is:

$$t_{min} = \frac{-(\bar{P}_1 - \bar{Q}_1) \cdot (\bar{v} - \bar{w})}{\mid \bar{v} - \bar{w} \mid^2}$$

If t_{min} is found for $t \in [t_{current}, t_{min\_TOA}]$, where t_{min_TOA} is the minimum time of arrival at the end of the lane for flights f_1 and f_2, then the minimum distance, d_{min}, between the flights across these intervals is just $\mid \bar{P}(t_{min}) - \bar{Q}(t_{min}) \mid$. If $d_{min} < d_S$, then a conflict exists between the two flights. Figure 2 illustrates the CPA method.

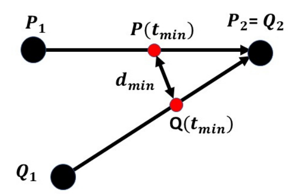

Fig. 2: CPA Algorithm: two flights at closest points $P_{t_{min}}$ and $Q_{t_{min}}$.

If a flight, f_1, has a conflict with flight f_2, then the two flights can be deconflicted as follows:

Deconflict_Pair

while conflict(f_1,f_2)
  reduce speed, s_1, of f_1
  if $s_1 < s_{min}$
  then flight f_1 fails

This allows the definition of the Closest Point of Approach Deconfliction (CPAD) algorithm:

Algorithm 1: Closest Point of Approach

∀ active flight, f
if f enters a new lane
  OR a neighboring flight has slowed
  OR f has reduced speed on its own
then call Deconflict_Pair for all flights in neighboring lanes
if f has reduced speed
then f broadcasts this information.

2.1 Approximate Global Deconfliction using CPAD

Global tactical deconfliction is achieved by having each UAS run the CPAD algorithm. CPAD does not guarantee strategic deconfliction (i.e., that no two flights get within distance d_S across the entire set of current flight plans), however, it does guarantee that no two flights are ever within distance d_S of each other at any time. The benefits of this approach include that that there is no centralized flight planning, no sharing of detailed flight info between USS, and robustness in the face of contingencies. The cost of the approach is that some flights may be forced to fail; however, this can be mitigated by choosing appropriate lane structure, controlling the number of flights, and eventually by dynamic flight route selection (currently the lane sequence is fixed). Certain communication requirements are imposed, however, the data shared between flights is essentially their telemetry data which the FAA-NASA UTM requires broadcasting anyway.

3 Experiments

A discrete event simulation is run which allows specification of the simulation time interval, $[0, t_{max}]$, and the number of flights, n_f. One unit distance corresponds to 50 feet, and one unit time corresponds to 10 seconds. Two maximum speeds are considered: 5 and 9, which correspond to about 17 and 30 mph, respectively. Each flight has randomly selected launch and land sites, as well as a random desired launch time. The desired speed is set to a max speed of 5 units distance per unit time. A fixed 3x4 grid of lanes at altitude 10 units are serviced by 10 launch lanes and 10 land lanes(see Figure 1).

When a flight plan is created for a flight, it consists of a sequence of lanes and for each a specific Time of Departure (TOD: departs entry point to lane) and Time of Arrival (TOA: arrives exit point of lane). The next event is just the flight with the earliest TOA in its current lane, unless it has not yet launched in which case it is the current launch time. The launch times of the flights are uniformly distributed across the simulation time interval. Note that if a flight cannot launch at its desired launch time due to conflicts in the launch lane, then it is rescheduled to a later time (with fixed delay). Once an event is selected, all flights are advanced according to their respective speeds in their current lanes. Next, the flights are deconflicted.

We consider two aspects for study: (1) maximum simulated time (set to 100 and 200 units), and (2) maximum UAS speed (set to 5 and 9 units distance per unit time). These correspond to about 17 and 33 minutes, and 17 and 31 mph, respectively. The number of flights is chosen to equal the maximum time since this represents on average one launch per launch site every 50 seconds. Given a max time, UAS max speed, and number of flights, the simulation is run using the CPAD algorithm. Table 1 gives the data for five representative runs, as well as the means. As can be seen, these results indicate that the CPAD algorithm works well in these scenarios with only one flight failure in all of the experiments (3000 flights overall). Moreover, the average speed is quite near the maximum allowed speed, and there are very few delays (68 out of 3000). The most critical

Table 1: Delays and Failures in Experimental Simulations

t_{max}	n_f	s_{max}	Wait	Fly	Done	Fail	Avg Speed	Delays
100	100	5	1	18	81	0	4.98	2
			2	12	86	0	4.98	2
			0	15	85	0	4.99	1
			0	11	89	0	4.98	2
			1	18	81	0	4.96	4
means			0.8	14.8	84.4	0	4.98	2.2
100	100	9	0	11	89	0	8.98	1
			1	8	91	0	8.94	2
			0	12	88	0	8.99	0
			0	6	94	0	8.99	0
			0	11	88	1	8.98	0
means			0.2	9.6	90	0.2	8.98	0.6
200	200	5	0	14	186	0	4.96	6
			0	11	189	0	4.97	8
			0	17	183	0	4.98	6
			1	13	186	0	4.99	10
			0	6	194	0	4.96	9
means			0.2	12.2	187.6	0	4.97	8.6
200	200	9	0	7	193	0	8.96	4
			1	6	193	0	8.97	2
			0	8	192	0	8.97	4
			0	7	193	0	8.98	3
			0	4	196	0	8.97	2
means			0.2	6.4	193.4	0	8.97	3

parameter for algorithm performance is the maximum speed of the UAS. Other trends revealed in the data include that the longer the time period, the more flights complete their mission, and the fewer flights are delayed or in the air (on average).

4 Conclusions and Future Work

The lane-based approach provides a viable model for large-scale urban air traffic, and CPAD closes the symbiotic DDDAS feedback loop to update the model based on measurements and communication as required by the model. The results here lay the foundation for a further study into the role of DDDAS in large-scale unmanned traffic management. System designers must consider the impact of airspace structure on information flow as well as the accessibility of the network (as measured in delay in this paper). This paper demonstrates the importance of considering the structure of the descretization of the configuration space and how a real-time dynamic flight deconfliction algorithm can operate under strong assumptions about the space/time structure of the environment. Future issues to be explored include: (1) a broader set of experiments will be run to study the role of the number of lanes, the distribution of flights over lanes, etc., as well as a sensitivity analysis of the experimental parameters, (2) flights are assigned a complete sequence of lanes in this study, but we intend to explore the application of the software defined networking paradigm to dynamically select the lane sequence, (3) the structural properties of the airway network also play a role in facilitating flight deconfliction, and those parameters will be studied, (4) experiments will be conducted on realistic airways scenarios; e.g., the Utah Department of Transportation is exploring the use of the lane-based approach in Utah, where the airways are located above roadways, and (5) CPAD imposes communication requirements on the aircraft, and this aspect will also be studied in terms of the likelihood of failure to communicate correctly and its impact on deconfliction.

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