On-Demand Virtual Highways for Dense UAS Operations

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Abstract

The methods and protocols for coordinating airspace access can impact a number of metrics that are important to operators and system designers. For example, the time when an operator would like to fly a particular trajectory may be delayed if there are many intersecting trajectories by other aircraft. From a system-level perspective, it would be helpful to know how the number of simultaneous operations affects this measure of delay. Regarding the method of coordination, it is also important to consider what information must be shared in order to provide safe access – it may be undesirable to share detailed trajectory information. This paper describes a method for building on-demand airspace networks and applies Lane-Based Strategic Deconfliction (LBSD) to support dense airspace operations.

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I. INTRODUCTION AND BACKGROUND

Currently, the most advanced method for coordinating dense airspace operations, under development in the first phase of NASA's Advanced Air Mobility (AAM) National Campaign, is distributed cell-based deconfliction [1], [2]. Under this method, proposed by designers of Urban Air Mobility (UAM) and small unmanned aircraft systems (sUAS) traffic management systems (UTM), Providers of Services for UAM (PSU) and UAS Service Suppliers (USS) are responsible for contacting other operators in the area, requesting their trajectories and designing conflict free trajectories. There are benefits to this approach: the computation for deconfliction is distributed among the PSU and operators, and the resulting paths are optimal with respect to the individual vehicles. However there are also some downsides that make it untenable for certain operational requirements. For example, in order for a PSU or operator to design a conflict-free trajectory prior to launch (termed *Strategic Deconfliction*), it must know the precise trajectories of other aircraft within a cell (predefined divisions of the airspace). This has both security and privacy implications, as complete trajectory information can reveal the intent of operations. A completely tactical method, whereby vehicles did not strategically deconflict prior to launch, would resolve this issue at the expense of safety and the possibility of cascading conflicts [3]. Another issue with this approach is that the information from contingencies, such as mechanical or communication failures, does not follow a uniform trajectory among the agents in the system. This again can result in cascading effects since decisions made by individuals across the system will inevitably be made with limited system observability (imagine all vehicles in an area having to replan simultaneously).

Structuring the airspace as virtual highways, coupled with the Lane-Based Approach to Strategic Deconfliction (LBSD) addresses the flaws in the cell-based (FAA/NASA) approach [4], [5], [6], [7]. LBSD eliminates the need for operators and PSUs to obtain detailed trajectory information from other operations in the area. Additionally, the lane system directs the flow of contingency information along their paths, and agents within the system can have a reasonable expectation of the decisions that other agents will make due to the enhanced system observability. On the other hand, the lane-based approach restricts the possible trajectories that are allowed in a given airspace, and a coordinated reservation database must be established (distributed coordination platforms such as Apache Zookeeper are still applicable).

We describe here methods for creating virtual highways over a given area on-demand, and a simulated operational scenario. The scenario envisions an earthquake disaster response in Salt Lake City, UT, a real prospect for the geologically active area. The goal of the designed system is to deliver water and food from designated depots to all nodes in an area. Figure 1 shows a sample of trajectories over a selected portion of the disaster area, over the University of Utah.

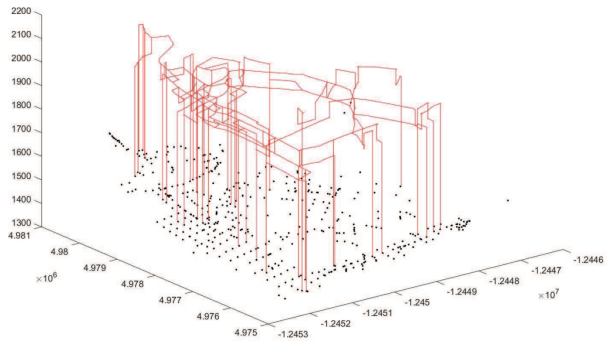

Fig. 1. Selected UAS Paths in a Lane Network over Salt Lake City, UT.

II. LANE CONSTRUCTION

Lanes compose a virtual highway network and are constructed with specific rules to best make use of Lane-Based Strategic Deconfliction. The FAA/NASA strategic deconfliction requirements do not specify the algorithm for generating

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a conflict-free trajectory, however the algorithm is explicitly defined for LBSD to ensure computational guarantees and enhanced system observability. To support on-demand lane-network creation, an algorithm was developed that takes an undirected two-dimensional graph and produces a three-dimensional system that is supported by LBSD (see Algorithm VERT2RA, which references Figure 2).

Algorithm VERT2RA (Vertex to Roundabout)
On input:
v_0: a vertex on the ground
e_{min}: minumum lane length
g_{up}: upper roundabout elevation
g_{down}: lower roundabout elevation
G: undirected ground network
On output:
r_up: Upper Elevation Roundabout
r_down: Lower Elevation Roundabout
begin
$n \leftarrow |edges|$
$\mathbf{v} = \{\mathbf{v_i}|(\mathbf{v_i}, \mathbf{v_0}) \in \mathbf{edges(G)}\}$
$\alpha_i \leftarrow angle(v_i - v_{i-1})$ for $v_i \in \mathbf{v}$
$r \leftarrow \frac{e_{min}}{2sin(\frac{min(\alpha_i)}{2})}$
for $i \in \{1..n\}$
$i_e \leftarrow mod(i, n) + 1$
$r_e \leftarrow \frac{rv_{i_e}}{\|v_{i_e}\|}$
$r_s \leftarrow \frac{rv_i}{\|v_i\|}$
$e_{i_e} \leftarrow r_e - r_s$
end
$r_{up} \leftarrow e_i + g_{up}$
$r_{down} \leftarrow e_i + g_{down}$

Roundabouts are augmented based on whether the designer requests land and/or launch lanes. Figure 3 shows an example four-way cross conflict replaced by an aerial roundabout with one launch lane (vertex 1) and three land lanes. Figure 4 shows an example of the same intersection replaced with a roundabout with land and launch lanes at every vertex.

Once roundabouts are established, the process continues to connect each with edges to form a fully connected (with respect to roundabout structures) airway network. The roundabouts are connected via the following rules: if the vector between roundabout vertexes has heading between $[0, \pi)$, then connect the lower structures (r_{down} in Algorithm VERT2RA). If the vector has a heading between $[\pi, 2\pi)$, then connect the upper structures (r_{up}).

The lane network represents a set of reusable corridors (virtual highways), defined by waypoints, and radius (lane width). Whether the lanes are designed as extruded squares or tubes depends on the packing requirements, but the space afforded for the range of vehicle trajectories is negligible. Figure 5 depicts a diverging lane system, with lane radius r_e and two possible trajectories, s_1 and s_2. Trajectories within a lane system must be executed according to vehicle

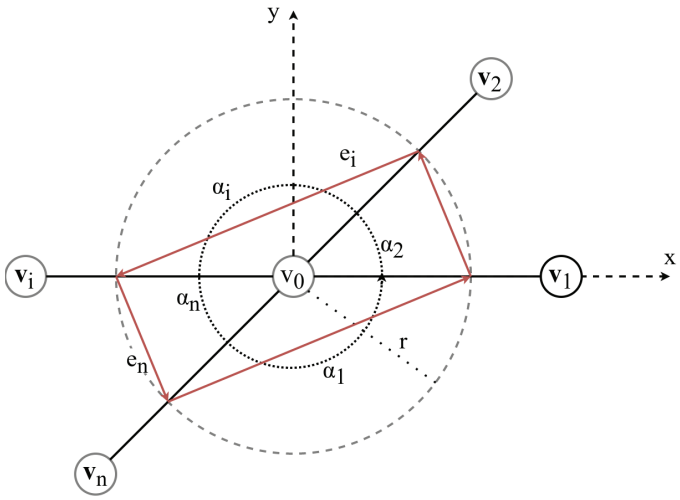


Fig. 2. Roundabout Formation Around Ground-Vertex $\mathbf{v_0}$

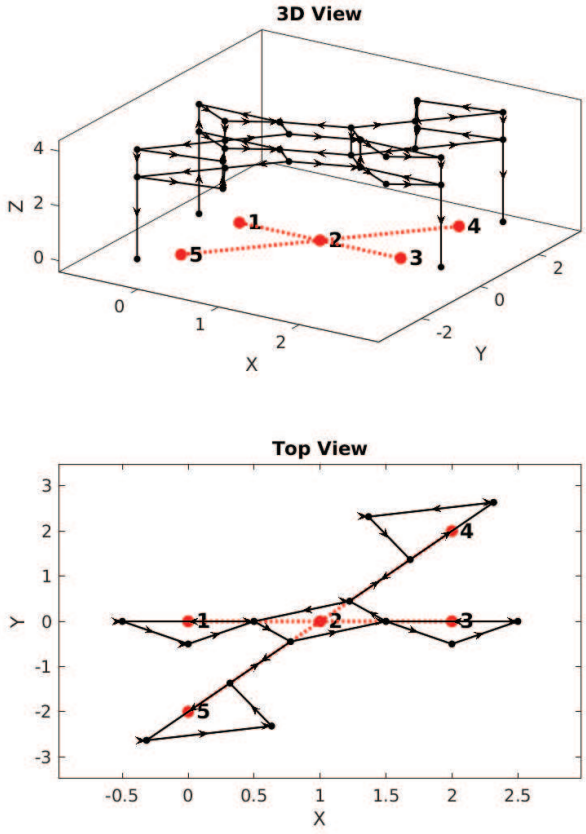


Fig. 3. Single Launch, Multiple Land Lane System

requirements, and system designers must consider turning-rate limits before standardizing the speed and radius. For the purpose of demonstrating the lane construction and execution of the LBSD algorithm, agile vehicles are assumed.

III. Design Workflow

To demonstrate the scalability and design methodology, a subset of the road network in Salt Lake City, Utah, near

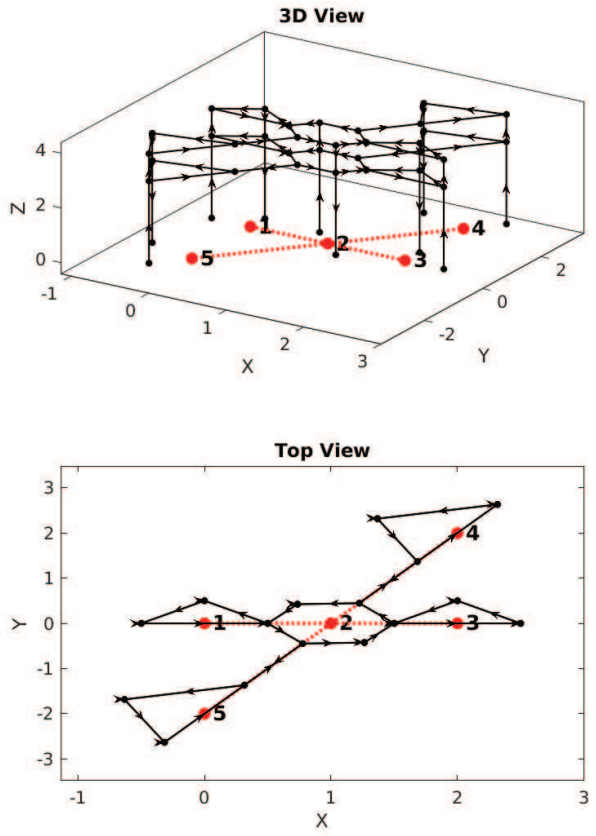


Fig. 4. Launch and Land Lanes for Every Ground Node

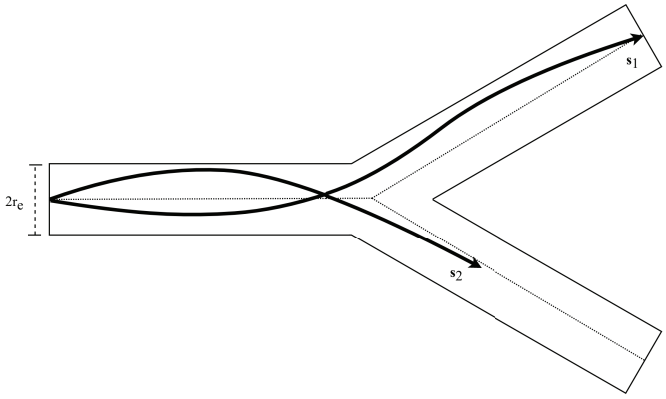


Fig. 5. Vehicle Trajectories Through Lanes

the University of Utah, was taken from the complete road network dataset provided by the Automated Geographic Reference Center (AGRC). This data was selected and stored in a GeoRq workspace (an integrated development environment developed by the authors during the first phase of NASA's Advanced Air Mobility National Campaign). The workspace exposes several web application programming interfaces (API) that take the 2-dimensional road layer, build an undirected graph from the raw linestrings, and query elevation datasets to return a 3-dimensional graph for lane processing.

The prototype lane design and LBSD code runs in MATLAB, so a client program queries the workspace through the web API, builds the lanes, and then runs the simulations. The resulting lane sets then are published through the web API so that the resulting airways can be accessed by other agents. Figure 6 shows the representative dataset over the roads in Salt Lake City.

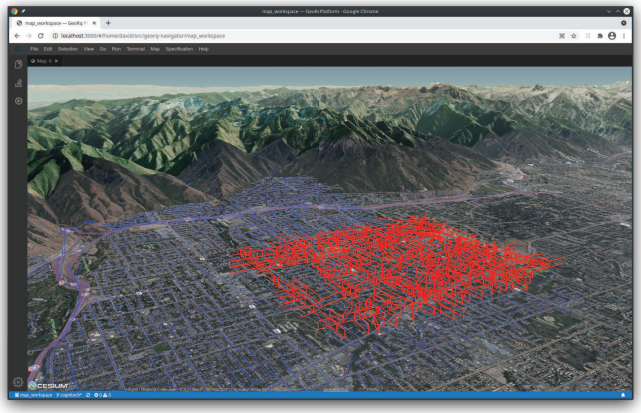


Fig. 6. Virtual Highway System GIS Layer in GeoRq Workspace

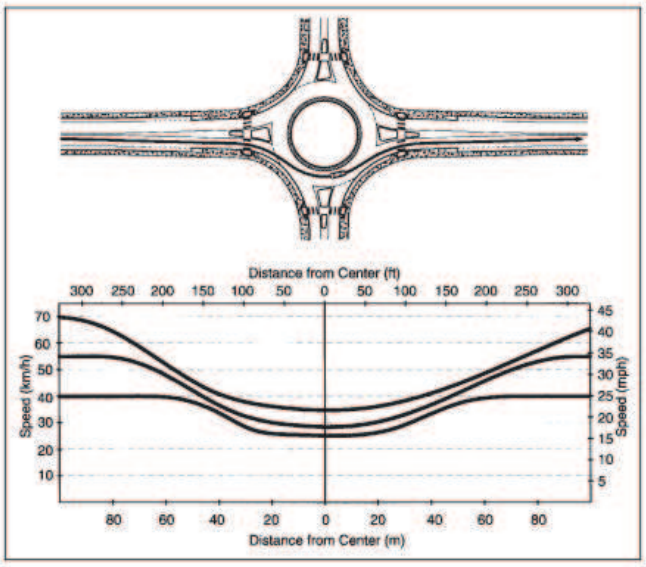
The GeoRq workspace is composed of a web map server, which exposes a standard Geographic Information Systems (GIS) web interface, a PostGIS database for storing geospatial data, and a web-based integrated development environment (IDE) for viewing and manipulating data. Parameters, such as the lane radius and shape, can be prototyped on this interface while design requirements are stored automatically in human/machine readable JSON files. While vehicle performance capabilities still remain somewhat proprietary, standards such as those for roads and roundabouts established by the United States Federal Highway Administration (FHWA) should be expected for these networks. For example, the FHWA establishes standards for entry and exit speed at roundabouts [8] based on their geometric properties (specifically, turning radius and lane width; see Figure 7).

IV. LANE-BASED UAS TRAFFIC MANAGEMENT

The UTM proposed here supports efficient and effective:

- *lane creation*: the definition of a set of lanes (airways) to allow flight from one ground location to another.
- *flight path determination*: given launch and land ground locations, return a sequence of lanes which goes from the launch location to the land location.
- *flight reservations*: given a lane sequence defined by a flight path, and a time interval of possible launch times, find the set of possible launch times that stay safely separated from any scheduled flights.
- *contingency mitigation*: lanes may be either pre-defined (e.g., emergency side lanes) or dynamically created (e.g., emergency landing lanes) in order to handle real-time departures from nominal flight paths.

In addition to the description of these, we provide a set of MATLAB functions to deliver these capabilities; these can



Recommended maximum entry design speeds for roundabouts at various intersection site categories are provided in Exhibit 6-4.

Site Category	Recommended Maximum Entry Design Speed
Mini-Roundabout	25 km/h (15 mph)
Urban Compact	25 km/h (15 mph)
Urban Single Lane	35 km/h (20 mph)
Urban Double Lane	40 km/h (25 mph)
Rural Single Lane	40 km/h (25 mph)
Rural Double Lane	50 km/h (30 mph)

Fig. 7. FHWA Recommendations for Max Speed in Ground Roundabouts [8].

be found at http://www.cs.utah.edu/∼tch/notes/UAM.

A. Lane Creation

Airways are defined by giving a set of ground locations and edges between them. For example, this may be directly obtained from GIS data by finding roads (the edge) and their intersection points (the vertexes), or by manual specification of the desired locations and their connectivity. In urban environments, it may be desirable to locate the airways above roads. For example, the Utah Department of Transportation, Aeronautics Division, which is developing the UTM system in Utah, wants airways above roadways since these are public spaces, and a great deal of infrastructure is already in place on the roadways to support UTM operations (existing access to power and networking for new radar and GPS systems, etc.). Moreover, NASA supports this idea [9]:

> With regard to the routes that UAM will traverse between two vertiports, a natural starting point for emergent UAM operations is to fly along defined helicopter routes ... These helicopter routes tend to overlay highways and freeways on the ground to mitigate social concerns.

However, the lane-based approach does not require that airways be placed above roadways.

Thus, let $V = \{x_i, y_i\}$ be the ground vertexes and $E = \{i, j\}$ be the edges where i and j are indexes into V. Launch and land vertexes must be specified (as indexes into V). Other required information includes the upper and lower altitudes for airway lanes, as well as a minimum length lane for roundabout structures. The airway constructed from this data defines the 3D vertexes created for the airway lanes, the airway lanes (as directed 3D line segments), and the indexes into the launch and land lanes.

All airway lanes are one-way, and in order to allow two-way movement between ground vertexes requires two separate lanes which are separated vertically at some safe distance. Roundabouts are created at intersections to allow flights to choose outbound directions from a vertex. Thus, there are 3 types of basic lanes: (1) launch/land lanes, (2) roundabout lanes, and (3) between ground vertex lanes. Other types of lanes may be introduced for contingency handling.

V. Alternate Route Calculation

One of the issues with routing between launch and land sites is the possibility of congestion if all UAS follow the same path to a destination. However, finding alternate paths in the two-level airway network is complicated by the wish to avoid changing altitude multiple times. In order to overcome this, we have developed a method to produce a set of alternate lane sequences from a launch site to a land site by exploiting the fact that an altitude change is necessitated whenever the heading of the UAS changes from directions $[0, \pi)$ to $[\pi, 2\pi)$ or vice versa. Thus, a search is carried out in the 2D ground network which minimizes the distance of each node from the line defined by the launch/land vertexes, as well as the number of changes of altitude. Figure 8 shows an example of alternate routes in the SLC ground road network data. Once a path through the ground vertexes is found, then it is possible to find the corresponding path through the airway lanes (see Figure 9).

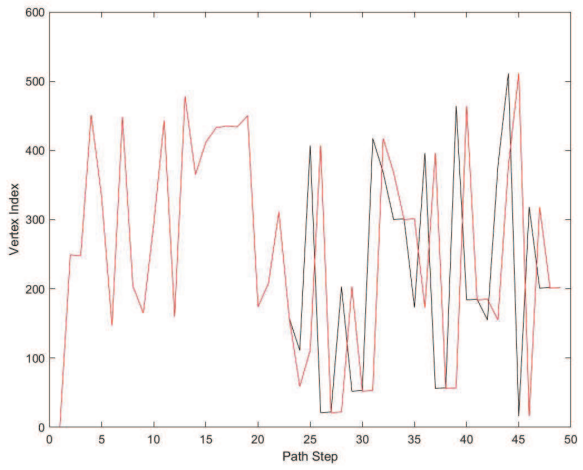


Fig. 8. Two Alternative Routes through the Ground Network which Minimize Distance and Number of Altitude Changes.

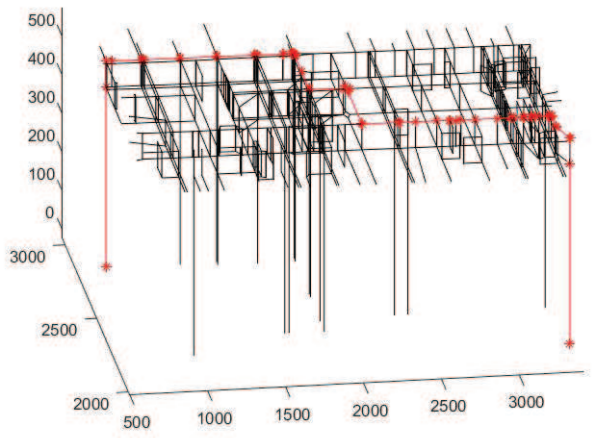


Fig. 9. Airway Path Corresponding to Ground Path.

VI. EXPERIMENTS

The lane-based approach has been tested on a number of scenarios. Figure 6 shows a set of airway lanes above part of Salt Lake City which have been used to help determine UAS Air Mobility structure and parameters for the Utah UTM.

Consider a Salt Lake City earthquake disaster scenario in the East Bench area; about 25,000 people must receive a ration of 1 gallon of water (8 pounds) and 3 pounds of food each per day to be delivered by a set of UAS to 477 distribution sites throughout the area; this makes a total of 275,000 pounds per day. Assume each UAS has a load capacity of 100 pounds (note there are current models with a 200 pound capacity). Each delivery site will be serviced from a small set of depot sites where major supply reserves are housed. A performance comparison is made between the FAA and lane-based strategic deconfliction methods. The parameters to be selected include: the number of depots (10 or 50), the number of UAS (500 or 1000), the UAS speed (30 or 60 feet per second – about 20 and 40 mph, respectively), and the deconfliction method. Note that 6 deliveries are required for 500 UAS, whereas only 3 per day are nedeed for 1,000 UAS. Performance measures include: average delay (time difference between actual and desired launch times in seconds), maximum delay, average deconfliction time (in seconds), and maximum deconfliction time. In addition, three types of lane-based layouts are considered: lane networks placed above actual roads (see Figure 10), a rectangular grid (see Figure 11), and a Delaunay triangulation of a set of comparable nodes over the area. Results for the lanes and FAA methods are given in Table I. For each set of parameters, 10 trials are run, and the averages of the performance measures are given in the table. For every set of parameter assignments, the LBSD algorithm provides flight plans with no delay, whereas the FAA method results in significant delays; e.g., consider the 10 depot, 1000 UAS, speed 30 scenario: the average delay is 9.21 seconds which over the total of 5604 flights is over 14 hours of lost time. The lane-based deconfliction times are higher than the

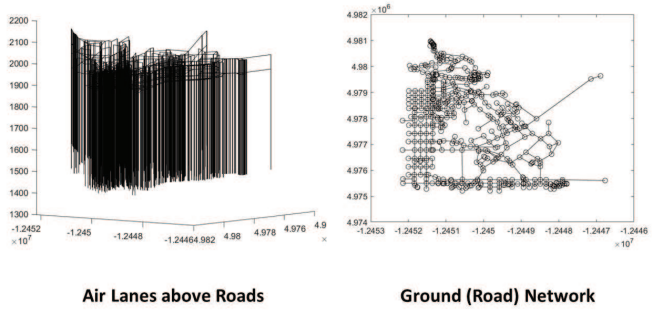


Fig. 10. Lanes above Existing Roads (left: airways; right: road network).

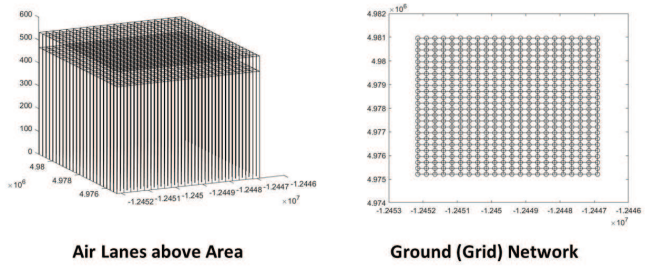


Fig. 11. Lanes Constructed from Rectangular Grid (left: airways; right: ground network).

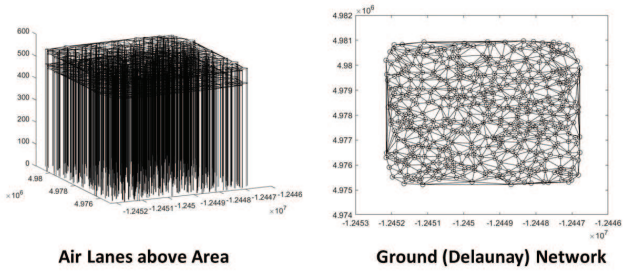


Fig. 12. Lanes Constructed from Delaunay Triangulation (left: airways; right: ground network).

FAA method since we use a simple up-over-down, three segment trajectory for FAA flights and deconflict them using the Closest Point of Approach method [10]. However, the average lane-based deconfliction time is under one second, and the LBSD algorithm translates to an embarrasingly parallel version if desired. Table I also include results for the grid and Delaunay lane networks, and as can be seen, not only do they produce no delay, their deconfliction times are an order of magnitude faster than the FAA method.

VII. CONCLUSIONS AND FUTURE WORK

We have demonstrated the efficiency and effectiveness of a lane-based approach to large-scale UAS Traffic Management.

Num Dep/UAS	*UAS Speed*	*Method*	*Avg Delay*	*Max Delay*	*Avg Decon*	*Max Decon*
10/500	30	FAA	11.07	277.5	0.0770	2.64
		GIS	0	0	0.0322	0.18
		grid	0	0	0.1902	1.11
		Del	0	0	0.0066	0.03
	60	FAA	3.64	174.5	0.0770	0.54
		GIS	0	0	0.0323	0.19
		grid	0	0	0.1838	1.01
		Del	0	0	0.0064	0.03
10/1000	30	FAA	15.28	509.5	0.0660	0.48
		GIS	0	0	0.0250	0.18
		grid	0	0	0.2063	1.10
		Del	0	0	0.0054	0.02
	60	FAA	1.87	143	0.0630	0.45
		GIS	0	0	0.0235	0.13
		grid	0	0	0.1660	0.09
		Del	0	0	0.0054	0.02
50/500	30	FAA	11.08	277.0	0.0860	0.60
		GIS	0	0	0.0327	0.21
		grid	0	0	0.1846	1.12
		Del	0	0	0.0066	0.03
	60	FAA	3.61	154	0.0920	0.45
		GIS	0	0	0.0354	0.27
		grid	0	0	0.1777	1.02
		Del	0	0	0.0061	0.03
50/1000	30	FAA	15.11	530.5	0.1080	0.77
		GIS	0	0	0.0199	0.11
		grid	0	0	0.1939	1.13
		Del	0	0	0.0063	0.03
	60	FAA	1.84	135	0.0820	0.66
		GIS	0	0	0.0198	0.12
		grid	0	0	0.1722	0.86
		Del	0	0	0.0057	0.02

TABLE I

FAA-NASA VS. LBSD (GIS, GRID, DELAUNAY) ON SALT LAKE CITY, UT AIRWAY; TIMES ARE IN SECONDS; SPEED IS IN FEET PER SECOND.

A methodology is described for the creation of the lane structure, as well as for efficient path selection and strategic deconfliction. All of these are far superior to the current FAA-NASA arbitrary flight path creation and deconfliction approach in terms of average delay, max delay, and time to deconflict.

There are a number of things to consider in future work, several of which we are currently working on:

- dynamic lane creation and deletion,
- UTM parameter optimization (e.g., lane speeds, lane connectivity, airway volume around lane segments, etc.),
- inclusion of weather, congestion, and other parameters for path selection,
- dynamic UAS flight parameters and path selection,
- role of communications in UAS flight path planning (e.g., connectivity of UAS, relay support for communications outages, etc.).

ACKNOWLEDGMENT

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