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Report No. UT-22.10

AIR MOBILITY TRAJECTORY ANOMALY DETECTION AND OPERATIONAL ADVANCEMENT

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Final Report
June 2022

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ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals from UDOT on the Technical Advisory Committee for helping to guide the research:

- Robert Chamberlin (consultant)
- Jared Esselman
- Adam Robertson
- Chad Worthen
- Christopher Mitton
- Jordan Backman

TECHNICAL REPORT ABSTRACT

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UT-22.10	N/A	N/A
4. Title and Subtitle AIR MOBILITY TRAJECTORY ANOMALY DETECTION AND OPERATIONAL ADVANCEMENT		5. Report Date June 2022 6. Performing Organization Code
7. Author(s) David Sacharny, Thomas Henderson, and Xiaoyue Cathy Liu		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Utah Department of Civil and Environmental Engineering 110 Central Campus Drive, Suite 2000 Salt Lake City, UT 84112		10. Work Unit No. 5H08674H 11. Contract or Grant No. 228097
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Final September 2021 – June 2022 14. Sponsoring Agency Code UT21.501A

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The density of aircraft operating in the Salt Lake valley over the next several years is projected to explode in density and therefore push the complexity of air traffic operations beyond the ability of human air traffic controllers. Despite the progress made by NASA and industry during the AAM X3 simulation activities, a cohesive model of air travel in low altitude airspace remains at large. The research developed at the University of Utah, called the Lane-Based Approach, models the set of requestable trajectories of aircraft as a set of virtual highways and a specific method of deconfliction. This model does not preclude the current state of the art in unmanned air traffic management (UTM), but builds on it to enable policymakers and engineers to plan safe coordinated airspace access. This model also provides for a form of trajectory analysis that is not available with other deconfliction strategies. By using the virtual highways (or lanes) as a model for air travel, anomalous flights can be detected and classified within a unified framework. This framework enables regulators to potentially detect threats, such as hijacked, rogue, or misbehaving unmanned aerial systems (UAS).

17. Key Words		18. Distribution Statement		23. Registrant's Seal
Advanced Air Mobility, UAS Traffic Management, Unmanned Aircraft Systems		Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		N/A
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price	
Unclassified	Unclassified	37	N/A	

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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AAM	Advanced Air Mobility
CONOPS	Concept of Operations
CPAD	Closest Point of Approach
eVTOL	Electric Vertical Takeoff and Landing
GPS	Global Positioning System
FAA	Federal Aviation Administration
FNSD	FAA/NASA Strategic Deconfliction
LBSD	Lane-Based Strategic Deconfliction
NAB	Nominal Versus Anomalous Behavior
NASA	National Aerospace and Aeronautics Administration
UDOT	Utah Department of Transportation
UAS	Unmanned Aircraft Systems
UAAMS	Utah Advanced Air Mobility Simulator
UAM	Urban Air Mobility
USS	UAS Service Supplier
UTM	UAS Traffic Management

EXECUTIVE SUMMARY

The density of aircraft operating in the Salt Lake valley over the next several years is projected to explode in density and therefore push the complexity of air traffic operations beyond the ability of human air traffic controllers. Despite the progress made by NASA and industry during the AAM X3 simulation activities, a cohesive model of air travel in low altitude airspace remains at large. The research developed at the University of Utah, called the Lane-Based Approach, models the set of requestable trajectories of aircraft as a set of virtual highways and a specific method of deconfliction. This model does not preclude the current state of the art in unmanned air traffic management (UTM) but builds on it to enable policymakers and engineers to plan safe coordinated airspace access. This model also provides for a form of trajectory analysis that is not available with other deconfliction strategies. By using the virtual highways (or lanes) as a model for air travel, anomalous flights can be detected and classified within a unified framework. This framework enables regulators to potentially detect threats, such as hijacked, rogue, or misbehaving unmanned aerial systems (UAS).

1.0 INTRODUCTION

1.1 Problem Statement

The density of aircraft operating in the Salt Lake valley over the next several years is projected to explode in density and therefore push the complexity of air traffic operations beyond the ability of human air traffic controllers. Despite the progress made by NASA and industry during the AAM X3 simulation activities[1], a cohesive model of air travel in low altitude airspace remains at large. The research developed at the University of Utah, called the Lane-Based Approach, models the set of requestable trajectories of aircraft as a set of virtual highways and a specific method of deconfliction. This model does not preclude the current state of the art in unmanned air traffic management (UTM) but builds on it to enable policymakers and engineers to plan safe coordinated airspace access. This model also provides for a form of trajectory analysis that is not available with other deconfliction strategies. By using the virtual highways (or lanes) as a model for air travel, anomalous flights can be detected and classified within a unified framework. This framework enables regulators to potentially detect threats, such as hijacked, rogue, or misbehaving unmanned aerial systems (UAS).

1.2 Objectives

The primary objective of this research is to advance the state of the art in airspace digitization and provide UDOT with a prototype trajectory anomaly detection implementation for virtual highways. This research builds on the tools developed during the UTRAC project summarized in report number UT-21.33 [1], and thus a secondary objective of this research is to include a prototype virtual highway implementation for UDOT with a model for detecting anomalous flights (rogue aircraft, vulnerable aircraft, bad actors, etc.)

1.3 Scope

This research is divided into scenarios that consider:

[1] The X3 simulations are part of a continuing progression of research and implementation activities facilitated by NASA's Advanced Air Mobility (AAM) National Campaign Developmental Test (NC-DT).

1. The impact of configurations of virtual highways (lanes) on parameters such as airspace capacity and delay, as well as a comparison with the FAA/NASA approach to strategic deconfliction.
2. The impact of tactical contingency response on the lane system – a standard algorithm will also be presented.
3. An investigation into trajectory anomaly detection within the lane-based approach.

Additionally, a review is presented of published concepts of operations (CONOPS) and how UDOT-funded research is situated with respect to progress in the AAM/UTM industry, as well as a review of the literature on security concerns related to UTM.

1.4 Outline of Report

The rest of the report is structured as follows. First the review of CONOPS will be presented, since this applies most broadly to stakeholders interested in the state of the art in AAM/UTM. Then the scenarios described in the scope are presented, followed by a review of security concerns.

2.0 CONCEPT OF OPERATIONS REVIEW

2.1 Overview

This was a comprehensive review of published progress on the concept of operations for unmanned aircraft systems (UAS) traffic management (UTM) that situates current and past UTRAC-funded research. Under consideration are a series of publications that describe the roles and responsibilities of government and industry stakeholders, as well as a narrower assessment of recent X3 airspace simulation developmental activities held by NASA. The X3 simulations are part of a continuing progression of research and implementation activities facilitated by NASA's Advanced Air Mobility (AAM) National Campaign Developmental Test (NC-DT). The forerunning X1 and X2 activities involved only one industry partner and helped NASA understand what challenges lie ahead for coordinating airspace for multiple aircraft operators. X3 was the first time that multiple industry partners were gathered to assess the state of the art in automated air traffic control. Whereas published research continues to focus on UTM operations below 400 feet above ground level (AGL), the NC-DT X3 activities provide some insight into the current state of affairs with regard to AAM and operations that cross into uncontrolled (Class G) and controlled (Classes B, C, D, and E) airspace environments. While not standardized, the role of state agencies in regulating and catalyzing these activities is under development and likely expanding, and this UDOT-funded research is vital for this reason.

In 2020, the Utah Department of Transportation's (UDOT) Research & Innovation Division annual research prioritization workshop (also known as "UTRAC") began funding research in Advanced Air Mobility under the purview of the Aeronautics division. Numerous issues related to infrastructure and urban planning, economic development, public safety, and transportation have naturally risen in the effort to automate air traffic control and make low-altitude airspace an accessible mode of transport for people and goods (packages). Advanced Air Mobility (AAM) describes an emerging aviation market for local, regional, intra-regional, and urban-use cases, supported by a set of disruptive technologies (many of which are being developed in Utah). The most salient technologies are the vehicles, and the promise that they will fly themselves effortlessly throughout the city has generated billions of dollars in private and public investment. To name a few of the publicly traded companies in this space, Joby Aviation, Lilium, Archer, and Volocopter represent over $4 billion in market capital and have yet to transport a single paying customer. Each vehicle also has numerous other disruptive technologies, electric and hybrid propulsion systems, energy storage systems, guidance and control software, advanced materials, etc. Each of these systems must interoperate or contend with an ecosystem of other vehicles and disruptive technologies in infrastructure, simulation, monitoring, and air traffic management. The minimum set of disruptive technologies necessary to enable this vision of urban air mobility is a subject of debate, and in the United States it will be determined by the business models that are commercially successful. Disruptive technologies are innovations that alter the way people and industries operate, and the technologies that transform urban mobility are as certain to be disruptive as when selective availability was discontinued for GPS in the year 2000. Unlike GPS, however, the trajectory to enable mass adoption and commercial viability is much less clear.

In 2018, NASA hired two companies, Crown Consulting, Inc. and Booz Allen Hamilton, to study the market viability of urban air mobility (the term as applied then, now known as AAM). Around the same time that UDOT Aeronautics began seriously considering the ramifications of AAM, NASA published the reports which identified key technologies and barriers. Crown Consulting identified 34 technologies on the critical path of development, and divided them into 15 categories [2]:

- autonomy,
- sensing,
- cybersecurity,
- propulsion,
- energy storage,
- emissions,
- structures,
- safety,
- pilot training,
- certification,

- communications,
- controls,
- operations,
- traffic management, and
- infrastructure.

This categorization is not to say that these technologies do not depend on each other, rather, there are complex relationships that must be managed between them during both development and production. Additionally, the airspace is heavily regulated, particularly in the United States where regulations have been developed over the past 100 years; this increases the barrier of entry for innovators due to the capital requirements and consequences of liability. The National Aerospace and Aeronautics Administration (NASA) and the Federal Aviation Administration (FAA) have stepped in to help facilitate the coordination between industry and government; a mission statement from NASA's AAM website (https://www.nasa.gov/aam/overview) provides a concise description of how they see their role:

> -NASA's vision for Advanced Air Mobility's (AAM) Mission is to help emerging aviation markets to safely develop an air transportation system that moves people and cargo between places previously not served or underserved by aviation - local, regional, intraregional, urban - using revolutionary new aircraft that are only just now becoming possible. AAM includes NASA's work on Urban Air Mobility and will provide substantial benefit to U.S. industry and the public.
>
> -The Aeronautics Research Mission Directorate (ARMD) initiated the AAM Mission Integration Office during the 2020 fiscal year with the objective to promote flexibility and agility while fostering AAM mission success and to promote teamwork across ARMD projects contributing to the AAM Mission. The AAM Mission will address a broad set of barriers necessary to enable AAM which will be accomplished with the contributions made by projects across the mission directorate.

Aside from governmental players, large corporations with institutional reputations have also stepped in to offer commercial solutions that revolve around an *ecosystem* product concept, a location for providers of services for AAM to market their products. However, a specific assignment of roles, e.g., who will provide supplemental data services, who will act as authorized public safety officials, etc., is still an open question. UDOT and other DOTs, given their status as progenitors of transportation data, management, and infrastructure, are likely to play an outsized role in catalyzing this industry and facilitating this new mode of transportation.

2.2 UTM Concept of Operations

Recent publications that demonstrate the progression of UTM include versions 1.0 and 2.0 of the FAA's concept of operations (ConOps) for UAS traffic management (UTM) [3] [4]. A prominent architectural diagram is included in both versions (see Figure 1 and Figure 2) and shows that the overarching roles and responsibilities in UTM have remained stable between them. Around the same time that version 2 of the concept of operations was published, version 1 of the UAM concept of operations was also published [5], with a similar notional architecture shown in Figure 3. The UAM architecture adds a role called a PSU, or Providers of Services for UAM. These systems provide functionally the same role as UAS Service Suppliers (USS) in the UTM system, but enable different requirements to flow in from uncontrolled and controlled airspace operations. In fact, the software interfaces that were developed during the X3 simulation activities were derived from the latest USS software interfaces [6]. In the short term, it is reasonable to consider UTM and AAM as separate concerns, but eventually the coordination of airspace and ground-based resources (radar, communications, vertiport access) will require these concepts to merge. For this reason, UDOT should consider both concepts of operations for any large-scale projects or technology acquisitions.

The role that UDOT, and DOTs in general, will or should play in AAM operations is not explicitly spelled out in any of the *concept of operations* documents. They are likely grouped into the roles of "Public Stakeholders" in the UTM ConOps and "Public Interest Stakeholders" in the UAM ConOps, where they are defined as follows:

> Public interest stakeholders are entities declared by governing processes (e.g., FAA, CBR) to be able to access UAM operational information. This access may support activities including, but not limited to, public right to know, government regulatory, government assured safety and security, and public safety. Examples of public interest stakeholders are local law enforcement and US federal agencies.

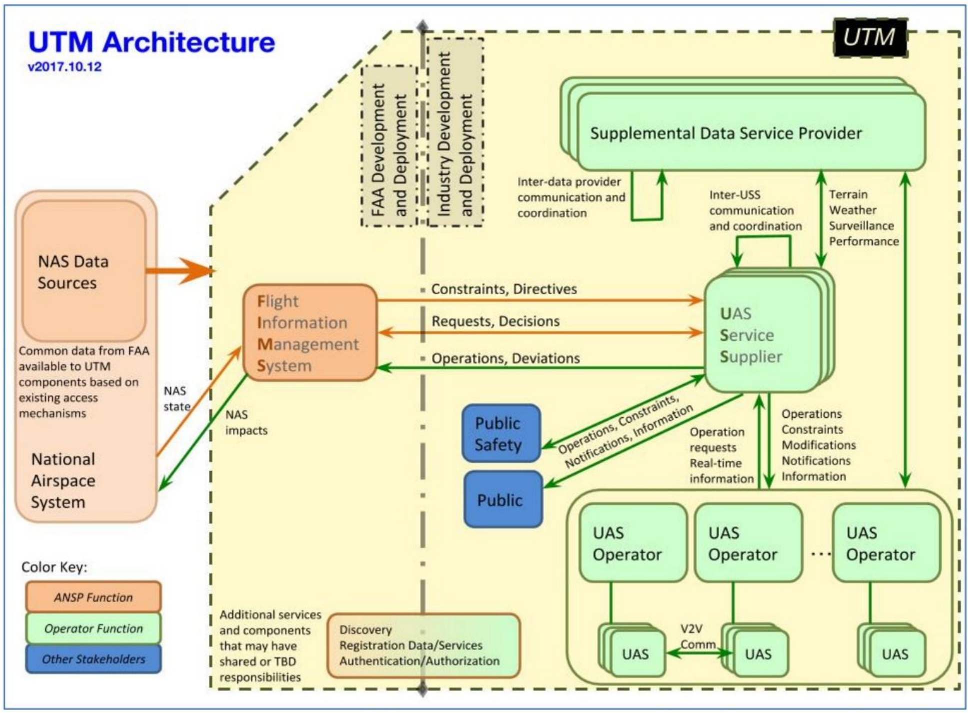

Figure 1. Version 1.0 Concept of Operations (from [2])

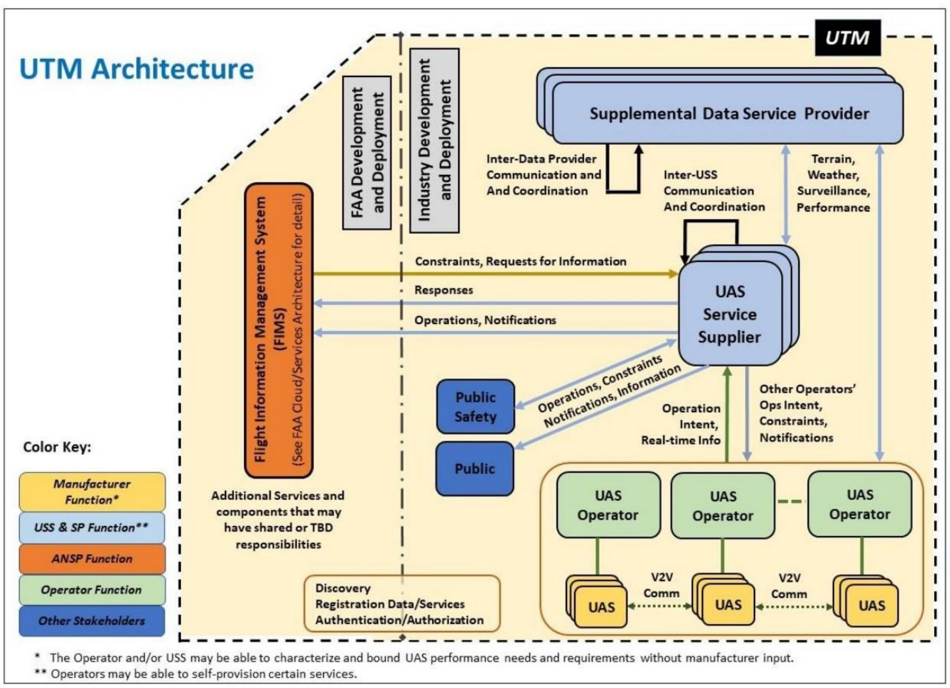

Figure 2. Version 2.0 Concept of Operations (from [3])

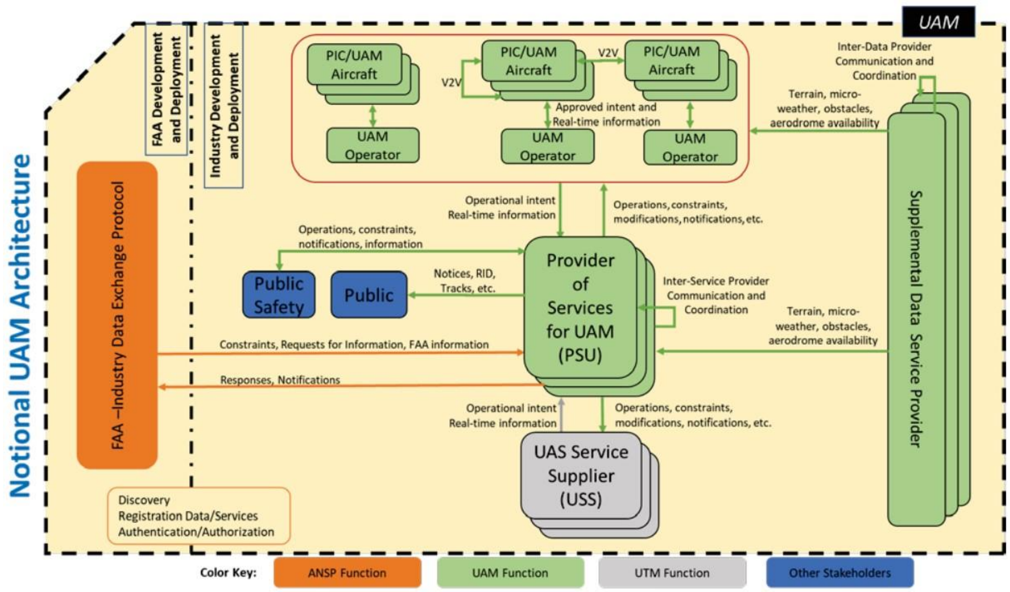

Figure 3. Version 1.0 Concept of Operations for UAM (from [4])

Hence, they are recognized as stakeholders that require access to information, but their responsibilities pertaining to public safety and security are not clear. In the UTM ConOps, a table is provided (replicated here in Figure 4) that describes the functions of the major players - public safety, security, and concerns in general are notably missing.

Several recent UTRAC-funded research activities suggest that DOTs have a larger role to play. *UT20.602 Long-Range Urban Air Mobility Land-Use Planning for Vertiports* (PI: Brent Chamberlain, project ongoing) suggests that AAM will require urban planning to facilitate operations to fulfill the promise that NASA underlines: "an air transportation system that moves people and cargo between places previously not served or underserved by aviation - local, regional, intraregional, and urban." *UT21.505 Electrification Plan of State of Utah Airport Infrastructure* (PI: Regan Zane, project ongoing) reveals the underlying issue that many of the airports in the country are regulated by state transportation policies and authorities, and their involvement is necessary to ensure that electric vertical takeoff and landing (eVTOL) aircraft have access to power. *UT-21.33 Strategic Deployment of Drone Centers and Fleet Size Planning for Drone Delivery* [6] resulted in simulations that indicate the numerous assumptions that must be considered to determine the environmental costs of AAM, and how requirements from state agencies (such as infrastructure placement) must be considered.

2.3 Simulations

The X3 simulation activities provide insight into the current state of industry, particularly where technology development intersects with automated air traffic control. To discover where our current understanding of automated air traffic control lies, consider the assumptions for the X3 simulations, which were published in the April 2021 report by NASA [6], and are shown in Figure 4. The goal of these simulation activities was to characterize airspace coordination issues under ideal conditions and no competing traffic. This is a reasonable step toward the path to automated air traffic control because there are currently no vehicles authorized or capable of performing this type of coordination. However, the issues that most require human intervention and that are difficult to automate arise when multiple vehicles are interacting, and under contingency scenarios (e.g., unexpected weather or mechanical malfunctions).

Function		Actors/Entities ✓ = Primary responsibility S = Support		
		UAS Operator	USS	FAA
Separation	UAS from UAS (VLOS and BVLOS)	✓	S	
	VLOS UAS from Low Altitude Manned Aircraft	✓	S	
	BVLOS UAS from Low Altitude Manned Aircraft [1]	✓	S	
Hazard/ Terrain Avoidance	Weather Avoidance	✓	S	
	Terrain Avoidance	✓	S	
	Obstacle Avoidance	✓	S	
Status	UTM Operations Status	S	✓	
	Flight Information Archive	✓	S	
	Flight Information Status	✓	S	
Advisories	Weather Information	✓	S	
	Alerts to Affected Airspace Users of UAS Hazard	✓	S	
	Hazard Information (e.g., obstacles, terrain)	✓	S	
	UAS Specific Hazard Information (e.g., Power Lines, No UAS Zones)	✓	S	
Planning, Intent & Authorization	Operation Plan Development	✓	S	
	Operation Intent Sharing (pre flight)	✓	S	
	Operation Intent Sharing (in flight)	✓	S	
	Operation Intent Negotiation	✓	S	
	Controlled Airspace Authorization		S	✓
	Control of Flight	✓		
	Airspace Allocation & Constraints Definition		S	✓

Figure 4. Allocation of Responsibilities for UTM Actors/Entities (from [3])

The simulation activities included three scenarios to represent challenges to the AAM airspace partners:

- Scenario 1 included flight and operation planning for nominal operations.
- Scenario 2 included en-route operation re-planning in response to an announced airspace constraint.
- Scenario 3 included en-route operation re-planning in response to an occupied or obstructed vertipad and emergency landing.

Element	Assumption
UAM Airspace Management System Authorization	Pre-authorization to submit operations; does not include airspace and/or performance authorization. Letter of Authorization (LOA) authorizes flight to enter Class D.
Weather Conditions	Daytime Visual Meteorological Conditions (VMC).
UAM Routes Interaction with Instrument Flight Rules (IFR) and Visual Flight Rules (VFR)	UAM airspace/routes are designed to be de-conflicted with Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) routes using current day separation requirements. UAM airspace/routes are expected to be high density routes that are notified to the rest of the VFR traffic in Class G for awareness. No interaction is assumed between UAM and IFR/VFR flights.
Background Traffic	None.
UAM Routes Sharing	Each UAM operator manages its own set of UAM routes (i.e., UAM routes are not shared among multiple UAM operators at the same time).
Vertiport Sharing	Each UAM operator manages its own set of Vertiports (i.e., Vertiports are not shared among multiple UAM operators at the same time).
Small Unmanned Aircraft Systems (sUAS) and Non-Transponder Flights	Not included in the traffic.
Simulation Environment	Only one airspace partner will run the scenario at any given time in X3.

Figure 5. X3 Simulation Assumptions (from [5])

The results in Figure 6 show that only two of the eleven airspace simulation partners were able to compete in the third scenario. Additionally, there were reported issues in maintaining vertical conformance, which may have been a result of non-standardized trajectory reservations. The UTRAC research presented in this report continues an investigation into a lane-based method for trajectory reservations, developed through conversations with UDOT Aeronautics, that could lead to this type of standardization.

Scenario	Number of Airspace Partners Participated	Total Number of Test Runs	Total Number of Operations Flown
1	9	13	70
2	4	8	39
3	2	4	14

Figure 6. X3 Simulation Participation Results (from [5])

3.0 SCENARIOS

3.1 UTM Scenario Set Design 1

In a complicated system like a UTM, answering questions such as "how many aircraft can fly at once in a geographic area?" or "what is the expected delay of an on-demand flight?" requires simulations to explore UTM performance with respect to parameters of interest. The experiments performed here are designed to allow both inter-UTM (e.g., lane-based versus the FAA/NASA approach) and intra-UTM (e.g., grid vs. Delaunay airspace structures) structural analysis, as well as a cursory system/behavioral analysis (relating the agents flexibility in scheduling to the overall system performance). The parameters studied here include:

- Launch Frequency (flights per hour): Comparable to an arrival rate of flights into the system [values: 100 and 1000]
- UAS Speed (m/s): Average UAS speed through lane [values: 5, 10, 15]
- Headway Distance (m): Minimum distance allowed between UAS [values: 5, 10, 30]
- Flex Time (sec): Interval of possible launch times for flight [values: 0, 300, 1800].

The simulation covers an area of 5 square km (roughly the size of the Salt Lake valley) with the FAA cells spaced as a 10x10 cell structure. The LBSD grid was chosen to correspond to this as an 11x11 node grid. The 121 launch (land) sites are located near the ground node points in both layouts. The Delaunay networks are generated with the same number of nodes, but they are distributed randomly (sampled from uniform distribution) in the given area. Road-based networks include an area over San Francisco and an area over Salt Lake City. Ten simulation trials were run for each of the 54 parameter combinations (note that for the Delaunay networks an additional ten trials were run for each due to the random nature of the node locations). The simulation period was set to 4 hours simulated time. The FAA flights are up, over and down trajectories scheduled between randomly selected launch and land sites; the flight altitude was randomly assigned between the min and max altitudes of the LBSD network. For both UTM methods, given the flight frequency, a random set of desired flight times are generated which are uniformly spread across the total simulation time.

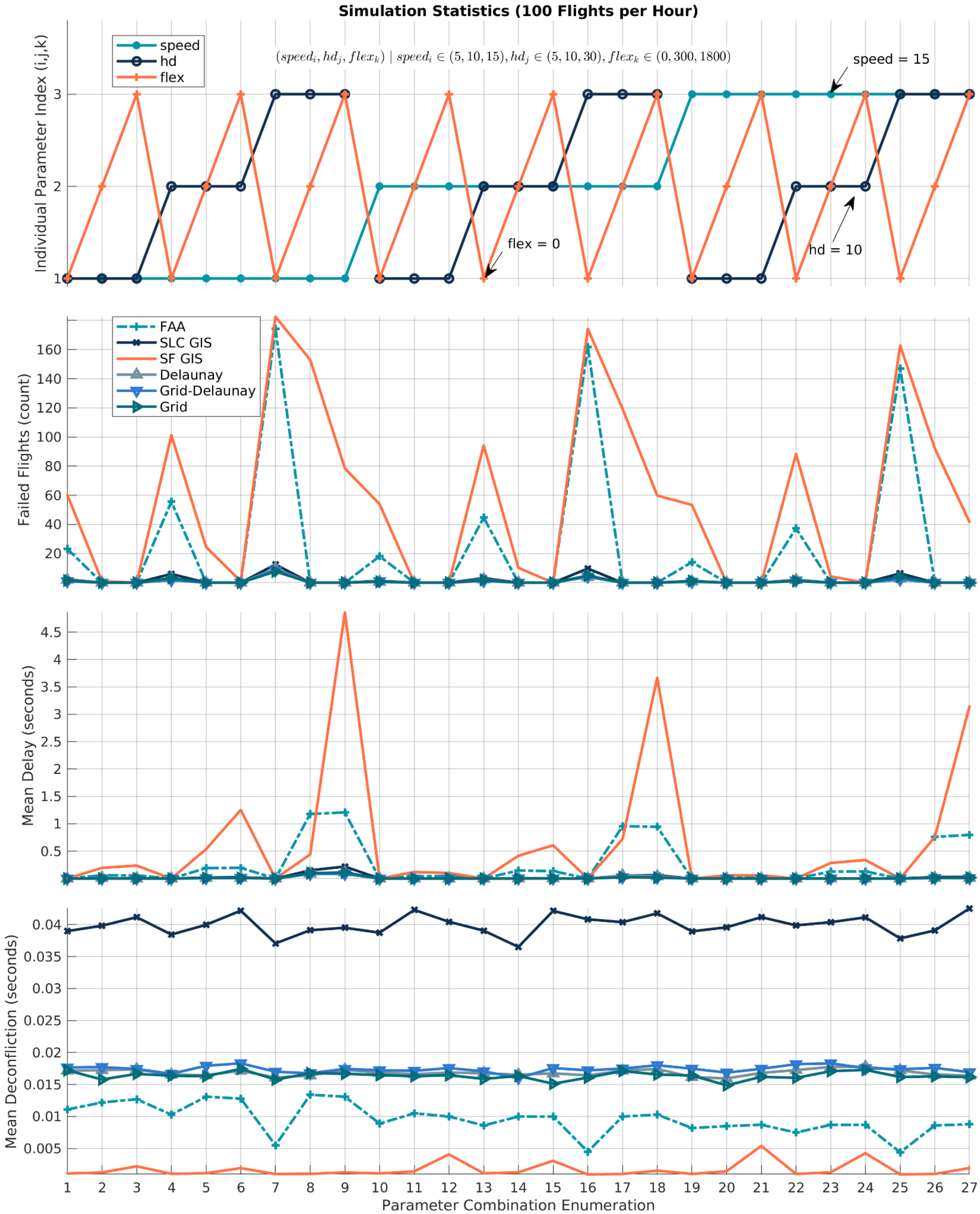

Figure 7 100 UAS/hour simulation means

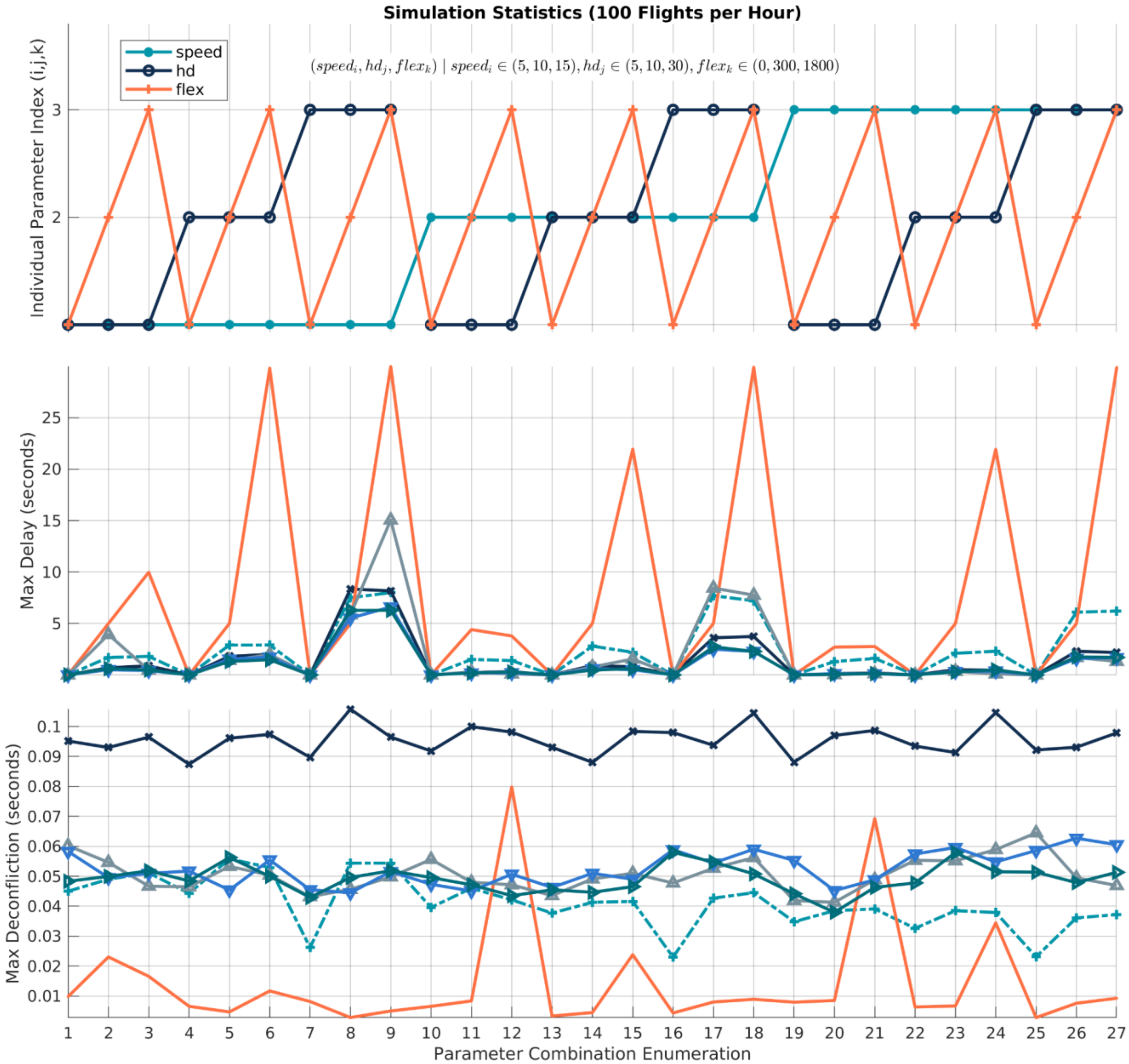

Figure 8 100 UAS/hour simulation maxes

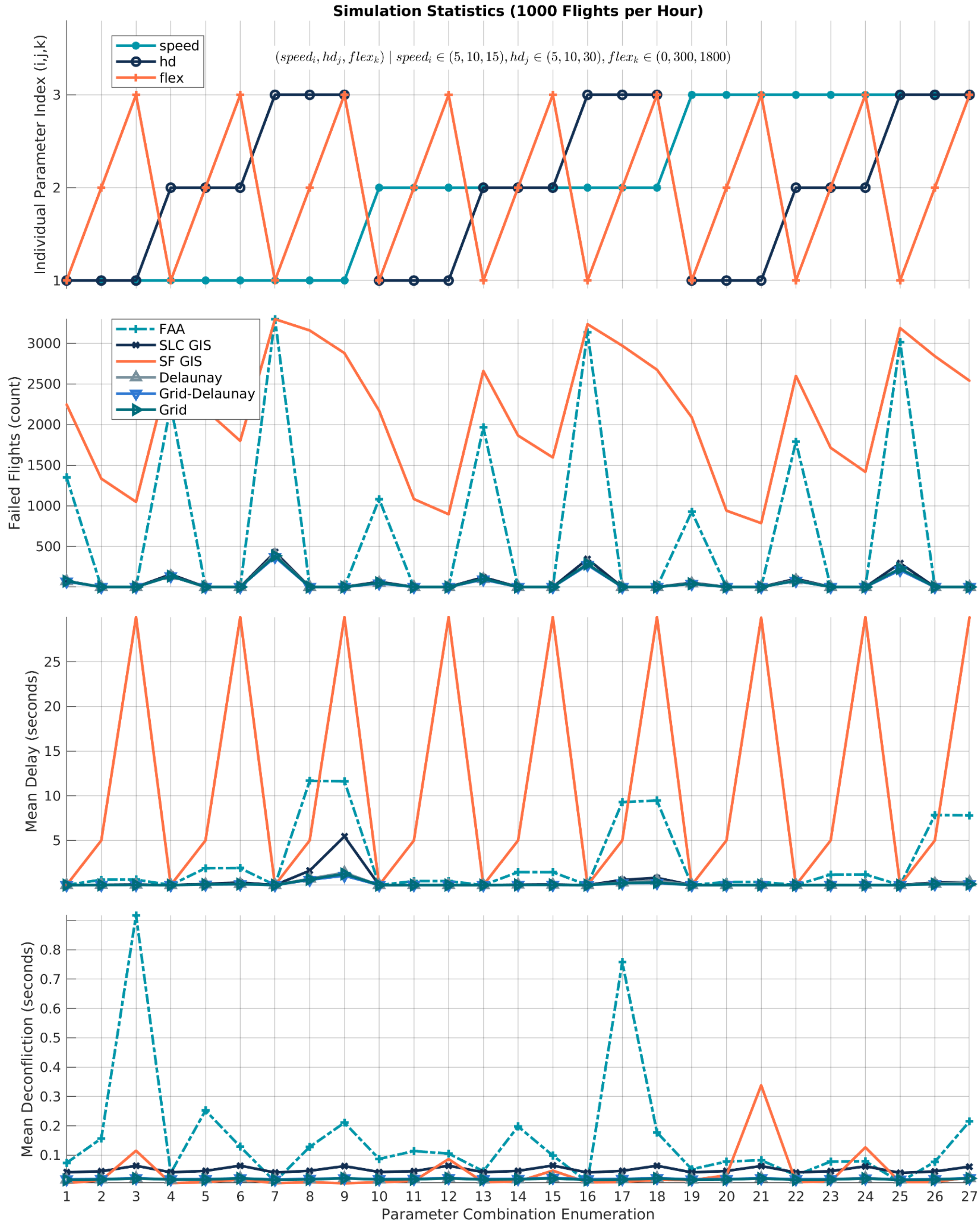

Figure 9 1000 UAS/hour simulation means

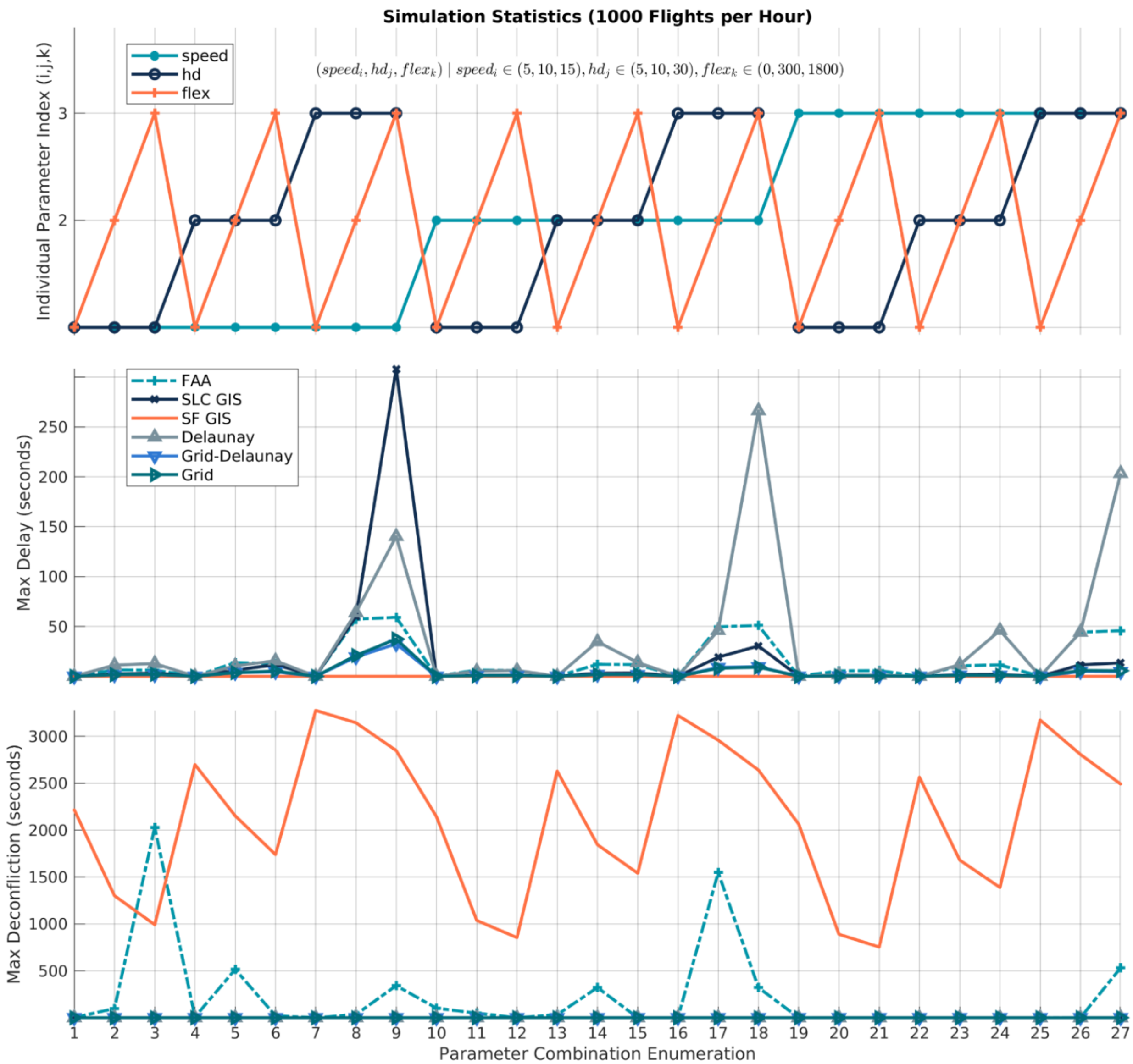

Figure 10 1000 UAS/hour simulation maxes

Figure 7 and Figure 9 show the mean statistics for launch frequency of 100 flights/hour and 1000 flights/hour, respectively. The means of the maxima over all trials are also given in Figure 8 and Figure 10. The statistics include delay (calculated as the time between the requested launch time and the assigned launch time), failed flights (flights that could not be accommodated due to time or space constraints), and deconfliction time (the amount of wall-clock time that the computer required to re-schedule a flight).

This data indicates that all six categories of structures have response characteristics that are most undesirable when the flex is low, the speed is low, and the headway is high. However, the unstructured FAA airspace and the road-based San Francisco networks are particularly sensitive to these inputs with respect to the mean statistics. The max statistics regarding delay show a somewhat different story where the FAA structure responded similarly to the others and the San Francisco graph performed the worst. These results indicate that small changes in the policies and behaviors may have dramatic effects on what the average UAS agent experiences accessing the unstructured (FNSD) airspace and complex road networks. Conversely, all the structured airspaces had relatively subdued effects related to these inputs (note that Salt Lake City has a grid-like road system).

3.2 UTM Scenario Set Design 2

A contingency occurs when a UAS does not follow its nominal flight path. This may happen due to UAS platform issues (power, control, etc.), or external factors (e.g., weather, other platforms, lane closures, or rogue flight interference). The UTM itself may provide mechanisms to handle contingencies, e.g.: re-planning flight paths, emergency lanes in the air alongside regular lanes, emergency landing lanes, etc. These may exist as part of the static structure of the UTM or may be created dynamically as the need arises.

Alternatively, it may be more effective to allow the UAS to perform tactical deconfliction by exploiting the lane structure. This can be achieved by having the UAS modify their speeds as they proceed through the prescribed lane sequence. This may propagate through the entire network, but, in general, results in a localized modification of flight plans.

In order to tactically deconflict a flight in a lane, it is only necessary to ensure that at no point along the lane is it within less than headway distance to a flight in the lane or in another lane sharing an endpoint with its lane. The Closest Point of Approach Deconfliction (CPAD) algorithm described here accomplished this task efficiently.

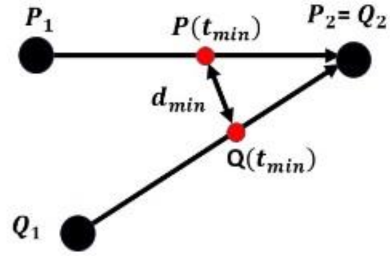

Figure 11 Closest Point of Approach (CPAD) diagram.

Consider Figure 11, and let $S_1 = \overrightarrow{P_1P_2}$ be Lane 1, L_1, and $S_2 = \overrightarrow{Q_1Q_2}$ be Lane 2, L_2 (i.e., vectors indicating the length and direction of travel in the lanes). Then the flight (f_1) traveling in L_1 has a trajectory described by the equation $P(t) = \boldsymbol{P}_1 + t\boldsymbol{v}$ and the flight (f_2) traveling in L_2 has a trajectory described by $Q(t) = \boldsymbol{Q}_1 + t\boldsymbol{w}$, where $\boldsymbol{v}$ and $\boldsymbol{w}$ represent the velocities of each flight and t is time in seconds. The velocities can further be described in terms of speed and the direction of travel along a lane, therefore $\boldsymbol{v} = \frac{s_1(\boldsymbol{P}_2 - \boldsymbol{P}_1)}{|\boldsymbol{P}_2 - \boldsymbol{P}1|}$ and $\boldsymbol{w} = \frac{s_2(\boldsymbol{Q}_2 - \boldsymbol{Q}_1\}}{|\boldsymbol{Q}_2 - \boldsymbol{Q}_1|}$, where s_1 and s_2 are the speeds of f_1 and f_2. The time when the two flights are closest in their trajectories is:

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

This calculation is performed between each pair of aircraft, selecting either t_{min} or the time at which the first flight reaches the end of the lane, whichever happens first, and recording the distance between the aircraft at this point in time. If this distance is smaller than the minimum separation required, then there is a *conflict,* and an action is taken to slow down one of the aircraft. The algorithm that is applied to all aircraft in the lane system goes as follows:

Algorithm 1: Closest Point of Approach (CPAD)

∀ 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.

The CPAD algorithm makes use of the following sub-algorithm that occurs between each pair of flights:

Algorithm 2: Deconflict_Pair

while *conflict*(f_1, f_2)
   reduce speed of f_1
   if the speed of f_1 is below a minimum
      exit lane system

Strategic deconfliction is not guaranteed under this method, however it does ensure that flights will never violate the minimum headway distance (with the caveat that failures to deconflict result in requiring a flight to exit the main lane system). There are several benefits to this approach: contingency handling is simple and robust, privacy is maintained (complete trajectory information is not required), and deconfliction occurs in a decentralized manner. Flights must communicate using radio and telemetry if sensor range (e.g., radar) is compromised by weather or is not available.

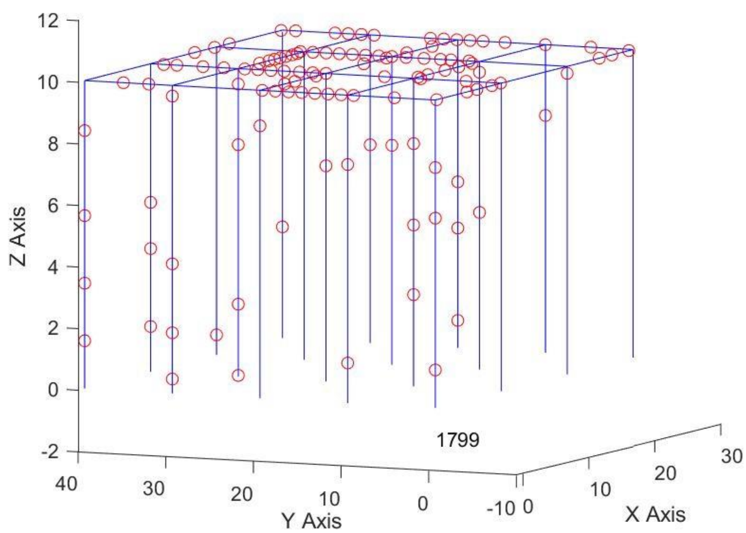

Figure 12 UAS in a lane system (in blue) during discrete event simulation. Red dots represent UAS in flight.

The CPAD algorithm was tested in a discrete event simulation with 100 or 200 UAS with launch and land sites randomly selected, and with desired max speeds of 5 and 9 (e.g., about 17 and 30 mph) in simulation units. These flights took place in a 3x4 grid network shown in Figure 12. Flights launch at uniformly sampled times across the simulation period. Table 1 provides the results for five sets of parameter values. Only one flight failed[2] (out of 3000), delay was kept to a minimum, and flights flew at or near the desired speeds.

[2] "Failed" in this context means that a flight could not be deconflicted and must exit the lane system.

Table 1 Discrete Event Simulation Results.

t_{max}	*nf*	*smax*	*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	15	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	188	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	0	8.97	3

3.3 UTM Scenario Set Design 3

The basic problem addressed in this scenario is how a lane-based UTM system supports the detection and classification of misbehaving flights. Considered here are trajectories that would be generated by amateur recreational hobbyists, UAS operators making an unscheduled point-to-point flight, malicious operators, etc. The detection of such flights involves the analysis of trajectories based on their deviation from the lane structure, including both location in space and direction of flight at that location. In this sense, the lane structure represents a model of what all the possible flight trajectories could be and provides a basis for anomaly detection. In contrast, the FAA approach would require knowledge of all four-dimensional flight trajectories via target tracking (using radar or visual methods) to monitor the flights and a rapid comparison of them to each scheduled flight. For the anomaly detection to be successful with the FAA approach, complete trajectory information of all scheduled flights would be needed. Thus, the proposed lane-based method is much more efficient and maintains privacy.

3.3.1 Nominal Versus Anomalous Behavior: NAB

Nominal cooperative flights report their telemetry at a pre-determined frequency (e.g., 1 HZ) to their associated PSU or USS, and this data from on-board sensors is expected to follow an approved trajectory (within reasonable constraints). Alternatively, or in conjunction with telemetry, radar or other sensors may be used to monitor flights and provide an independent source for trajectory data. Various flight trajectory classifications are possible depending on the intentions of the flight operator, for example point-to-point delivery or reconnaissance operations may have different expected profiles. These data sources and the expected variability in trajectory behavior must be considered to develop an effective airspace monitoring system.

Consider a planned flight and its associated trajectory, where the UAS nominally sends telemetry data and a unique identifier for that aircraft. This makes it possible to determine if the flight is off course and by how much. Independent verification of telemetry data is accomplished using external sensors for airspace monitoring, such as radar, which can produce locations of airborne objects. Assuming that it is possible to classify which objects are UAS with high probability (as opposed to birds, etc.), the expected result is that reported positions are consistent with ground sensor data.

In contrast to nominal cooperative flights, unplanned behavior produces classifiable trajectories in ground sensor data that may or may not have corroborating evidence in telemetry data. Misguided, malfunctioning, or malicious agents produce this class of behavior; more specifically, planned flights with unexpected trajectories are *anomalous*, and unplanned flights with unknown trajectories are *rogue*. The trajectory that a rogue vehicle takes through the airspace is determined by the type of flight it is, and generally will have one or more of the following characteristics: it does not correspond to any planned flight, it will not be corroborated by telemetry data, and it will not follow a sequence of connected lanes. It is possible that UAS can insert themselves into the lane structure and mimic a scheduled flight (e.g., by following a scheduled flight), but this can also be detected since they not likely to provide telemetry data (i.e., they are non-cooperative). Unscheduled flights in the airspace are called *rogue*, whereas unexpected trajectories are called anomalous.

In practice, an Air Traffic Operations Center (ATOC) needs to detect anomalous flights as robustly as possible, and the NAB method is an approach for classifying Nominal versus Anomalous behavior, described in Figure 13.

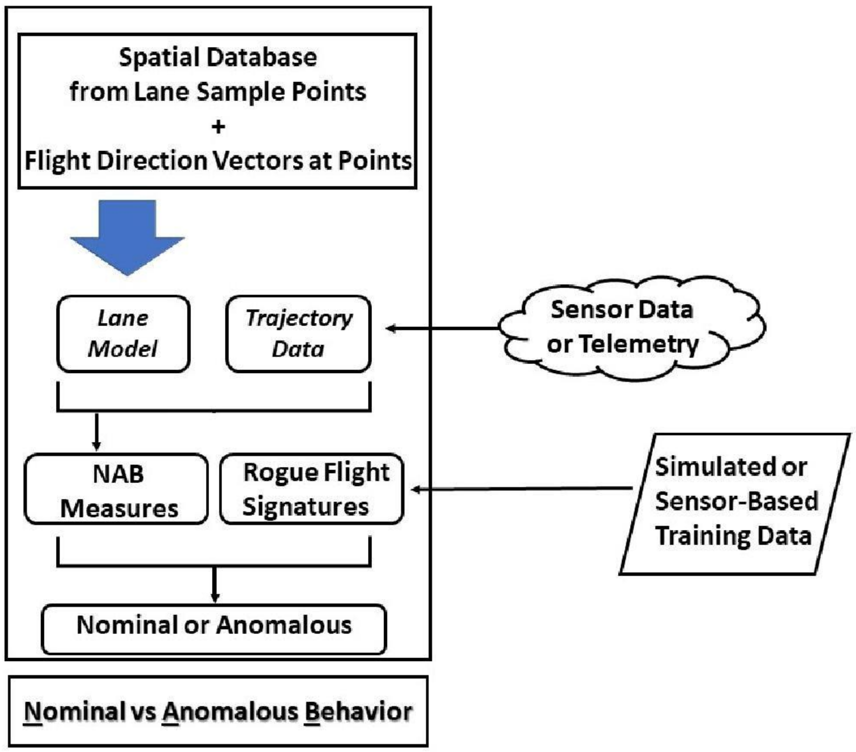

Figure 13 The Nominal versus Anomalous Behavior (NAB) method.

For NAB to operate effectively, lane data is made available along with the UTM policy parameters and the set of scheduled flights. A spatial database is constructed from this data and consists of a set of 3D points sampled along each lane, and to each of these points is associated a nominal direction vector (recall that lanes are one-way directed paths). The lane model consists of this data organized so as to be efficiently exploited. The inter-sample distance must be selected so as to minimize the number of points while at the same time allowing adequate discriminatory power to determine if a flight is near a lane and headed in the right direction.

Next, a set of NAB measures are determined which allow the discrimination of the different types of flights, both nominal and rogue. These are computed either by comparing the UAS trajectory to the lane data, or simply in terms of the trajectory itself. For example, two lane-related measures are:

1. M_{dist}: minimum distance to a lane at each time step, and
2. M_{dir}: cosine of the angle between UAS direction of travel and the lane direction of travel at each point.

These measures are applied at each point in the trajectory to produce a temporal signature to represent the flight. An example of a measure based solely on the trajectory data would be the amount of time spent hovering (i.e., staying for some minimal duration in time in one place in space). Given a characterization of the types of flights of interest, then a set of trajectory signature templates can be constructed and used as class models. Such templates can be the result of a set of simulations or produced from data sets of actual flight trajectories. Given a new trajectory, its measured features are compared to the flight signature templates and matched to the closest in order to classify the type of trajectory (i.e., nominal or anomalous).

Consider a nominal flight which does not perfectly follow the lane but rather has some noise associated with it. Figure 14 top row shows the x values of a nominal flight trajectory (with Gaussian noise of 0.16 variance), and a smoothed version of that data (in red). The middle row shows the distance to the closest lane, and the bottom row gives the cosine of the angle between the direction of flight and the lane direction. This distance and direction difference are NAB measures. For the distance measure, over 96% of the trajectory points are within one unit of the lane, and for the angle difference measure, 70% are within 10 degrees. The large angle differences arise at lane changes.

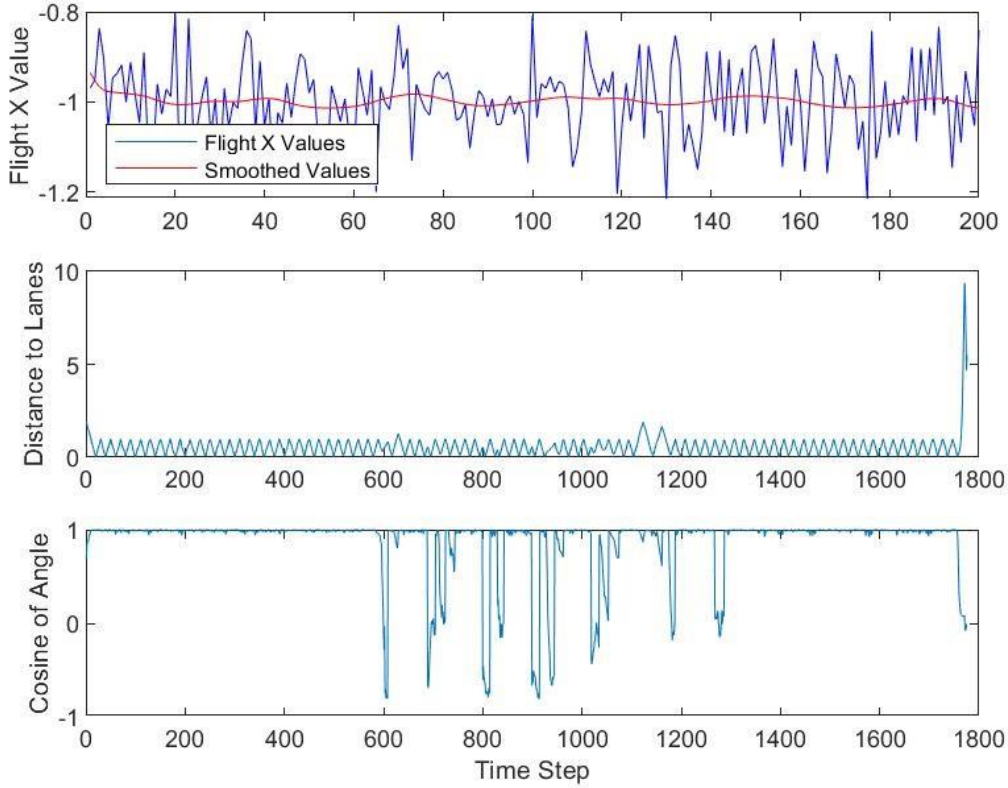

Figure 14 NAB measures for a nominal flight.

Once an anomalous flight has been identified, it is possible to develop more refined and model-based techniques to distinguish between the sub-classes. Some characteristics of anomalous flights are:

- *Hobbyist Type I:* not on lanes, not in correct direction, change of altitude in nonvertical direction, launches and lands near same site.

- *Hobbyist Type II:* not on lanes, not in correct direction, change of altitude in nonvertical direction, launches and lands near same site, hovers for short periods of time.

- *Hobbyist Type III:* not on lanes, not in correct direction, change of altitude in nonvertical direction, launches and lands near same site, makes circular motion.

- *Rogue Type I:* not on lanes; only goes up, over and down; middle segment may not align with lane; may not be at normal lane altitude; launch and land sites may not be near lanes.

- *Rogue Type II:* not on lanes some of the time, not in correct direction some of the time, lanes followed may not be connected in lane network, some changes of altitude not vertical.

These anomalous flight patterns are representative of the types of flights to be expected. Figure 15 shows examples of each of these types.

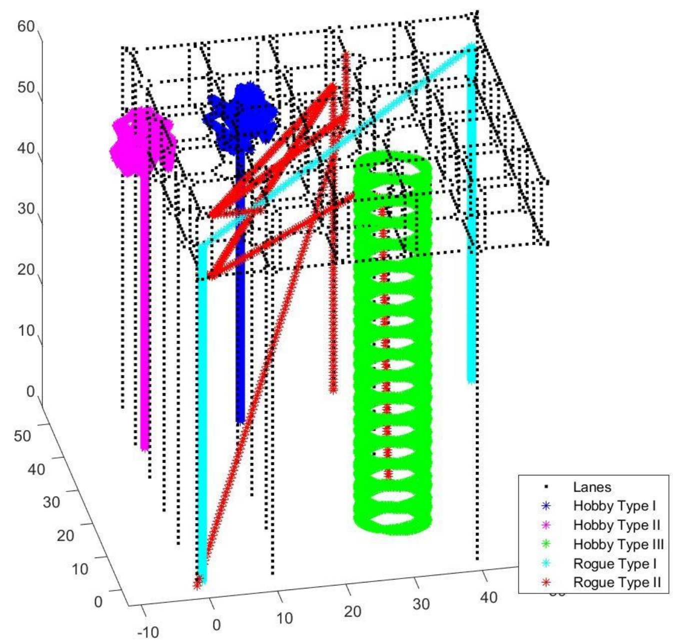

Figure 15 Examples of the five anomalous flight trajectories.

3.3.2 Nominal Versus Anomalous Behavior Analysis

Given a set of UTM lanes, a convenient model is just a set of point samples on the lanes, each with an associated direction of travel in the lane. Figure 16 shows a set of sample points from the lanes given in Figure 17. These provide a good model since any nominal flight (i.e., following its assigned lane sequence) should be near a lane and headed in the direction of the (one-way) lane.

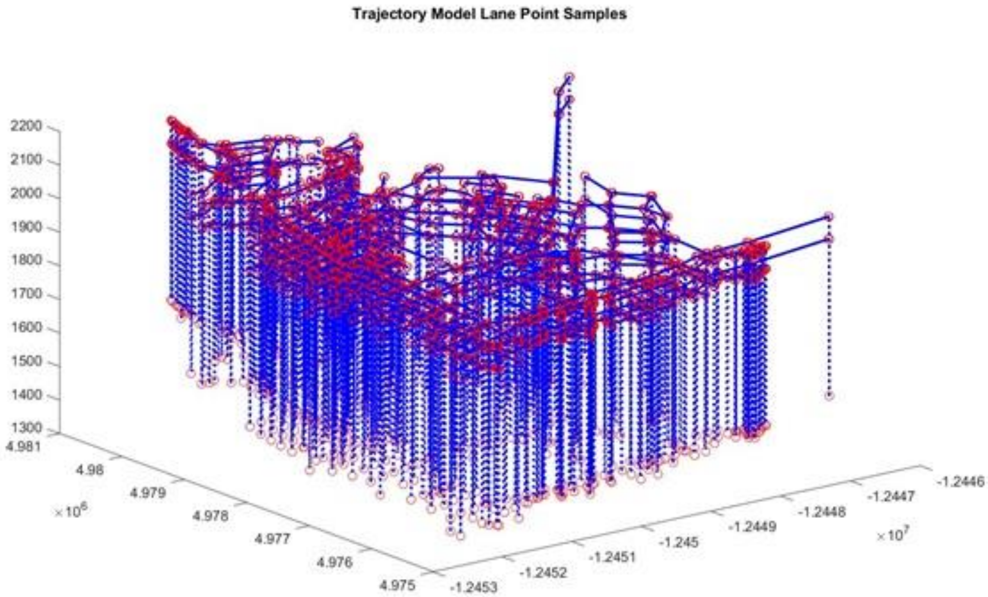

Figure 16 Trajectory point set model of airway lanes over East Bench of Salt Lake City, UT. Red circles are lane endpoints; blue points are samples along the lane.

The trajectory model is then just the set of 3D sample points along the lanes and the direction of travel vector at each of those points. In the example here, for the Salt Lake City East Bench airways, an inter-sample distance of 2 meters produces a set of 454,331 points. The model is organized as a kd-tree using the 3D points. Any nominal flight should be near one of the sample points and headed in the appropriate direction. Of course, a temporal analysis can be performed by checking the associated Space-Time-Lane Diagram which specifies the position of each flight in a lane at each time instant. Also, with the FAA-NASA unstructured airspace approach, there is no fixed set of lanes, and therefore, every existing flight would require target tracking against the set of all flights.

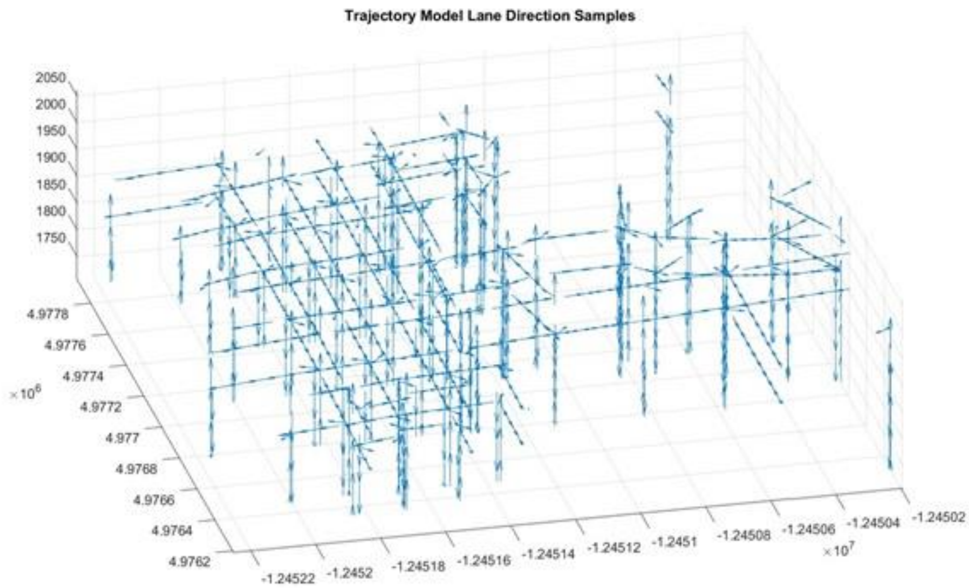

Figure 17 Trajectory direction vector model of airway lanes over East Bench of Salt Lake City, UT.

The two NAB measures given previously allow the discrimination of nominal from anomalous flight trajectories in almost all cases. This is because anomalous flights, generally speaking, do not stay near the lanes nor do they fly in the same direction as the nearest lane. However, trajectories (i.e., x,y,z,t 4-tuple sequences) are of variable length depending on the distance of the flight and the sampling rate. Thus, in order to compare trajectories, it may be necessary to normalize the length of each trajectory to some standard length.

The nominal flights can be distinguished from the anomalous flights by means of a simple feed-forward neural network. First, the trajectory lengths are normalized. Next, the NAB measures are computed at every point on the trajectory, and finally, the measures are concatenated into one vector (in this case, distance measure followed by cosine measure). A trajectory generator is created for each flight type based on random launch-land sites (uniformly selected over flight area), and appropriate parameters for the type of flight. Noise is added to the trajectory as follows (the same type of noise is added to all trajectories). First, the ideal trajectory is created. Then starting with the first point and moving to the second point, the error is defined by a circle around the goal point (the circle in the plane normal to the vector from the first point to the second point). A point in the circle (uniformly selected) is chosen as the target point. Next, a point on the line between the starting point and the circle point is chosen using a half Gaussian distribution centered at the circle point; this is the next point in the modified trajectory. When the circle has radius zero, and the Gaussian has zero mean and variance, then the resulting trajectory is the same as the original.

A set of 100 sample trajectories was generated for each flight type, including nominal, for a total of 600 trajectories; half of these were used to train the network to classify nominal versus anomalous flights (two classes), and half were used to validate the result.

These characteristics are used to develop models of the various trajectories, and a classifier built based on them. Using the same set of simulated trajectories already described, the classification confusion matrix shown in Table 2 is achieved. From these results it can be seen that the trajectories of the Hobbyist Type I and the Rogue Type II are similar and require further refinement for discrimination.

Table 2 Classification results as a confusion matrix

	Nominal	Hobbyist I	Hobbyist II	Hobbyist II	Rogue I	Rogue II
Nominal	100	0	0	0	0	0
Hobbyist I	0	92	0	3	2	3
Hobbyist II	0	0	100	0	0	0
Hobbyist II	0	4	0	83	10	3
Rogue I	0	0	0	0	100	0
Rogue II	0	14	0	0	0	86

4.0 SECURITY REVIEW

The UAS Traffic Management (UTM) architecture is a cyber-physical system, integrating sensing, computation, control and networking into physical objects and infrastructure. This fact exposes UTM to several possible threats that have the potential to augment operations that reduce safety margins, cause contingencies, or degrade subsystems such as telemetry. An early characterization of possible attacks was provided in a publication titled, *Cyber Security of Unmanned Aircraft System Traffic Management (UTM)* [7], shown in Table 3. This characterization divides up the possible threats by type: threats that exist or are accomplished by software or networking comprise cyberattacks, and threats that affect or are accomplished by physical systems comprise physical attacks. For example, Stuxnet is a famous cyberweapon, believed to have caused significant damage to Iran's nuclear program, that could be characterized as a cyberattack type that affected physical systems and therefore would exist in the lower left quadrant of Table 3. This was a case of a malicious computer worm that took control of physical centrifuges, spinning themselves to failure while reporting false information to personnel who remained unalerted of any issues [8]. At a high level, UTM threats can also be categorized by their resulting effects on the system, some of which are:

- Attacks that alter perceptions of space and time
    - Manipulation of an aircraft's own perception of position and orientation, or that of other aircraft in the airspace.
    - Manipulation of an aircraft's perception of the presence or absence of physical obstacles.
    - Manipulation of an aircraft's perception of spatial environment and restrictions, e.g., geofences, virtual corridors, weather, and terrain.
    - Manipulation of an entity's perception of time

Table 3 Cyber-Physical System Attack Characterization.

		Attacked Asset	
		Physical	**Cyber**
Attack Type	**Physical**	*Physical Attacks* - Sabotage of infrastructure - Physical weapons to disable UAS - Coercion of authorized persons	*Cyber-Physical Attacks* - Radio signal jamming - Compromising unattended sensors - EM radiation-based attack on security keys
	Cyber	*Cyber-Physical Threats* - ADS-B/GNSS spoofing - Sensor data manipulation - Telemetry data/link manipulation	*Cyber Attacks* - Malware insertion - Network traffic analysis - Data theft and corruption - Identification spoofing - Cryptanalysis

- Attacks that misuse UTM resources
    - Manipulation of vehicle trajectories or rogue aircraft.
    - Unauthorized airspace access.
    - Data theft or privacy violations.
- Attacks that deny or degrade UTM accessibility and operations for users.

Given a categorization of threats, the subsequent analysis includes a deeper assessment of risks within each category, their possible treatments (i.e., mitigation strategy), and finally agreement on acceptable risks if they cannot be mitigated. This is the process that was followed by a group of UTM stakeholders and published in a document titled, *Security Considerations for Operationalization of UTM Architecture* [9], published in January of 2021. Stakeholders included the Virginia Tech Mid-Atlantic Aviation Partnership (MAAP) UTM Pilot Program (UPP2) team, and industry representatives from AirMap, AiRXOS (part of GE Aviation), ANRA, Wing, and Google, as well as FAA and NASA security representatives. In that report, the authors categorized threats by the likelihood of a successful attack and the estimated cost for executing it. Table 4 summarizes the criteria that the authors used to consider which risks they considered acceptable, and which required mitigation, indicated by the gray highlighted cells (e.g., Remote, Occasional, and Frequent categories).

Table 4 Cost and Likelihood of Successful Attack [9]

Likelihood Level	Quantification of Likelihood
Extremely Improbably	Zero-day exploit available; multi-lateral staged attack; +$10M in cost
Improbable	$1M-$10M in cost; complex mission planning with staff; bot herder, fleet of bots
Remote	Multi-thousand to millions of dollars in cost; sophisticated malware, ransomware, phishing, etc.
Occasional	Unsophisticated malware
Frequent	Low cost or free; pay for hire

The authors then identified four scenarios that were not mitigated by standard security practices and that were focused on the important task of Strategic Deconfliction:

1. A UAS Service Supplier (USS) attempts to obtain Operational Intent details from another USS that was under a Denial-of-Service (DoS) attack.
2. A USS attempts to post Operational Intent details to another USS in response to a subscription notification from the Discovery Service (DSS), but it is under DoS attack.
3. A USS attempts to obtain airspace constraint details from a USS that is under a DoS attack.
4. A USS attempts to post constraint details to another USS but it is under DoS attack.

Denial-of-service (DoS) attacks occur when legitimate users are unable to access information systems, devices, or other network resources due to the actions of a malicious cyber threat actor [10] . The authors of [9] did not publish their proposed mitigation techniques, however, generally this involves detecting abnormal network traffic conditions, such as slowness, and redirecting the abnormal traffic away from the affected systems. Other mitigation strategies include forming a disaster recovery plan if normal communications are disrupted for an extended period. The CPAD algorithm that was introduced in the previous section is one way to maintain a fallback plan that requires only onboard sense-and-avoid capabilities or local/short-range communications and not the wider network services in the UTM.

The few security publications highlighted on NASA's UTM technical documents website [11] categorize some of the risks and mitigation strategies, but they don't describe the expected impact of these attacks on the resulting behavior of the entire UTM system. For example, if any of the four scenarios described above occurred and the mitigation strategy includes flying back to the launch site, what happens if all the aircraft in operation experience a similar attack and perform the same action? This situation could result in a cascade of conflicts that may not be computationally feasible to solve depending on the density of aircraft in the area. For this reason, the research and engineering in this space is still nascent and will require greater simulation capabilities to determine effective strategies.

5.0 CONCLUSIONS

5.1 Summary

If thousands of autonomous aircraft are to operate safely and efficiently over constrained airspaces, it will be necessary to develop well-defined processes and structures for coordination, contingency handling, and security. This report provides overviews of the current state of the art as published in public reports and research, and offers a few innovative solutions to consider in the development of this new mode of transportation. A lane-based approach to strategic deconfliction offers regulators a way to structure the airspace and autonomous agents a way to reason about contingencies. We presented a contingency handling protocol for mitigating in-air delays as well as an efficient way for detecting and classifying anomalous aircraft trajectories. Finally, we offered an overview of the current research regarding security risks associated with the published architecture of UTM.

5.2 Conclusion

The current progress in developing advanced air mobility, as indicated through published reports and research, has produced some stable concepts as well as issues that still need to be resolved. The notional architecture for UTM and UAM (Figures 2 and 3) have held up quite well, and both government and industry stakeholders have been able to use this framework for development and business planning. While the overarching roles and responsibilities are well defined, the specific actors that will fulfill them are still in flux. Notably, the role of Departments of Transportation is still lacking in the literature even though the added value of including them in the conversation is clear. Departments of Transportation can serve many roles in this growing industry, as supplemental data service providers, public safety officials, and/or urban planners. Additionally, they can be a major source of research funding that considers these concerns.

The lane-based approach is an effective way to structure the airspace and enables a host of downstream architectures for detecting and classifying anomalous flights, and for dealing with contingency scenarios. The NAB method for detecting and classifying anomalous flights is a computationally efficient way to characterize the state of the airspace and to alert regulators of issues. The CPAD algorithm additionally provides autonomous aircraft with a standardized method for performing tactical deconfliction in the case of a contingency in a lane-based airspace structure. The security review indicates that there is still much to understand about how advanced air mobility will effectively handle contingencies that are the result of bad actors.

5.3 Future Research and Improvements

In this report we considered only a single type of contingency, one in which an air delay causes a reduction in safety margins. In future research, different types of contingencies will be considered, such as communication outages or bad actors. Mitigation strategies such as additional or dynamic lane generation will be considered to offer regulators with more control over the behavior of the air traffic system under these contingent scenarios. The nominal versus anomalous behavior method will also be expanded to take into account more complex trajectories and a larger number of classifications. Lastly, a system where the lane-based approach co-exists with other airspace systems (e.g., the FAA/NASA model) will be explicitly modeled and simulated. This would represent a step towards implementation and testing with real aircraft.

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