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Lane-Based Unmanned Aircraft Systems Traffic Management

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To all those who participated in developing the ideas and systems presented here (especially to Vista Marston), to our families, and to the future of autonomous systems!

Preface

This book is the result of many years of effort in trying to develop an efficient and effective approach for large-scale UAS traffic management. The methods we present apply to a future of air mobility that imagines a dense network of autonomous aircraft, transporting people and things within and between cities. Throughout the book, we make connections to the ground transportation network, and we take inspiration from the engineering that has developed there over the last century. We combine aspects of ground traffic engineering with the latest research in advanced air mobility.

At the time of writing of this book, advanced air mobility is still in its infancy. This is apparent by the absence of low-altitude vehicles flying overhead, but also by the lack of standardization and the pervasive questioning of whether such a future is yet possible. Among all the problems that motivate this skepticism, the problem of automating air traffic control is particularly interesting to the authors of this book. It is an engineering problem that is susceptible to catastrophic consequences due to computational intractability, and so demands the attention of researchers in computer science and robotics. The current iteration of the autonomous air traffic control system proposed by NASA and the FAA draws heavily from current human air traffic control practices.

Both ground transportation and air traffic control systems incorporate many trade-offs when it comes to safety, reliability, and innovation. However, they share the characteristic of relying on human cognition to make critical decisions. If advanced air mobility requires aircraft to fly autonomously, then it follows that those critical decisions must be made predictably by machines. Just as roundabouts can replace signalized intersections, thereby reducing the coordination complexity for humans, the lane-based approach is an attempt to simplify the environment for autonomous vehicles.

Much remains to be done, and we have tried to point out research directions at the end of each chapter. Thus, this book should provide some guideposts to the future of UAS traffic management as well as an exposition of the current state of the art. We look forward to participating in discovering that future!

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Current State of Affairs: Economic Impact

1.1 Motivation

Our research team entered the Advanced Air Mobility (AAM) arena in August of 2018, when Andrew W. Buffmire, Research Corporate Ambassador for the College of Engineering at University of Utah, invited our research team to a meeting titled "UAS Modeling and Management," held in the Halverson Conference Room in the Warnock Engineering Building. Among the twelve attendees was Jared Esselman, the Director of Aeronautics at the Utah Department of Transportation (UDOT), as well as a representative from the Governor's Office of Economic Opportunity, the University of Utah Hospital System, the university's Entertainment Arts Engineering program, and Fortem Technologies. Before the meeting, an invitee from Utah's Automated Geographic Reference Center (AGRC) sent an email to the group apologizing in advance and providing some data that foreshadowed the discussion:

```
Hello all,

I am unable to attend the meeting this Friday, but
wanted to send out a few maps that may be helpful while
having this discussion and let you know that we have
access to several GIS datasets that may be helpful in
putting together the air space model.

Please let me know how I can help.

Sean
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In one attachment (Fig. 1.1), a map of features and the Salt Lake valley included locations of GPS sensors for Real-Time Kinematic (RTK) positioning, liquor stores, libraries, post offices, correctional facilities, and schools. At the meeting, we discussed how the GPS network could be used by autonomous vehicles to accurately report their telemetry and maintain safe separation. The other features on the map were endpoints in an imagined airspace network that transported cargo and passengers quickly, quietly, and efficiently between locations within city limits. We treated the availability of vehicles that could meet the challenges of urban air mobility (UAM) as an inevitability, and we focused on how our city could become a platform for developing this new transportation system. In Utah, a well-established and growing aeronautics and technology industry, research institutions with a running start on robotics, and a forward-looking governmental body at UDOT provided a means for making serious contributions to this vision of the future.

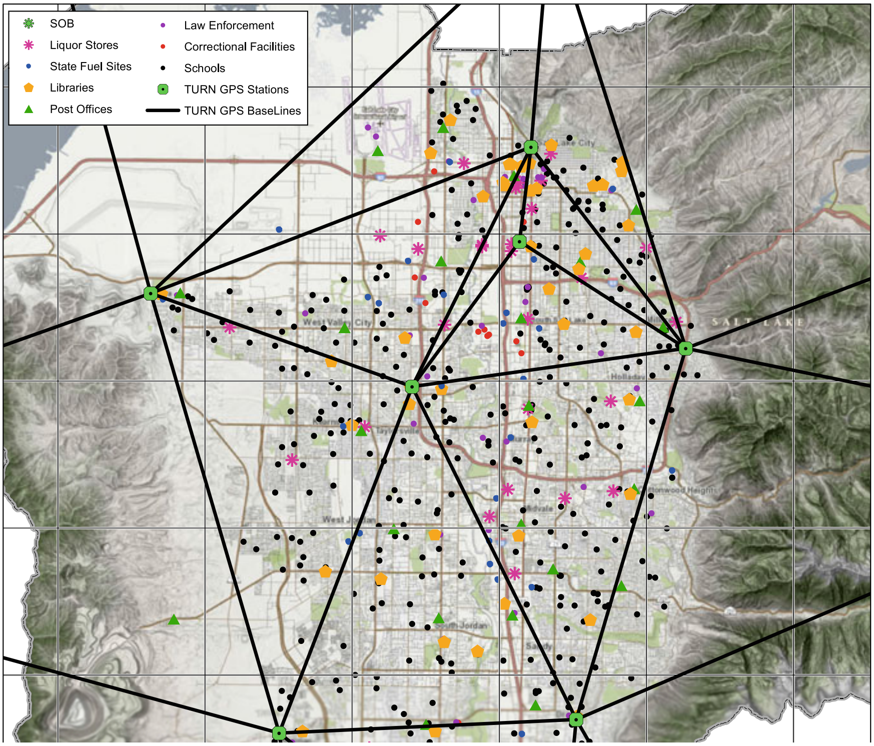

Fig. 1.1 Map of selected features in Utah for urban airspace modeling

However, it was also clear that this vision entailed considerable technical, logistical, and business challenges to overcome.

Advanced Air Mobility describes an emerging aviation market for local, regional, intraregional, and urban use-cases, supported by a set of disruptive technologies. 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. Just a few of the publicly traded companies in this space, Joby Aviation, Lilium, Archer, and Volocopter represent over $4 Billion in market cap and have yet to transport a single paying customer. With so much investment and engineering effort going into vehicle development, it is no wonder that early adopters and innovators are bullish, and it is easy to imagine, given the state of traffic in many cities, that a scenic ride inside a Tesla-like aircraft would be popular (assuming the price was right). Within each vehicle also exist 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 businesses 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. A couple of months after our first meeting with UDOT and local stakeholders, NASA published the reports that identified key technologies and barriers. In one figure [67], Crown Consulting identified 34 technologies on the critical path of development and divided them into 15 categories: 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, and 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 coördination 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 (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 that 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.

1.2 Visuals and Concepts

After the first meeting with UDOT, our research group produced a conceptual simulation of airspace corridors over Salt Lake City. One of the issues that we had discussed was the problem of where low-altitude aircraft would fly and how the public concerns about privacy and noise might be addressed. At the state level, the roads are public property, and so the idea was floated that aircraft should simply fly over the roads. Presented as a short video with a camera that rotated over the city, we demonstrated how 3D semi-transparent rectangular corridors could be constructed from geographic information system (GIS) data that was available from state agencies. Although the simulation lacked precise placement of corridors and their merge points, the visualization had the effect of catalyzing more conversation in the state and generating interest from multiple industry stakeholders, including GE (AirXOS), AirMap, and Bell Aircraft.

Airspace visualizations and simulations are a powerful tool to guide conversation and facilitate coordination. Visit any website of the major players, Joby Aviation, Uber, Google, AirBus, etc., and you are bound to find an animated visualization depicting the future of air travel. However, simulations are normally constructed to answer more specific engineering problems, rather than as a marketing tool to generate interest. Our initial visualization was constructed using an open-source library called NASA Worldwind. This is a 3D geospatial visualization library with bindings for Java and web technologies such as Javascript. The video that we shared with UDOT and others was a Java program that read GeoJSON data describing the road network around the University of Utah and then constructed three-dimensional corridors at a fixed height above the ground. A small applet with 3D controls then allowed the user to pan and rotate around the area of interest. A movie was then created by programming incremental rotations about a fixed center and storing frames from the applet at a rate of 15 frames per second (fps). The width and height of these corridors were chosen arbitrarily to make the visualization appealing. Additionally, several spherical objects, representing aircraft, were programmed to “fly” through the corridors.

That same year, NASA announced that it would end support for Worldwind, so our team looked elsewhere for a visualization tool. Most of our rapid prototyping efforts utilize MATLAB, with visualization presented on a generic 3D canvas (using the plot3 function). However, there is also a sense, garnered through many conversations with stakeholders, that to make AAM research palatable to a large audience, it would require more specialized geospatial visualization tools. To this end, a business opportunity arose: a platform for AAM related products could support and accelerate advanced air mobility by making it easier to pitch, develop, test, and deploy research and software technology.

1.3 Technology Opportunity

In the push to adopt Advanced Air Mobility, stakeholders include governmental bodies charged with overseeing airspace utilization, as well as Providers of Services for Urban Air Mobility (PSU), and UAS Service Suppliers (USS). UAS operators such as Amazon, UPS, hospitals, etc. are anxiously awaiting operational Unmanned Aircraft System (UAS) Traffic Management (UTM), which will enable package and drug delivery, as well as unmanned air taxi services. The Global UTM Association defines UAV Traffic Management as a system of stakeholders and technical systems collaborating in certain interactions, and according to certain regulations, to maintain safe separation of unmanned aircraft, between themselves and from Air Traffic Management, at very low level, and to provide an efficient and orderly flow of traffic [43]. Companies such as AirMap, Bell Helicopter, GE, and others have expressed great interest in exploiting such a system. NASA has done market surveys that indicate that by 2030 there may be 750M air taxi flights and 500M package deliveries per year in 15 major cities. In addition, this work may allow efficient integration and synergy between ground and air vehicles. Finally, the existence of such a system will also enable the acquisition of a whole new source of big data (flight data, sensor data, communications data, weather data, etc.) that may form the basis for a wide variety of new services.

Current research and product development aim to catalyze the adoption cycle that underlies the nascent industry of urban air mobility (UAM). In its 2020 forecast publication [37], the FAA acknowledges that “it is extremely difficult to put a floor on the growth of the commercial UAS sector due to its composition and the varying business opportunities and growth paths.” However in the same study, they say, “if, for example, professional grade small UAS (sUAS) meet feasibility criteria of operations, safety, regulations, and satisfy economics and business principles and enter into the logistics chain via small package delivery, the growth in this sector will likely be phenomenal;” phenomenal, relative to the forecast of about one million non-model aircraft operating for commercial reasons in 2024, each registering multiple flights per day [37]. This fleet does not include the vehicles expected to deliver about one million express packages in that same year, according to a study conducted by NASA [67, 78]. The FAA also estimates between 12,000 and 23,000 passenger-carrying autonomous aircraft operating within urban environments by the year 2030. As the FAA suggested in their assessment however, these estimates rely on the assumption that UAM technology will be adopted and that efficient concepts of operations (CONOPS) can be developed.

Consulting reports and conversations with industry stakeholders indicate that most believe *regulation* to be the highest inhibiting factor to growth of the UAM industry. However, NASA's own funded study regarding the barriers to adoption indicates a much more complex landscape, including technical factors as well as market conditions. Therefore, the more realistic view sees regulation as an outcome of progress in the technological development of this industry. The more realistic characterization is where conflicts exist between every pair of stakeholders, and it is the complexity of these relationships that inhibits growth.

One of the authors, D. Sacharny, has developed the GeoRq platform that addresses these complexities by providing a collaborative integrated development environment with specialized system development tools and by structuring the problem in terms of system-level policies and agent behaviors (see Fig. 1.2) using the lane-based approach described throughout the book. Three organizational components form the platform: tools to create and store requirements (specifically geospatial–temporal requirements), tools to create impact and benchmark metrics, and tools to create real or simulated deployments. Both the lane-based approach and the platform are critical components because one provides the conceptual

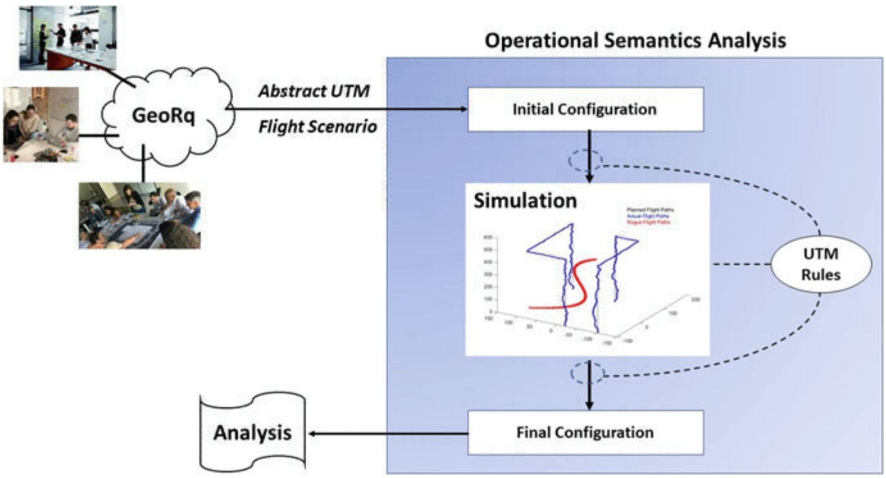

Fig. 1.2 The core component of the GeoRq platform

and computational framework for analysis, and the other provides a vehicle for collaborative engineering and commercialization.

Example Business Model

The main revenue streams for such a product include subscription to cloud services (deployed and secured platform workspaces) and access to APIs and microservices such as the Lane-Based UAS Management System, licensing, and data-access fees. For example, the *GeoRq Workspace* is a cloud deployment consisting of multiple connected instances of virtual machines (VM), databases, and configurations. A GeoRq Workspace may feature an instance of a flight scheduling system, an instance of Eclipse Theia with GeoRq extensions, GeoServer to provide web map services, two instances of GeoRq's PSU, an OIDC security server, and 2TB of Google-backed storage. This setup supports designing, testing, and deploying large-scale logistics operations: one PSU communicates with the region's UTM, while the other forms a digital twin to simulate deployments, and the Eclipse Theia instance with GeoRq extensions serves both the end-user as an Air Traffic Operations Center (ATOC) and the developers as an integrated development environment. Workspace configurations can be updated dynamically with fine-grained resource pricing, and each workspace supports multiple users (contingent upon resource requirements).

In a nascent industry such as UAM, companies must replicate a similar structure of computational instances to conform to UAM system policies. However, the intense competition between current players to develop, and become the standard bearer of UTM software, has forced much of the common architecture into proprietary silos. The result is that non-recurring engineering (NRE) in this space, such as required by new-product development, is expensive and compounds with each new engineer that must climb the same hill.

Open-source development, as with GeoRq, overcomes this problem by packaging up the common architecture, making it configurable, extensible, and deployable, and by providing an integrated open-source systems development tool. Product developers can then repackage proprietary APIs, datasets, microservices, user interfaces, etc., and deploy the white-labeled GeoRq Workspaces as a new product for their clients. Reducing NRE by building products using open-source and collaborative software enlarges the pool of qualified designers, engineers, and users, and it can have dramatic effects on the growth of industries.

In the case of a minimal GeoRq Workspace, not including strategic deconfliction or PSU deployments, a standard software estimation tool applied to the current code base estimates approximately 17 months and 8 engineers to complete this common architecture. The cost estimate of $\$1.6M$ assumes an average wage of $\$56{,}286$; however, a higher average wage is likely due to the narrow expertise required.

After many discussions with potential subscribers, industry stakeholders, and government, our observation is that the drive to create products for the UAM industry exists across many disciplines. Table 1.1 shows a sample of the companies interviewed during our research of this problem. For example, a company might acquire a patent for advanced trajectory generation. After integrating the capability into a web-based API, they would spend considerable NRE developing visualiza-

Table 1.1 Stakeholders interviewed

Firm name
Crown Castle
Crown Consulting
Skytelligence
SmartSky Networks
AiRXOS (GE)
UPS
Aerial Transportation Solutions (ATS)
AirMap
ANRA Technologies
University of North Texas
Camel Works Design (Dubai Road Transit Authority)
Anne Arundel Hospital System
Alakaí Technologies
Westinghouse Electric Company
Fortem Technologies
CogniTech Corporation
University of Utah Health

tions using, for example, NASA's WorldWind libraries for marketing purposes. Given the chance to use a tool such as the GeoRq workspace and the visualization capabilities available there, the API strategy might change considerably. The realization would be that packaging a company's technical capability within a platform such as GeoRq provides a powerful channel to market their product as part of a deployable system. Another example would be a developer engaged in the NASA AAM national campaign in order to commercialize communications research. This would require the development of a PSU for a valid simulation and the necessary infrastructure to deploy a production instance of their technology—this is a costly endeavor considering the NRE required. Access to a GeoRq-like system could accelerate their research. Integration of UAM infrastructure would allow product developers across industry to demonstrate the feasibility and potential for commercial investment. It would not be necessary to spend a considerable amount of NRE developing a web-based system for exploring and visualizing their data, including updates for changes in the AAM framework as this industry develops; systems such as GeoRq are a cost-effective alternative.

A viable business model emerged through these discussions: offer product developers a configurable, cloud-deployable package containing the prerequisites for any UAM product. A basic set of features would be included, with additional cloud capabilities and deployments (such as large-scale publish/subscribe frameworks) available through fine-grained resource pricing. An open-source tier is provided to generate community engagement and sustainable commitment to the platform, allowing developers to customize the platform as the UAM industry evolves. An *Individual* tier addresses the needs of smaller firms, individual entrepreneurs, and researchers. The *Enterprise* tier is for firms that plan to develop multiple products or to deliver the white-labeled platform as a product to downstream clients.

To estimate potential revenue given this pricing model, a sample list of potential subscribers was collected from pre-certified consulting firms for several state departments of transportation (U.S. based). The list was narrowed to consulting firms with the following capabilities, having a high likelihood of serving UAM requirements: surveying and mapping, geotechnical services, traffic operations design, traffic engineering and operations studies, and environmental studies. This compiled list included 1383 firms with an estimated median of 32 technical staff per firm. We expect that technical staff will be drivers, as well as end-users, for adopting a platform such as GeoRq. As an example, the total number of technical staff present in one dataset (the most descriptive dataset) was 158,286 people. For this sample of the total addressable market, if 0.3% of the technical staff see potential in serving UAM requirements with their capabilities and each adopts a single enterprise tier package, then the total annual revenue exceeds $28M. This figure considers the first workspace adopted by these developers, and it becomes compounded as more products are developed, white-labeled, and adopted by downstream clients. Furthermore, this sample market represents a fraction of the developers that will enter this industry in the next few years. The total addressable market for a GeoRq-like tool is likely orders of magnitude above this sample, especially if complementary markets (GIS, programming IDEs, cloud computing) are considered.

The margins on selling this type of NRE are large, the marginal cost to run the enterprise tier in the cloud runs annually about $362. For a firm, or even an individual, deciding whether to venture into product development in this nascent UAM industry, the value proposition is dramatic: a GeoRq-like product reduces the necessary investment by at least $2*M* and accelerates development by at least 1.5 years.

Commercialization Approach

The GeoRq platform is an example vehicle for commercializing research. Research efforts produce software to perform simulations, record and validate benchmarks, and test assumptions. Source code can be delivered directly as part of a workspace configuration or wrapped in a microservice. Front-end code is engineered by programmers using GeoRq extensions and then included with individual or enterprise tiers. The commercial feasibility of each product is measured by the value (the marginal price of selecting this feature with a GeoRq workspace) over the cost of the computational resources required to run that feature in the cloud (e.g., required datasets, storage requirements, etc.) and the NRE required to produce it.

Developers of systems such as GeoRq can apply for a variety of assistance from state and local entities to assist with portions of business development and commercialization. It is usually possible to work with the state agencies to identify, bid, and win procurement opportunities with federal, state, and local government entities. Furthermore, it is possible to seek assistance from the appropriate Small Business Development Center (SBDC) to receive business counseling and assistance in business plan development.