Handling demand- capacity imbalances in aerial vehicle traffic

Leonid Sedov

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Leonid Sedov

Department of Science and Technology
Linköping University, SE-601 74 Norrköping, Sweden

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Linköping University

Department of Science and Technology

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Abstract

It is expected that the number of drones used in both commercial and leisure operations will grow significantly in the coming years, which raises the need for a solid framework for management of this traffic. Unmanned traffic management (UTM) is a system for handling autonomous drone flights over urban areas. This thesis addresses the central questions in UTM: how much traffic is sustainable in a city scenario and what are the possible ways of managing the flights. We consider both horizontal-maneuver collision avoidance and vertical deconfliction strategies, including risk management solutions inspired by performance-based navigation (PBN) – a unifying theme for ongoing airspace modernization efforts (we also consider traffic management for the conventional, manned aviation). We use mathematical modeling and conduct numerical simulations to obtain capacity estimations for a geographical area and present algorithms for airspace management. To our knowledge this is the first thesis on UTM, and several directions for future research are also identified.

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Abbreviations

UAVs Unmanned Aerial Vehicles

FAA Federal Aviation Administration

UTM Unmanned Traffic Management

VLL Very Low Level

BVLOS beyond visual line of sight

sUAS small Unmanned Aircraft Systems

RPAS Remotely Piloted Aircraft Systems

ATM Air Traffic Management

CD&R Conflict Detection & Resolution

PBN Performance-based navigation

SDA Software-Defined Airspace

RAF Royal Aircraft Factory

V2V vehicle-to-vehicle

KPI Key Performance Indicator

Chapter 1

Introduction

In this chapter we describe the setting for the problems studied in the thesis and provide a basic background. The rest of the thesis is organized as follows. Chapter 2 outlines the papers on which the thesis is based and summarizes the contribution of the thesis. Chapter 3 discusses future work. Finally, the papers, comprising the thesis, are reprinted.

1.1 Background

Unmanned Aerial Vehicles (UAVs) have served in the military for quite some time: combat and surveillance drones have been in use by the army for several decades. Mentions of the first attempts to build a remotely controlled warplane can be tracked back to The First World War - in 1917 a radio-controlled aircraft *Aerial Target* was manufactured by Royal Aircraft Factory (RAF) [1] and it was a loitering munition (i.e., a flying bomb) controlled by the Remote Control technology developed by Nikola Tesla. Since then, military drones got a huge technological boost and today are manufactured by many countries.

These days, commercial drone operations are picking up as well: before long, drones will be flying everywhere, greatly improving quality of a multitude of services. According to European drone outlook study [2], over 7 million drones are expected in Europe by year 2025 (of which ≈ 200 thousands will be commercial and governmental drones and approximately one thousand military drones). Federal

Aviation Administration (FAA) states in their recent report [3] that they expect up to 3.17 millions of UAVs by year 2022 in the United States.

Civilian drone operations may be roughly split into two major categories: rural (low density, unpopulated areas) and urban (congested city scenarios with drones potentially flying over people on the ground). Applications of the former include precision farming [4, 5], crowd herding [6, 7], movie filming [4], inspection and monitoring [8], and many other. Urban uses of drones range from building inspection [4, 9] to small package delivery operations [4, 10, 11].

Recent technological advances let the drones make tremendous business impact. Gartner’s research estimated commercial drones market at \$2.8 billion in 2016, with predictions to reach \$11.2 billion by 2020 (not counting military missions which are outside the scope of this thesis) [10]. Even though Gartner’s research concludes that it is unlikely that delivery market will exceed 1% of the market share by 2020 because of the uncertainty in the expected profitability and present logistical issues, a more long-term oriented forecast [11] sees delivery as the main application for drones and projects more than 8 million operations per day within 20 years in the US alone as the most pessimistic scenario.

One of the most exciting developments is the unprecedented level of drone autonomy: it is envisioned that most of the flights will run beyond visual line of sight (BVLOS), using a remote communication and control (C2) link (see, e.g., [2, 11]). Highly autonomous BVLOS high-density operations in a Very Low Level (VLL) uncontrolled (below 400ft) urban airspace are the focus of this thesis.

As a terminological note, we remark that a variety of abbreviations can be found in the literature: small Unmanned Aircraft Systems (sUAS), Remotely Piloted Aircraft Systems (RPAS), UAVs and so on. Subtle terminological differences between all these names are irrelevant for our research, so we will use the terms interchangeably and, in fact, most of the time will simply use the word ”drone”.

1.1.1 UTM

Unmanned flights are not new: a story of a remotely piloted trans-Atlantic flight was reported by The New York Times back in 1947 [12]. Such one-off endeavors, however do not scale up, because huge investments and a whole fleet of operation management helpers are

required to execute a single flight. On the contrary, we work towards thousands of flights per day in a metropolitan area, managed with little human oversight. We are motivated by the need to establish a guidance and control network for autonomous drones and elaborate on the rules governing the future use of airspace by the UAVs.

Indeed, city-scale drone operations pose significant challenges in managing the new type of air traffic and regulating the rules of the game so as not to jeopardize the social potential of the emerging technology while keeping a grasp on it. Addressing this challenge led to the very recent emergence of a whole new discipline – UTM, which is the UAV-focused counterpart of the conventional Air Traffic Management (ATM) [13, 14].

NASA was the first to establish the UTM program (demonstrating several technology capability levels at its test sites throughout the US) and producing the concept of operations (ConOps) [15]. Since then, many other ConOpses have been produced in various parts of the world [14, 13, 16, 17, 18, 19].

These ConOpses differentiate between controlled (where air traffic control services are provided) and uncontrolled airspaces and pose different requirements depending on where drones want to operate. While the requirements are not consistent between ConOpses, they commonly impose much more strict regulations on flights in the controlled airspace as not to jeopardize the safety of manned aviation. These regulations usually require extensive operation planning and coordination with authorities to get an approval, which makes such flights rather exceptional.

On another terminological note, we remark that the abbreviation UTM (and especially UTM 2.0) is now sometimes used to mean *Unified* traffic management – the envisioned system for integrated handling of both the drone traffic and conventional manned aviation. In this thesis, UTM stands for management of *Unmanned traffic only* – even though airspace segregation may eventually give way to the more advanced, integrated management paradigm.

1.1.2 Capacity in UTM

Airspace capacity will likely become the central question within UTM (as it is now in ATM; e.g., it is the primary Key Performance Indicator (KPI) in the current ATM research [20]): How much UAV traffic can we have in a certain area (within a certain time interval)? While today

one sees (or hears) drones flying only occasionally, the capacity will be reached quickly with the growth of demand for unmanned traffic (e.g., in urban areas – not the least due to the noise limitations [21]). It is therefore of utmost importance to define and estimate the capacity of the airspace and pave the way for implementing measures for its management and increase. Aviation industry experience teaches us that this needs to be done proactively, before capacity bottlenecks become a major issue in traffic management (as is currently the case in ATM).

Contrary to the conventional manned ATM reality which deals with planned in advance point-to-point flights occurring between predetermined locations (i.e., airports), the future UTM is expected to feature much higher level of unpredictability. Among the reasons for the uncertainty are: the drones' capability to take-off or land virtually anywhere (as supported by NASA's vision which was expressed by Dr. Parimal Kopardekar's [22] words: "every home will have a drone and every home will serve as an aerodrome"), volatile operating environment (e.g., due to dependence on weather conditions), less predictable demands and others.

Since the regulations for UAV traffic have not been firmly decided yet, several possible "futures" are to be explored. One unknown is the expected number N of daily drone operations in the area of interest. The other important parameter, which is likely to evolve with time, is the safety radius r around a UAV, representing the communication and navigation capabilities of the vehicle. Naturally, the maximum allowed radius r of safety zone around drones is defined by the capacity of an airspace, and in its turn is the base for the requirements to the UAVs equipment precision and quality. Knowing this requirement is of utmost importance for both business and aviation communities to be able to do long-term investments into UAVs as they need to know what equipment is required and how these requirements could evolve over time.

Safety-related capacity metrics depend not only on the equipment precision, but also on the chosen Conflict Detection & Resolution (CD&R) algorithms. In fact, CD&R is one of the most widely studied problems in ATM and UTM; we refer the reader to, e.g., the review [23], and [24, 25] for some recent work. In particular, Muñoz et al. [26] presented a reference implementation of NASA's DAIDALUS - detect and avoid concept for integration of UAS into the national airspace.

Another essential decision for UTM development is whether a centralized traffic management system is needed or a decentralized one will suffice. The main difference between centralized and decentralized systems is in the level of control imposed by a regulatory authority on flights – in the former case the authority requires full situational knowledge and dictates how drones must operate (e.g., what routes drones must follow, how they must deconflict with each other, and so on) and in the latter case there is no centralized body which controls everything, so drone operators bear responsibility to make their own decisions. While decentralized systems provide drone operators with more freedom, it is not clear whether such systems are efficient enough to handle dense traffic. On the other hand, having a central management body with full knowledge is associated with higher degree of safety and efficiency of operations, but often requires advanced planning from the users. Even if a distributed system is not good for continuous use, it can serve as a fallback solution for the situations when the main system is unavailable.

1.1.3 UTM airspace structure

One of the factors that affect capacity is the design of airspace: more efficient use of the airspace could improve capacity. Many ConOpses envision that unmanned sUAS operations will be limited to low altitudes. For example, in the US, the upper limit is 400ft [27] (these restrictions are not consistent among countries and could evolve over time). The current restrictive limitations are likely to create the situation in which it will not be possible for UAVs to use vertical conflict avoidance because of little room, forcing all drones to fly on the same altitude.

Some works [28, 29, 30, 31] explore the *Layered concept* and its effect on the capacity. In this concept the airspace is divided into multiple sectors defined by their altitudes, i.e., the airspace is a pile of vertically stacked bands. The drones are then distributed among the layers based on their heading direction, so that drones in each layer have a similar heading within some allowed range.

The *zoning* concept is similar to the layered concept, but instead of having several layers, the city is divided into zones with restricted heading directions [30]. Along with a virtual 4D *tube network* through which drones fly [30], these airspace designs are special cases of the more general *geovectoring* concept [32].

Our work studies different airspace structures and aims to develop an approach for evaluation and comparison of airspace designs. It also raises the question of dividing airspace into zones with different sets of requirements for aircraft, which is discussed in the following subsection.

1.1.4 PBN for UTM

PBN is a concept initially created for conventional manned aviation [33], which proposes using different sets of navigation systems performance requirements for different airspaces. The requirements must be defined in terms of the accuracy, integrity, availability, continuity, and functionality (or, in layman's terms, the equipment performance), as opposed to requiring specific navigation sensors.

The concept has been lately promoted for use in UTM by, for example, NASA ConOps [15] and SESAR U-space Blueprint [16]. The central idea is to acknowledge the users diversity and to provide them with the required level of navigational services and access to airspaces according to their equipment level. PBN provides for better utilization of the airspace and makes it more accessible to the operators of less performant UAVs.

One possible scenario when this concept could be beneficial arises in metropolitan areas, where the city center experiences extremely dense traffic, while the less-populated surrounding territories can be much less congested. Therefore, it might be economically reasonable to allow operations for cheaper drones with less precise equipment in the less congested areas to create more accessible airspace.

1.1.5 Software-defined airspace

PBN for UTM and different types of airspace designs can be technologically deployed using geofencing (which is a part of U-space U1 foundation services [16] and CORUS [13] ConOpses) or geovectoring. Still, the essential question of how and how often the information about the airspace can be updated remains to be addressed. The current ATM practices, such as keeping Aeronautical Information Publication (AIP) on Aeronautical Information Regulation And Control (AIRAC) cycles, are too slow and may be ineffective as sUAS traffic demand is associated with a high degree of uncertainty. The demand may also be affected by many factors such as, for example, daily

patterns or public events. Enabling the possibility to automatically (or with little human oversight) recompute the airspace structure frequently (or even on-demand) and share it with the airspace users using communication channels is what can be called a Software-Defined Airspace (SDA) concept. SDA caters to improve the efficiency of operations by quickly responding to changes in the demand and helps to utilize airspace better.

In this work we develop algorithms that enable SDA by providing automated approaches for the airspace sectorization with respect to the drones traffic demand. Additionally, our study of capacity estimation with respect to wireless broadband used for data transfer helps to understand whether frequent updates to the airspace could be delivered to drones without jamming the channel.

1.2 Problem description and research questions

Based on the introduction to the research area from the previous section, we now formulate the research problems which are the focus of this thesis and summarize them as a set of questions.

With the predicted urban UAVs traffic growth, it is essential for establishing UTM to understand how much traffic is sustainable in a city and what are the possible ways of managing the flights. Quantitative approach to urban UAVs traffic management requires a reliable way of comparing airspace designs and conflict management tools efficiency (possibly individually for each urban area) to ensure that the airspace capacity along with the safety and efficiency of operations are not affected by a suboptimal choice of the airspace design and conflict management tools.

While high requirements for drones' equipage level can improve airspace capacity, they can at the same time decrease the accessibility of the airspace due to restricting the cheaper range of drone models from entering the airspace. However, since in metropolitan areas traffic density will likely be highly non-uniform, it might be the case that it will be beneficial to allow drones with more imprecise equipment to operate in less congested areas. In order to implement this, a PBN concept must be established in the airspace.

Finally, when a UTM is set up, a system overload can happen in case of a temporary traffic increase. In this scenario, it is essential

to establish a way for reducing the traffic management problem size. One possible solution is to temporarily split the airspace into several separately managed parts.

We summarize the problems, described in this section, as a set of research questions:

- Q1: How many operations can be managed in an airspace under a given set of constraints, i.e., what is the airspace capacity?
- Q2: Can unmanned traffic be managed in a decentralized manner? And how does the performance of decentralized UTM systems compare with the performance of centralized systems?
- Q3: What airspace design and structure suits a given airspace best?
- Q4: How to evaluate the efficiency of CD&R approaches?
- Q5: How can PBN be established in UTM?
- Q6: How can an airspace be divided into separate zones (sectors) in order to manage traffic more efficiently?

In the following chapter we present a summary of the papers included in the thesis and discuss how the papers treat the research questions.

Chapter 2

Contributions and Summary of the papers

In this chapter we discuss the contributions of this thesis and list all the publications included in it along with a summary for each of them.

2.1 Papers included in the licentiate thesis

- **Paper 1** - Vishwanath Bulusu, Raja Sengupta, Valentin Polishchuk, and Leonid Sedov. “Operational Capacity of Future Low-Altitude Urban Airspace Evaluation Techniques”. Working paper. ([34])
- **Paper 2** - Leonid Sedov, Valentin Polishchuk, and Vishwanath Bulusu. “Decentralized self-propagating ground delay for UTM: Capitalizing on domino effect”. This work is an extension of the results presented on 2017 Integrated Communications, Navigation and Surveillance Conference (ICNS) [35] (Best Paper Award). Working paper. ([36])
- **Paper 3** - Leonid Sedov and Valentin Polishchuk. “Centralized and Distributed UTM in Layered Airspace”. In: Proceedings of the 8th International Conference on Research in Air Transportation (ICRAT 2018). 2018. ([37])

- **Paper 4** - Vincent Duchamp, Leonid Sedov, and Valentin Polishchuk. “Density-Adapting Layers towards PBN for UTM”. In: 2019 ATM Research&Development Seminar. 2019. ([38])
- **Paper 5** - Leonid Sedov, Valentin Polishchuk, and Billy Josefsson. “Towards Simplified Optimal Sector Splitting”. In: SESAR Innovation Days. 2017. ([39])

2.2 Publications not included in the thesis

- **L. Sedov**, A. Krasnochub, V. Polishchuk. “Modeling quarantine during epidemics by mass-testing with drones”. PLOS One. 2020.
- K. A. Buchin, V. Polishchuk, **L. Sedov**, R. Voronov. “Geometric secluded paths and planar satisfiability”. SoCG 2020.
- B. Josefsson, J. Jakobi, A. Papenfuss, T. Polishchuk, C. Schmidt, **L. Sedov**. “Identification of Complexity Factors for Remote Towers”. SID 2018.
- J. Dahlberg, T. Andersson Granberg, T. Polishchuk, C. Schmidt, **L. Sedov**. “Capacity-Driven Automatic Design of Dynamic Aircraft Arrival Routes”. DASC 2018.
- V. Polishchuk, **L. Sedov**. “Gender-aware facility location in multi-gender world”. FUN with algorithms 2018.
- V. Bulusu, **L. Sedov**, V. Polishchuk. “Noise Estimation for future large-scale small UAS Operations”. NoiseCon 2017.
- V. Angelakis, A. Efrat, E. Packer, V. Polishchuk, **L. Sedov**. “BBTM: New life for old ATM paradigms”. DASC 2016.

2.3 Contributions and Summary of the papers

This thesis contributes with a series of approaches that support establishing a safe and effective UTM program and is based on five publications. In this section we describe the connection between the papers and provide a summary for each of them.

First, we present an approach which helps to decide whether UTM is needed at all in a given airspace. We achieve this in Paper 1 by estimating the capacity with respect to several different metrics and for varied traffic densities and safety zones radii. The paper shows that if the expected number of drones is low or their equipment performance is good, then it may be possible that the drones can fly freely using only embedded on-board CD&R.

If a UTM system is needed, then the next logical step is to decide which of the available deconfliction approaches will fit the airspace best, given the drones' technological level and geographical distribution of the demand. The important part of this decision process is to understand whether a centralized system is necessary or if conflicts can be resolved in a distributed manner. Papers 2 and 3 are devoted to this subject.

It should be decided whether a PBN using software-defined airspace can be established under the given constraints and whether it will be beneficial. Paper 4 studies implementing PBN in a multi-layered urban airspace. While the densely populated city center can see busy traffic during the day, the skies above the sparsely populated suburbs are less likely to be overcrowded. Therefore, the idea of the paper is to separate zones where many drones are flying simultaneously (and, hence, better equipment is required for efficient deconfliction) from the less busy areas by dividing the airspace into sectors according to the number of layers required in each of them for safe operation of drones.

Finally, Paper 5 presents an algorithm for sectorization which splits the airspace into two sectors with the same maximum and average numbers of simultaneously flying aircraft in every part. The approach is based on the famous *ham-sandwich theorem* [40]. We believe that this algorithm may prove to be useful as a tool in future UTM systems for dividing the traffic problem to be solved into several problems of smaller size.

In the rest of this section we provide a summary for each paper and explain in detail the connection among them.

2.3.1 Paper 1: Capacity estimation

The IEEE/AIAA Digital Avionics Systems Conference (DASC) is a major yearly event in the aviation community. DASC 2016 was themed on "Enabling Avionics for UAS/UTM". The plenary talk

at the conference by Dr. Parimal Kopardekar, the Principal Investigator of NASA UTM program, highlighted understanding the role of volume, noise and spectrum considerations in airspace demand-capacity modeling as the three requests from UTM developers to the avionics research community [41]. Following up on NASA’s request, we evaluated noise impact and radio spectrum demand for a range of values for N (traffic volume). We also studied the urban VLL airspace capacity limits for a range of N and r (the drone safety radius), estimating the ”breakpoint” values at which large-size conflicts involving multiple aircraft simultaneously become inevitable.

This paper is a merger of three conference publications [42, 43, 44] into one streamlined coherent approach. We distinguish three scientific approaches for computing capacity, that is, simulation, sampling, and theoretical estimation, and discuss when these approaches should be used. We use the *Cal model* (introduced in [45]) to generate traffic demand for simulation, and introduce the *LiU model* which is an extension of the Cal model. Essentially, the LiU model defines the probability of observing a drone in each point of the area. It creates the ground for computing theoretical estimations of the wireless broadband bandwidth capacity (i.e., when the communication network will be jammed). Using our model we estimated the probability of exceeding the bandwidth capacity of a typical cell tower assuming the scenario where all UAVs are actively using the network for streaming high-definition videos. Next, we used the LiU model to generate snapshots of traffic, the process dubbed as *sampling*, to estimate the probability of observing a large cluster of simultaneously conflicting drones in the airspace during an operational day. We obtained the probabilities for different cluster sizes which correspond to the possible technological limitations of CD&R for drones – UAVs with more advanced equipment may be able to sustain conflicts involving a higher number of simultaneously flying drones. Finally, the simulation approach was used to compute two other capacity metrics in the presence of a CD&R algorithm: the first one is the safety-related *losses of flights per flight hour* metric and the other one is the performance-related *percentage extension of travel distance*.

We concluded that radio frequency capacity is not likely to be the limiting factor, while safety metrics, such as, for example, appearance of large conflict clusters involving multiple aircraft simultaneously, may become a problem if drones a low level of navigational precision. For example, if the radius of safety zone around drones $r = 300\text{m}$, large

conflict clusters of size > 3 are likely to start occurring already at ~ 15000 operations per day in the area around Norrköping city in Sweden (our guinea pig), with population of more than ~ 100000 people.

2.3.2 Paper 2: Decentralized conflict management

Due to the flight level restrictions (FAA [27]) and imprecise drone equipment, it is possible that the future sUAS airspace will be single-layered. In such a scenario it is of essence to understand the effect of horizontal deconfliction on the system performance. The other problem is to understand whether a global stability of the system can be achieved using only local information which may enable use of a decentralized UTM system. This work attempts to tackle these problems by abstracting local conflict avoidance among UAVs. Drones are represented as disks with some safety radius r which accounts for imprecise navigational capabilities, effects of winds, and other factors. We assume a distributed conflict management strategy based on local vehicle-to-vehicle (V2V) communication. Whenever two drones violate the safety distance, i.e., the respective disks overlap, they are being enclosed with a larger disk which represents a zone reserved for deconfliction maneuvers; whenever two larger disks touch, they are enclosed with even larger disk, and so on. We simulate traffic generated with the Cal model and compare the performance of the system with a decentralized version of ground delay to maintain system safety (the drones were not allowed to take off into airspace covered by a disk) and without it. The paper compares two strategies for reserving an airspace for deconfliction maneuvers: using static and dynamic enclosing disks. A static disk is created once two disks touched and it does not change over time, i.e., from the start it encloses the whole airspace needed for the deconfliction procedures. The creation of such a disk may require extensive communication among UAVs to share information about their intentions. Dynamic disks, on the other hand, at each moment of conflict reserve just a portion of airspace which is currently needed, and thus continuously move and change radius with the conflict evolution.

As a result, we show how the amount of reserved airspace evolves with r and N , and when conflicts move from small local spots to a city-wide phenomenon (e.g., with $r = 300\text{m}$, the area around Norrköping city in Sweden is completely covered already at ~ 30000 operations per

day). Our work concludes that having only local information may be enough for traffic management, provided that the information can be spread around on-demand and that taking CD&R from the global UTM system can be a viable option to reduce the strain on it.

2.3.3 Paper 3: Single- and multi-layer airspace designs

Paper 3 is a counterpart to Paper 2 in the sense that it studies the case where drones use vertical maneuvers for deconfliction. The paper compares single-layered and multi-layered airspace designs and aims to measure the difference in efficiency between centralized and distributed UTM systems. For the centralized systems, we assume that global strategic deconfliction is in place, and for distributed systems we equip drones with tactical CD&R. The following four deconfliction schemes were studied.

In the single-layer airspace design we compare a centralized approach in which drones are waiting on the ground until the planned route is safe vs. a decentralized one in which whenever two drones come into conflict, one of them goes to the lower altitude and hovers there. For the multi-layered airspace we compare a centralized approach featuring the optimal assignment of drones to layers so that each layer is conflict-free vs. a decentralized approach in which all drones start from the top level and whenever a loss of separation occurs, one of the drones descends to the layer below.

All estimations were done by simulating traffic over one operational day for each configuration of deconfliction schemes and parameters N and r . It was concluded that distributed systems may be viable and therefore it might be of interest for regulating authorities to further investigate whether distributed systems can be implemented from the technological perspective. We also evaluated a multi-layer airspace design introduced in [30], where the drones were distributed among the layers based on their heading direction and concluded that it does not always result in a conflict-free airspace even when many layers are present. As a result, this work contributes with an approach which could help regulators in the process of deciding between CD&R approaches and airspace designs.

2.3.4 Paper 4: PBN for UTM

The estimates from Paper 3 imply that with the multi-layer design, dense urban traffic requires a high number of layers for safe operation. Naturally, the distribution of conflicts in urban areas is not uniform, e.g., the city center may have more traffic going through (and, thus, more conflicts) than some less-populated areas around the city. Not surprisingly, the number of layers needed in an area corresponds to the number of conflicts that happen there. The central idea of the paper is to divide an urban area into several sectors based on the number of layers needed in each of them. The main result of the work is an algorithm which sectorizes the airspace by sampling traffic with the LiU model introduced in Paper 1 and building a *conflict graph* for each of the samples, i.e., a graph in which the nodes are the drones in the snapshot and two nodes are connected with an edge if the corresponding drones are in conflict. The algorithm enumerates all *maximal cliques* in a conflict graph (i.e., all maximal subsets of pairwise-connected vertices of the graph) using a *Bron-Kerbosch algorithm* [46] and looks at their sizes and geographical locations. We give different approaches for dividing the resulting cliques map into sectors using one of the following techniques: convex hulls, k -order hulls, α -shapes, and k -order α -shapes.

We implemented the algorithm and showed how the Norrköping Municipality area in Sweden can be sectorized for different values of r and N . For example, a viable sectorization for values $r = 200\text{m}$ and $N = 60000$ daily operations with k -order α -shapes technique applied is presented on Figure 2.1 (we note that it is not necessary to divide the airspace into so many sectors, some of them can be merged together). We conclude that our approach can serve as a starting point for further research in the PBN for UTM area.

2.3.5 Paper 5: Sectorization

While Paper 4 establishes a sectorization approach for the scenario with vertical deconfliction in multi-layered airspace, presented in Paper 3, the main result of Paper 5 is an algorithm which recursively partitions an airspace with a straight line so that the maximum and average numbers of simultaneously flying aircraft in each part are perfectly balanced. Our algorithm falls into the category of geometrical decomposition algorithms (we refer the reader to [47] for a taxonomy of sectorization approaches) and produces convex sectors in the

Figure 2.1: A sectorization of Norrköping Municipality area based on the number of layers required in each of them for $N = 60000$ and $r = 200\text{m}$ with k -order α -shapes technique applied.

output (if the divided airspace originally was convex). The method is based on the well-known *ham sandwich theorem* which originally stated that any three objects in 3-dimensional space can be bisected with a single plane [40].

We believe that our bisecting algorithm can be applied in the future UTM in the situations when a sudden increase in traffic demand overloads the UTM system. In such a case, splitting the airspace into two (or more) separately controlled parts with the same average and maximum numbers of UAVs could reduce the difficulty of the traffic management problem solved for each part.

Despite the fact that the paper was written from the conventional ATM perspective, the algorithm can be applied to unmanned traffic (e.g., from the *Cal model* introduced in Paper 1) without any changes.

2.4 Contributions

In this section we repeat the research questions formulated in Section 1.2 and for each question we explain in which papers and how it was addressed.

- Q1: How many operations can be managed in an airspace under a given set of constraints, i.e., what is the airspace capacity?
  - In Paper 1 we described, evaluated and compared three capacity estimation techniques (simulation, sampling and theoretical estimations). Using these techniques, we estimated airspace capacity of an urban area with respect to wireless broadband bandwidth and operational safety and efficiency considerations for a range of r and N . The range can be narrowed down (or, even concrete estimations can be made) when the performance of drones flying in dense VLL airspace is known, as with the current pace of technological development any estimate would be speculative.
- Q2: Can unmanned traffic be managed in a decentralized manner? And how does the performance of decentralized UTM systems compare with the performance of centralized systems?
  - Paper 2 studies the efficiency of a decentralized conflict management system which is based on local V2V communication. We evaluated two scenarios (with and without

a decentralized version of ground delay) by conducting a simulation of UAVs traffic. Our main conclusion is that a decentralized conflict management is a viable option and regulating authorities should further investigate the possibility of moving conflict avoidance from centralized UTM systems to drones themselves.

- We compared UTM systems with centralized and decentralized deconfliction strategies in both single- and multi-layered airspaces in Paper 3 using a simulation of drones traffic. We conclude that centralized and decentralized strategies which we explored exhibit similar performance.
- Q3: What airspace design and structure suits a given airspace best?
  - We compare two different airspace designs (single- and multi-layered concepts) and describe an approach for an airspace design evaluation in Paper 3. Strategies for multi-layered airspace which we have explored exhibit better performance in terms of flight time extension than single-layer strategies, but require more performant equipment (especially in maintaining the correct altitude), so they may better suit the congested areas where a lot of traffic is expected.
- Q4: How to evaluate the efficiency of CD&R approaches?
  - In Paper 2 we present a model and an approach for estimating the efficiency of a horizontal-maneuver deconfliction strategy. Our approach allows to blackbox the actual deconfliction maneuvers which makes it useful for estimations when complicated conflict resolution strategies are used in the airspace.
  - In Paper 3, four vertical deconfliction strategies were evaluated and compared by simulating a full day of operations for each of them. Simulations based on ours can be used for estimations when similar deconfliction strategies are present in the airspace.
- Q5: How can PBN be established in UTM?

- The sectorization approach from Paper 4 divides an urban airspace into several zones based on the expected number of airspace layers required for safe drone operations. This way, zones with dense traffic (i.e., where more layers are expected to be used) can have strict requirements for UAVs equipment performance, while less congested suburban and surrounding rural areas can opt to allow a wider range of drones to operate.
- Q6: How can an airspace be divided into separate zones (sectors) in order to manage traffic more efficiently?
  - The algorithm from Paper 5 can be used to split an airspace into two parts with perfectly balanced maximum and average number of simultaneously flying aircraft. It can be useful for the cases when an excessive amount of traffic is expected in an airspace to split it into parts with more manageable traffic density.

Chapter 3

Discussion and Future work

With the envisioned unpredictability of UAVs traffic in urban airspace, it is likely that the current laws and regulations will evolve over time when a denser traffic situation becomes reality. This thesis delivers several approaches which can help regulators and stakeholders with the decision-making process.

We showed how to estimate airspace capacity under given operational constraints with some embedded CD&R algorithm. Our work suggests that it is not always true that a completely centralized UTM is necessary – it is possible that some decisions can be moved from a centralized UTM system to the on-board conflict avoidance equipment. We presented a way for airspace designs and CD&R algorithms evaluation which can help regulators to assess how the decentralization affects the efficiency of operations.

We also designed two sectorization algorithms based on the SDA concept. One algorithm helps in establishing a PBN for UTM which seeks to increase airspace accessibility for the cheaper range of drones in less congested areas. This can be beneficial from many points of view: economical (e.g., if a user does not want to operate in congested airspace, then there is no need to buy a more expensive drone), environmental (e.g., with the evolution of requirements for drones in congested areas, older drones with worse equipment can be reused for operations in rural areas), and others. The other algorithm was designed to be used in case of system overload. It splits an airspace

into two parts with balanced workload. Even though it is envisioned that in future UTM there will be no place for human controllers, still an unexpected dense traffic could create a computational traffic management problem of excessive size, which could be solved faster when split into separate problems.

There are multiple possible extensions to this work. In the rest of this section we discuss some of them.

First of all, in our work we used a very simplistic approach where we assumed that all drones are essentially equivalent, i.e., they all have the same safety radius r , technological capabilities and so on. This probably will not be the case with the future urban unmanned air traffic, wherefore one may consider taking into account the diversity of users by accounting for the possibility of having drones with different safety radii, CD&R capabilities, and so on.

The other possible alley of future research is to look into the design of economic mechanisms for capacity management. This will address the problems of choosing the level of provided service and flight prioritization, which come up whenever capacity management implements a limit to the density. Market-based mechanisms for agent-based regulation of strategic deconfliction will allow the authorities to charge correctly for the services and airspace use.

Finally, while for manned aviation, the primary risk concerns vehicle occupants (1st party risk), for drone operations the primary risk is overflying the population (3rd party risk). Thus the unmanned aviation community needs a streamlined, repeatable approach for mapping mission profiles to key risk variables (use case based risk assessment stemming from operational characteristics). Such an approach will enable the development of algorithms for minimizing ground risk metrics. Some algorithms, such as an algorithm for determining good locations for safe landing zones (which may actually be drone crashing zones) and for finding flight paths with low ground risk (such paths with minimal impact on the ground should go close to safe zones, follow rivers, etc.) are of special interest for the community.

Bibliography

- [1] P. Stemp. *Kites, Birds & Stuff - The Royal Aircraft Factory + Inflatables*. Lulu.com, 2011. ISBN: 9781446134658.
- [2] SESAR. *European Drones Outlook Study*. 2016.
- [3] Federal Aviation Administration. *FAA Aerospace Forecast. Fiscal Years 2018-2038*. 2018.
- [4] M. Mazur, A. Wiśniewski, and J. McMillan. *PwC global report on the commercial applications of drone technology. Clarity from above*. 2016.
- [5] U. R. Mogili and B. B. V. L. Deepak. “Review on Application of Drone Systems in Precision Agriculture”. In: *Procedia Computer Science* 133 (2018). International Conference on Robotics and Smart Manufacturing (RoSMa2018), pp. 502–509. DOI: <https://doi.org/10.1016/j.procs.2018.07.063>.
- [6] A. A. Paranjape, S. Chung, K. Kim, and D. H. Shim. “Robotic Herding of a Flock of Birds Using an Unmanned Aerial Vehicle”. In: *IEEE Transactions on Robotics* 34.4 (Aug. 2018), pp. 901–915. DOI: 10.1109/TR0.2018.2853610.
- [7] P. Holley. “New Zealand farmers have a new tool for herding sheep: drones that bark like dogs”. In: *The Washington Post*. 2019.
- [8] L. Fauteux and N. Jolin. *Use of Drones for Wind Turbine Inspections*. 2018.
- [9] J. Jo, Z. Jadidi, and B. Stantic. “A Drone-Based Building Inspection System Using Software-Agents”. In: *Intelligent Distributed Computing XI*. Ed. by M. Ivanović, C. Bădică, J. Dix,

- Z. Jovanović, M. Malgeri, and M. Savić. Cham: Springer International Publishing, 2018, pp. 115–121. ISBN: 978-3-319-66379-1. DOI: 10.1007/978-3-319-66379-1_11. URL: https://doi.org/10.1007/978-3-319-66379-1_11.
- [10] Gartner. *Forecast: Personal and Commercial Drones, Worldwide*. 2016.
- [11] D. Jenkins, B. Vasigh, C. Oster, and T. Larsen. *Forecast of the Commercial UAS Package Delivery Market*. 2017.
- [12] A. Leviero. “Robot-Piloted Plane Makes Safe Crossing of Atlantic”. In: *The New York Times*. 1947.
- [13] CORUS. *U-space Concept of Operations*. <https://www.sesarju.eu/node/3411>. 2019.
- [14] Federal Aviation Administration. *Federal Aviation Administration - Concept of Operations v2.0*. https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf. 2020.
- [15] T. Prevot, J. Rios, P. Kopardekar, J. E. Robinson III, M. Johnson, and J. Jung. “UAS traffic management (UTM) concept of operations to safely enable low altitude flight operations”. In: *16th AIAA Aviation Technology, Integration, and Operations Conference*. 2016, p. 3292.
- [16] SESAR. *U-space Blueprint*. 2017.
- [17] METI. *Roadmap for Application and Technology Development of UAVs in Japan*. 2016.
- [18] Global UTM Association. *UAS Traffic Management Architecture*. 2017.
- [19] Airservices. *Management of Remotely Piloted Aircraft Systems (RPAS) in ATM operations*. 2016.
- [20] SESAR. *European ATM Master Plan*. 2015.
- [21] V. Bulusu, L. Sedov, and V. Polishchuk. “Noise estimation for future large scale small UAS operations”. In: *NOISECON*. 2017. URL: <http://unmanned.berkeley.edu/#publications>.
- [22] P. Kopardekar. *Unmanned Aerial System Traffic Management System*. Talks at Google. 2016.

- [23] J. K. Kuchar and L. C. Yang. “A review of conflict detection and resolution modeling methods”. In: *IEEE Transactions on Intelligent Transportation Systems* 1.4 (Dec. 2000), pp. 179–189.
- [24] S. Balachandran, C. Muñoz, and M. C. Consiglio. “Implicitly Coordinated Detect and Avoid Capability for Safe Autonomous Operation of Small UAS”. In: *17th AIAA Aviation Technology, Integration, and Operations Conference*. 2017, p. 4484.
- [25] R. E. Tompa, B. Wulfe, M. P. Owen, and M. J. Kochenderfer. “Collision avoidance for unmanned aircraft using coordination tables”. In: *Digital Avionics Systems Conference (DASC), 2016 IEEE/AIAA 35th*. IEEE. 2016, pp. 1–9.
- [26] C. Muñoz, A. Narkawicz, G. Hagen, J. Upchurch, A. Dutle, M. Consiglio, and J. Chamberlain. “DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems”. In: *2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*. Sept. 2015, 5A1-1-5A1-12.
- [27] Federal Aviation Administration. *Federal Aviation Administration - Unmanned Aircraft Systems*. <https://www.faa.gov/uas/>. 2016.
- [28] J. M. Hoekstra, J. Maas, M. Tra, and E. Sunil. “How do layered airspace design parameters affect airspace capacity and safety?”. In: *Proceedings of the 7th International Conference on Research in Air Transportation*. 2016.
- [29] E. Sunil, J. Ellerbroek, J. Hoekstra, and J. Maas. “Modeling Airspace Stability and Capacity for Decentralized Separation”. In: *DEP 3* (2017), R1.
- [30] E. Sunil, J. Hoekstra, J. Ellerbroek, F. Bussink, D. Nieuwenhuisen, A. Vidosavljevic, and S. Kern. “Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities”. In: *11th USA/EUROPE Air Traffic Management R&D Seminar*. June 2015.
- [31] M. Tra, E. Sunil, J. Ellerbroek, and J. Hoekstra. “Modeling the Intrinsic Safety of Unstructured and Layered Airspace Designs”. In: *2017 ATM R&D Seminar*. 2017.

- [32] J. M. Hoekstra, J. Ellerbroek, E. Sunil, and J. Maas. “Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace”. In: *International Conference for Research in Air Transportation, Barcelona, Spain*. 2018.
- [33] International Civil Aviation Organization. *Performance-based Navigation (PBN) Manual*. 2008.
- [34] V. Bulusu, R. Sengupta, V. Polishchuk, and L. Sedov. “Operational Capacity of Future Low-Altitude Urban Airspace Evaluation Techniques”. In: *Working paper*. 2020.
- [35] L. Sedov, V. Polishchuk, and V. Bulusu. “Decentralized self-propagating ground delay for UTM: Capitalizing on domino effect”. In: *2017 Integrated Communications, Navigation and Surveillance Conference (ICNS)*. Apr. 2017, pp. 6C1-1-6C1-9.
- [36] L. Sedov, V. Polishchuk, and V. Bulusu. “Decentralized self-propagating ground delay for UTM: Capitalizing on domino effect”. In: *Working paper*. 2019.
- [37] L. Sedov and V. Polishchuk. “Centralized and Distributed UTM in Layered Airspace”. In: *Proceedings of the 8th International Conference on Research in Air Transportation (ICRAT 2018)*. 2018.
- [38] V. Duchamp, L. Sedov, and V. Polishchuk. “Density-Adapting Layers towards PBN for UTM”. In: *2019 ATM Research&Development Seminar*. 2018.
- [39] L. Sedov, V. Polishchuk, and B. Josefsson. “Towards Simplified Optimal Sector Splitting”. In: *SESAR Innovation Days*. 2017.
- [40] W. A. Beyer and A. Zardecki. “The Early History of the Ham Sandwich Theorem”. English. In: *The American Mathematical Monthly* 111.1 (Jan. 2004). Copyright - Copyright Mathematical Association Of America Jan 2004; Last updated - 2017-11-08; CODEN - AMMYAE, pp. 58–61. URL: <https://search.proquest.com/docview/203746537?accountid=12109>.
- [41] P. Kopaderkar. “Safely Enabling UAS Operations in Low-Altitude Airspace”. In: *IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*. Plenary talk. 2016, p. 33.

- [42] L. Sedov, V. Polishchuk, and V. Bulusu. “Sampling-based capacity estimation for unmanned traffic management”. In: *2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC)*. Sept. 2017, pp. 1–10.
- [43] V. Bulusu and V. Polishchuk. “A Threshold Based Airspace Capacity Estimation Method for UAS Traffic Management”. In: *IEEE Systems Conference*. 2017.
- [44] V. Bulusu, V. Polishchuk, R. Sengupta, and L. Sedov. “Capacity estimation for low altitude airspace”. In: *17th AIAA Aviation Technology, Integration, and Operations Conference*. 2017, p. 4266.
- [45] V. Bulusu, R. Sengupta, and Z. Liu. “Unmanned Aviation: To Be Free or Not To Be Free? A Complexity Based Approach”. In: *7th International Conference on Research in Air Transportation IC RAT*. 2016.
- [46] C. Bron and J. Kerbosch. “Algorithm 457: Finding All Cliques of an Undirected Graph”. In: *Commun. ACM* 16.9 (Sept. 1973), pp. 575–577. DOI: 10.1145/362342.362367. URL: <http://doi.acm.org/10.1145/362342.362367>.
- [47] P. Flener and J. Pearson. “Automatic Airspace Sectorisation: A Survey”. In: *CoRR* abs/1311.0653 (2013). URL: <http://arxiv.org/abs/1311.0653>.

Papers

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Linköping University
SE-581 83 Linköping, Sweden

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