Interactive Risk-Based Planning for High-Density Unmanned Airborne System ('Drone') Traffic Management (UTM)

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Abstract

There is significant commercial pressure to relax existing regulations on the segregation of Unmanned Airborne Systems (UAS). Innovative applications have been constrained by justified safety concerns. Strict limits have been placed on organizations wishing to use these aircraft near people, buildings, vehicles, or beyond line of sight. Some of these constraints must be relaxed if we are to realize the benefits that many people predict for UAS. In consequence, governments in Europe and North America have mandated their Air Traffic Management (ATM) organizations to facilitate the deployment of these technologies. This requires concepts of operation (CONOPS) that minimize the risks from UAS both to existing airspace users and to people on the ground. The following pages use techniques from 'big data' and the Internet of Things to inform UAS trajectory planning. In particular, we combine data about ground-based infrastructures and population densities, with techniques from debris modeling to calculate the potential risks from high-volume UAS operations. The aim is to identify trajectories that minimize the risks associated with the operations being planned by major distribution companies. A key concept is that risks change over time; for instance, the distribution of people who might be affected on the ground will change to reflect patterns of work and leisure. We exploit this information within trajectory planning. Our intention is to balance the need of drone operators to reach areas of high population density and at the same time minimize the risk to people on the ground.

Introduction

This paper focuses on small UAS (sUAS) defined by the FAA as between 0.55 lbs. (250 grams) and up to 55 lbs. (25 kg) or by the UK CAA as less than 20kg (Ref. 1, 2). These aircraft, typically, cannot be flown beyond the visual line of sight of the operator (BVLOS), near airports and airfields, or in controlled airspace (Ref. 3). This has placed considerable constraints on the commercial exploitation of rapidly evolving technologies. In consequence, governments around the globe are seeking ways that enable the widespread operation of sUAS without creating unacceptable levels of risk both to other airspace users and to people/systems on the ground.

Governments have responded by creating restricted areas where companies can experiment with new concepts of operation. In the UK, Amazon's Prime Air service received special permission from the CAA to test the feasibility of one-off deliveries in the City of Cambridge (Ref. 4). This involved BVLOS flights over residential areas (Ref. 5). Similarly, DHL have flown their Parcelcopter service over distances of 5 miles within a restricted flight zone granted by the German Federal Ministry for Transportation (Ref. 6). However, these limited and temporary waivers do little to address the underlying concerns that arise from more widespread sUAS operations.

Conventional Air Traffic Control (ATC) relies on categories of airspace defined by the International Civil Aviation Organization (ICAO); these distinguish between Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). VFR, as the name suggests, assume that the pilot can see enough of their surroundings to navigate and to ensure adequate separation from both air/ground hazards. IFR governs flights where outside visual reference is not safe and requires the use of flight deck instruments. With some small differences between individual nations we can identify the following categories of airspace:

- **Class A:** All operations must be conducted under IFR. All aircraft are subject to ATC clearance. All flights are separated from each other by ATC;
- **Class B:** Operations may be conducted under IFR or VFR. All aircraft are subject to ATC clearance. All flights are separated from each other by ATC;
- **Class C:** Operations may be conducted under IFR or VFR. All aircraft are subject to ATC clearance. Aircraft operating under IFR are separated from each other and from flights operating under VFR, but VFR

flights are not separated from each other. Flights operating under VFR are given traffic information in respect of other VFR flights;

- **Class D:** Operations may be conducted under IFR or VFR. All flights are subject to ATC clearance. Aircraft operating under IFR are separated from each other, and are given traffic information in respect of VFR flights. Flights operating under VFR are given traffic information in respect of all other flights;
- **Class E:** Operations may be conducted under IFR or VFR. Aircraft operating under IFR are separated from each other, and are subject to ATC clearance. Flights under VFR are not subject to ATC clearance. As far as is practical, traffic information is given to all flights in respect of VFR flights.
- **Class F:** Operations may be conducted under IFR or VFR. ATC separation will be provided, so far as practical, to aircraft operating under IFR. Traffic Information may be given as far as is practical in respect of other flights.
- **Class G:** Operations may be conducted under IFR or VFR. ATC has no authority but VFR minimums are to be known by pilots. Traffic Information may be given as far as is practical in respect of other flights.

It is unclear where envisioned sUAS operations fit within these existing distinctions. We might extend concepts from controlled airspace; based on ICAO categories A to E. This creates significant technical and organizational challenges. For example, there must be a communications link between sUAS operators and Air Traffic Control Officers (ATCO). This would require careful coordination to ensure that the number of sUAS being operated in an area did not overwhelm the ATCO responsible for supporting their activities. Without a more detailed Concept of Operations (CONOPS) and associated financial model underpinning ATM operations, it is difficult to envisage how such an infrastructure might be sustained. Alternatively, an uncontrolled model, based on classes F and G, raise acute questions about whether the operation of sUAS for BVLOS flights might be capable of meeting acceptable levels of safety. Most sUAS cannot meet the requirements to 'sense and avoid' other air space users, which are expected of conventional flight.

Further concerns relate to the privacy, security and safety of the general public. sUAS fly at lower altitudes and at slower speeds than conventional aircraft. The US Department of Defense employs a 5-tier model that focuses on capability as well as mass, illustrated in Table 1. Notice that according to the FAA distinctions, sUAS are in groups 1 and 2 operating at less than 3,500 feet above ground level often well below 250 knots. Given the requirements for sense and avoid in BVLOS flights, these operations rely on a range or remote sensing technologies that exacerbate public concerns over civil liberties. Table 1 also illustrates some of the safety issues that arise from the operation of small UAS, especially over high-density urban environments given the kinetic energy implicit within these operating characteristics.

UAS Group	Maximum weight (lbs)	Nominal operating altitude (ft)	Speed (kn)
1	0-20	<1,200 AGL	100
2	21-55	<3,500 AGL	< 250
3	<1,320	< FL 180	
4	> 1,320	>FL 180	Any airspeed
5			

Table 1: US Department of Defense UAS Groupings for Airspace Integration (Ref. 7)

The Mitre Corporation recently presented some preliminary hazard assessments within the FAA's UAS Science and Research Panel (SARP) (Ref. 8). This drew upon the opinions of aviation and safety experts to determine levels of tolerability for sUAS integration in airspace over different locations. These assessments are illustrated in Table 2. They substantiate these assessments using a calculation for the Tolerable Level of Safety (TLS) in sUAS operations:

TLS = Probability of Fatality x Shelter Factor x Population Density x Crash Area x Probability of Flight Loss

Many of the terms in this equation are hard to validate. For instance, both the crash area and the probability of a fatality are strongly influenced by prevailing meteorological conditions as well as by aerodynamic properties of debris from the loss of flight. However, they propose that a heuristic value for an acceptable rate of risk should be 5 x 10-8 for third parties not involved in sUAS operations per flight hour.

Class of sUAS		Micro	Mini	Limited	Bantam
	Weight	0.25 Kg (0.55lb)	2 kg (4.4lb)	9 kg (20lb)	25 kg (55lb)
	Kinetic Energy Class	0-100J	100-1,000J	1,000-10,000J	10,000-100,000J
Population Density	Open Air Assembly (eg Stadium)	Medium Perceived Operational Risk	High Perceived Operational Risk	High Perceived Operational Risk	High Perceived Operational Risk
	Urban	Low Perceived Operational Risk	Medium Perceived Operational Risk	Medium Perceived Operational Risk	High Perceived Operational Risk
	Rural	Low Perceived Operational Risk	Low Perceived Operational Risk	Low Perceived Operational Risk	Medium Perceived Operational Risk

Table 2: US UAS SARP Risk Assessments for sUAS Integration (Ref. 8)

UAS Traffic Management (UTM)

The work of the FAA SARP provides the initial scientific and engineering foundations for what has become known as UAS Traffic Management (UTM). The aims behind UTM include the integration of UAS with conventional traffic. It must also ensure adequate separation between UAS operations, without increasing the risks to ground infrastructures beyond acceptable levels, measured using TLS (Ref. 8). More formally, NASA (Ref. 9) have identified the following attributes for UTM operations, it:

- uses airspace management and geofencing;
- has weather and severe wind integration;
- can predict and manage congestion;
- uses terrain and man-made objects: database and avoidance;
- can maintain safe operation;
- will allow only authenticated operations.

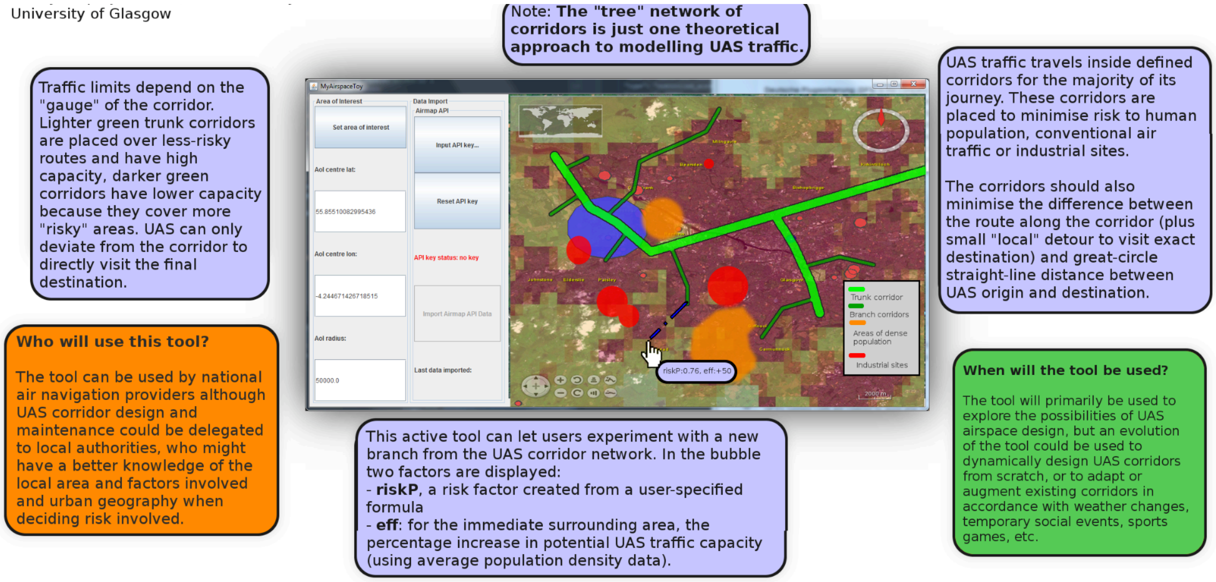
There is very little agreement beyond these high-level aims. Some UTM proposals mimic VFR operations. Others are based on distributed control– where individual sUAS will coordinate with neighboring flights to self-organize, for example using algorithms that produce flocking behaviors. These approaches are, typically, better suited to areas with low sUAS congestion or with homogenous, low population densities. It can be hard to prove that conflict between two or more sUAS could never have knock-on effects that force a UAS to divert with a significant increased risk for ground based infrastructures. Other UTM proposals assume more centralized architectures; where approval is explicitly granted for a particular trajectory during a particular interval of time. This extends 4D CONOPS from the SESAR and NextGen programmes to support sUAS UTM operations (Ref. 9). Networks of corridors can be constructed using known waypoints where risk factors for ground-based infrastructures can be pre-calculated. Modeling corridors in this way enables the application of graphs analysis to produce efficient networks; building dynamic routing algorithms to maximize flow. The development of these algorithms has been a central achievement of both US and European initiatives for ATM; although many have yet to be deployed.

Previous research has proposed UTM corridors mapped over city streets (Ref. 10), as well as source-backbone-destination models, where small low-capacity routes join major arterial flows (Ref. 11). These techniques are important because they show how hybrid topologies may be necessary to support many of the CONOPS being developed by potential drone operators. In particular, pre-computed networks are unlikely to provide full connectivity from a point of departure to every destination for a delivery company. One alternative would be to terminate the sUAS flight at a node or collection point where a customer could retrieve their delivery. This negates many of the benefits of using airborne services; undermining the flexibility and convenience offered by UTM implementations. Another approach would be to use conventional ground based delivery from the terminal node. However, in this case the use of RPAS would not address the major cost in deliveries in the last mile to the customer. Hence, our simulation can be used to assess the ground-based risks of combining networks of corridors with elements of an “air parcel” approach. As we shall see, a key strength of the toolset is that it helps to identify when networks of corridors provide an acceptable high-density structure for UTM over urban areas.

Further hybrid options exploit dynamic corridors where the pre-calculated routings can be varied to reflect changing patterns of risk. This is useful when population densities change over time; for example, an sUAS corridor may be opened over a highway when ground traffic densities fall below threshold values. Such benefits must be balanced against the efficiency costs that can arise – for example, when some areas cannot be reached without passing over high population densities or other ‘at risk’ ground infrastructures.

The Glasgow UTM Development Process

Our aim was to develop tools that could plan higher-density UTM operations in urban areas for autonomous vehicles used both in newsgathering and package delivery. In previous work, we had extended an existing UAS mission planner developed by the Ecole Polytechnique Fédérale de Lausanne (EPFL) (Ref. 10) with a debris-modeling tool (Ref. 11). This enabled users to determine the potential impact of larger UAS on ground infrastructures, including nearby sites listed as part of the UK Control Of Major Accident Hazards (COMAH) regulations. Figure 1 provides an initial story-board that was shown to European Air Navigation Service Providers to elicit feedback about key functionality and concepts. Figure 2 provides an architectural overview of the system components. This was important because the interfaces between these components enable us to test out a range of different corridor topologies, different population density estimates and different kinetic impact algorithms; all embedded within the FAA/Mitre TLS formulae summarized in previous sections.


University of Glasgow

Note: **The "tree" network of corridors is just one theoretical approach to modelling UAS traffic.**

Traffic limits depend on the "gauge" of the corridor. Lighter green trunk corridors are placed over less-risky routes and have high capacity, darker green corridors have lower capacity because they cover more "risky" areas. UAS can only deviate from the corridor to directly visit the final destination.

MyAirspaceToy

Area of Interest

AoI centre lat: 55.85510082995436

AoI centre lon: -4.244671426718515

AoI radius: 50000.0

Data Import

Airmap API

API key status: no key

Last data imported:

UAS traffic travels inside defined corridors for the majority of its journey. These corridors are placed to minimise risk to human population, conventional air traffic or industrial sites.

The corridors should also minimise the difference between the route along the corridor (plus small "local" detour to visit exact destination) and great-circle straight-line distance between UAS origin and destination.

Who will use this tool?

The tool can be used by national air navigation providers although UAS corridor design and maintenance could be delegated to local authorities, who might have a better knowledge of the local area and factors involved and urban geography when deciding risk involved.

This active tool can let users experiment with a new branch from the UAS corridor network. In the bubble two factors are displayed:
- **riskP**, a risk factor created from a user-specified formula
- **eff**: for the immediate surrounding area, the percentage increase in potential UAS traffic capacity (using average population density data).

When will the tool be used?

The tool will primarily be used to explore the possibilities of UAS airspace design, but an evolution of the tool could be used to dynamically design UAS corridors from scratch, or to adapt or augment existing corridors in accordance with weather changes, temporary social events, sports games, etc.

Figure 1: Initial Glasgow UTM prototype

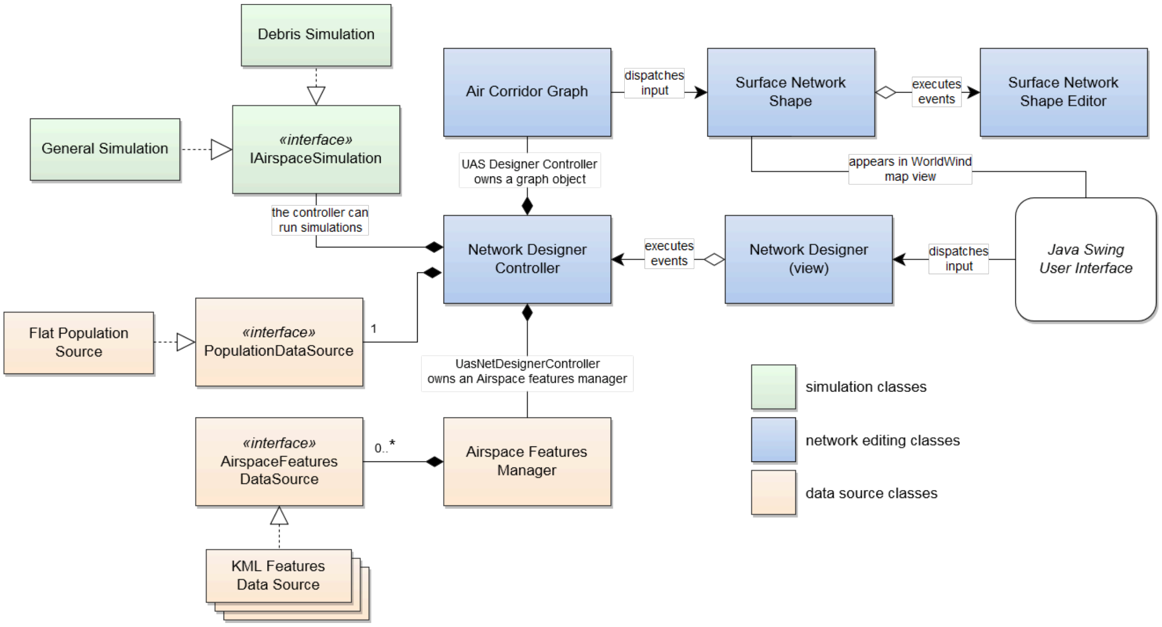
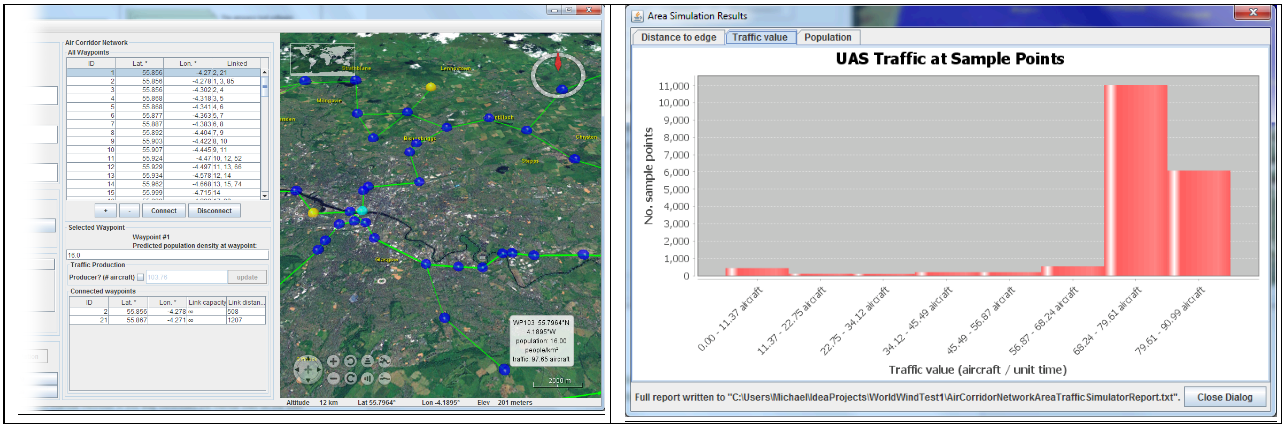


Figure 2: Structural Overview of the Glasgow UTM Environment

The resulting tools provide a development environment in which to explore a range of CONOPS for UTM operation Figure 3 shows two key features of the present Glasgow toolset. The image on the left provides a 3D view of the corridor editor. Such visualizations are important for planning given that different altitudes may be reserved for high and low speed sUAS transit (Ref. 11). The image on the right of Figure 3 shows how the tools can be used to consider traffic densities through UTM corridors. In this case, the histogram shows a bi-modal distribution where over 50% of the sampled points account for the majority of sUAS over-flights. These distributions can be compared for different corridor topologies. However, they are of limited value without the ground risk information illustrated in Figure 4 and the network sUAS traffic flow models that provide an indication of risk exposure at different RPAS densities.



ID	Lat. °	Lon. °	Linked
1	55.856	-4.27	2, 21
2	55.856	-4.278	1, 3, 85
3	55.856	-4.302	2, 4
4	55.868	-4.318	3, 5
5	55.868	-4.341	4, 6
6	55.877	-4.363	5, 7
7	55.887	-4.383	6, 8
8	55.892	-4.404	7, 9
9	55.903	-4.422	8, 10
10	55.907	-4.445	9, 11
11	55.924	-4.47	10, 12, 52
12	55.929	-4.497	11, 13, 66
13	55.934	-4.578	12, 14
14	55.962	-4.668	13, 15, 74
15	55.999	-4.715	14

Waypoint #1
Predicted population density at waypoint:
16.0
Producer? (# aircraft) ☐ 103.76

ID	Lat. °	Lon. °	Link capacity	Link distan...
2	55.856	-4.278	∞	508
21	55.867	-4.271	∞	1207

WP103 55.7964°N 4.1895°W
population: 16.00 people/km²
traffic: 97.65 aircraft

Altitude 12 km Lat 55.7964° Lon -4.1895° Elev 201 meters

Full report written to "C:\Users\Michael\IdeaProjects\WorldWindTest1\AirCorridorNetworkAreaTrafficSimulatorReport.txt".

Figure 3: Glasgow UTM Corridor Modeling and Simulation

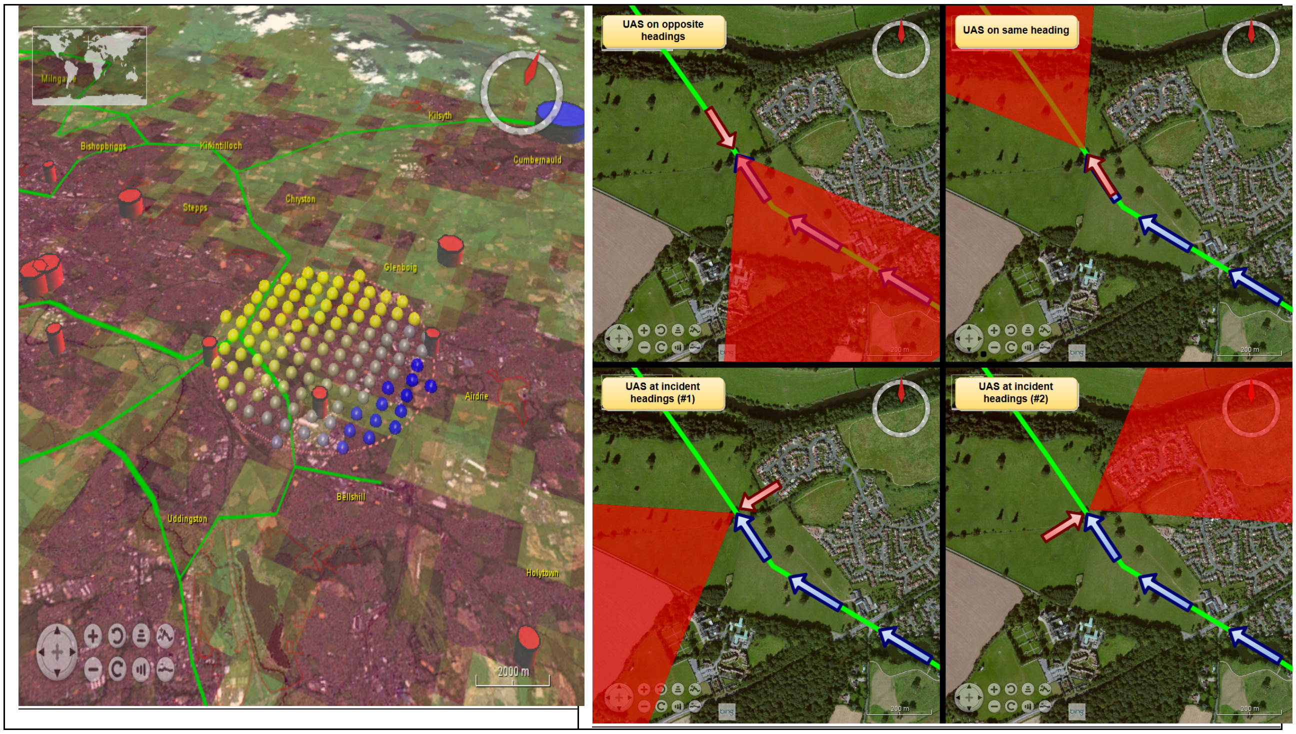


Figure 4: Glasgow UTM Ground Risk Simulation and Visualization

Previous sections have described how UTM is intended to minimize the risk both to ground populations and also to critical infrastructures. The image on the left uses publically available census data to model population densities beneath a sUAS corridor topology. This is combined with simulated/predicted traffic patterns to automatically calculate ground risk exposure at a much finer level of granularity than the High, Medium and Low classes derived from the initial, high-level SARPs models. More importantly, it provides tools that support tactical planning for sUAS operations in particular urban environments; taking into account at-risk infrastructures and population characteristics (Ref. 12).

The Glasgow UTM tools also include a debris simulator that can be tailored to model the outcome of mid-air collisions involving conventional aircraft as well as UAS. The system models the impact and distribution of debris that can be traced down onto population densities and major hazard sites. It is also possible to consider the impact on individual buildings if the ground based models are refined for well-defined areas of interest; the validation of these more details models remains a topic for further research.

The simulation is extensible; it can compute potential risks at arbitrary locations within the network. However, we reduce the computational overheads by configuring each run to consider a finite number of sample points. By default, at each sample point we consider the four incident scenarios shown in Figure 4. The debris field can then also be mapped onto the ground population data. In the past we have done this to derive more precise estimates of the risk from previous near-miss AIRPROX incidents that are typically classified using subjective, expert judgment (Ref. 13 and 14). The simulation creates a debris report file tat can be visualized or imported into other tools or simulations. The risk assessment part of the tool is primarily designed to help airspace designers or UTM providers to investigate the hazards of air corridor networks. It also fulfills a secondary requirement: increasing users' understanding of how air corridor networks might function by letting them calculate the risk and explore the associated hazards, for example how air corridors might be carefully routed over open spaces. Airspace co-design is one mechanism that might help to reduce some of the privacy concerns that otherwise might limit sUAS operations within urban environments.

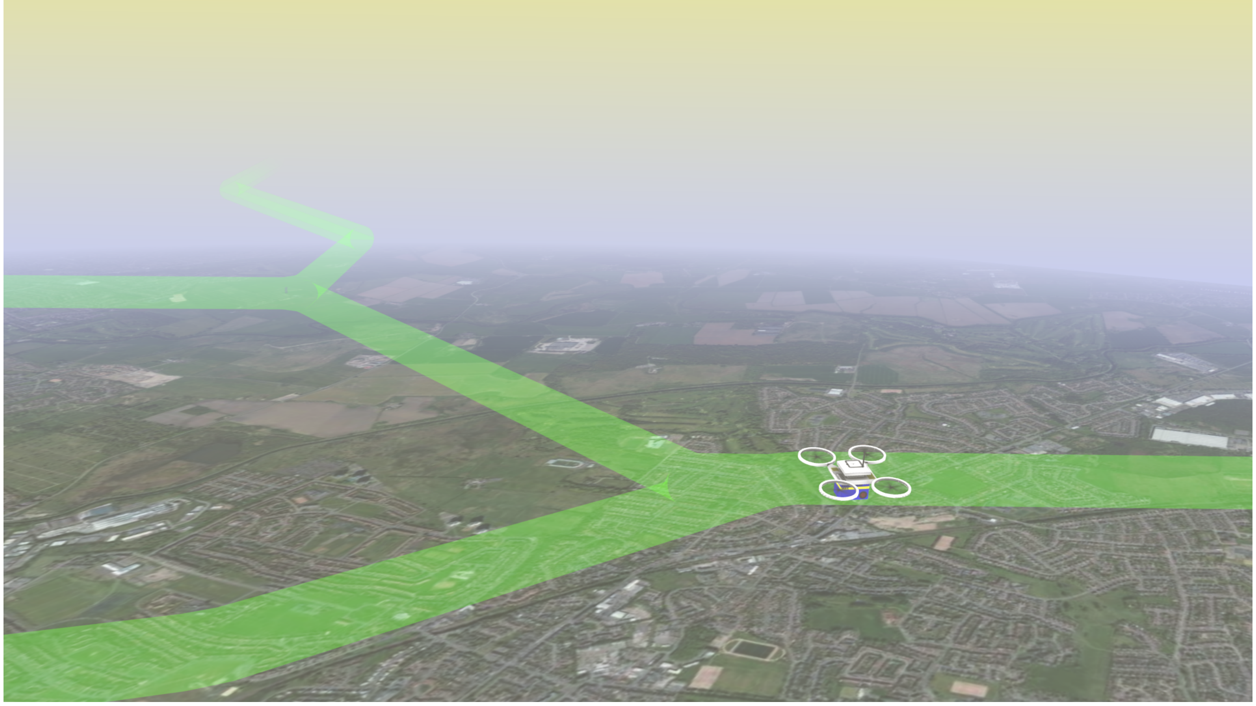


Figure 5: Rendering sUAS Within a Designated UTM Air Corridor

Conclusions and Further Work

This paper has described the design and implementation of tools that help regulators and operators consider the risks associated with sUAS operations over the urban centers that are a major focus for distribution companies. Existing systems-safety work on UTM and on performance based navigation in conventional ATM motivated our decision to focus on corridor planning – but at a level of granularity that was significantly more detailed than previous research. The resulting prototypes help airspace designers to explore interactions between UAS densities and the exposure both of ground based populations and of critical infrastructures. A key feature of our work was the development of a modular architecture that enables the low-cost substitution of key components – including the population models, UAS kinetic values, debris fields etc. A number of areas were identified for future research

- **Improved Visualizations/Usability.** Our tools support the use of the FAA/Mitre risk calculations. These formulae provide important insights but cannot easily convey critical information to members of the public in a clear and coherent manner. In contrast, our AIRPROX simulator overlays debris fields on top of a map view that shows population densities. This provides an interactive model that can be used to obtain a detailed understanding of the outcomes simulated for a single adverse event. However, if we use the simulator to drive multiple sUAS incidents we end up with a distribution showing the probability that debris falls on a particular point in the map/population visualization. Future work is required to identify the best means of presenting such data in a manner that supports sUAS trajectory risk management (Ref. 13, 14);

- **Automated Support for sUAS Trajectory Planning and Scheduling.** Our UTM tools calculate risk exposure based on sUAS trajectories that are input as parameters during a pre-configuration stage. The tools enable users to measure the impact of different UAS densities. This would enable an airspace planner to interactively improve trajectories against the multiple risk criteria identified within the SARPS work. There are alternatives. For example, future work might use automated trajectory-optimization tools, including machine-learning techniques. These more advanced techniques can be built upon our existing ability to compute risk exposure for ground based assets;

- **Diverse Data Sources**. The toolset is built around a modular architecture enabling the substitution of key data sources. At present we integrate population and census data from a range of national and international services. We also make use of available meteorological data when, for instance, the probability distributions for wind speeds have an impact on the generation and distribution of a debris field. In many cases, our handling of this information has been motivated by a desire to demonstrate what might be done through model integration rather than any claim that these individual sources are the best that might be obtained for all locations. Similarly, we might extend the existing tools to consider the interactions between high-density sUAS networks and anticipated population changes rather than existing urban densities within the existing implementation. Future work might, therefore, examine whether we can improve the debris simulation tool, the individual sources of population data and also live updates for meteorological information at all altitude levels in urban environments;

- **Scope of the Models.** Future work is needed to extend our tools to consider simulations the effects of low-level rotary/emergency services operations on UAS airspace. We might need to immediately clear all sUAS traffic to enable rescue or police operations. Similarly, further work can explore the development of the 'lost link' profiles that need to be executed when sUAS control is lost. These are the routes that are pre-programmed for drones in safety-related applications so that they will fly to an agreed recovery location minimizing risk when they lose contact with the ground control system. Although our models have access to data about some critical infrastructures, further work is required to determine the risks that sUAS pose to a range of ground assets – including motor and rail vehicles. Existing proposals to use highways and rail infrastructures during periods when they are not being used are often informed more by the kinetic potential of sUAS rather than any sustained analysis of Systems Safety concerns.

The work described in this paper represents the first step on a journey, rather than the end point. Previous discussions about airspace design for UTM have been based on very high-level metrics; often strongly influenced by subjective opinions. In contrast, we have developed tools that exploit existing data sources to inform the development of sUAS corridoors in high-density urban environments. Arguably, the most important results from this work have been the ensuing discussions about sUAS concepts of operation – on how flights should be scheduled, routed, coordinated – to minimize risks on the ground and to other airspace users. We have shown that these discussions can be based on data rather than introspection.

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Biography

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