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Conceptualising and prototyping a decision support system for safer urban unmanned aerial vehicle operations

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ABSTRACT

Currently, there is limited discourse surrounding the safe operational planning of UAVs within complex multi-stakeholder urban environments. This paper conceptualises a methodology for prototyping a decision support system for urban UAV flight operations planning. The proposition is based on integrating urban 3-dimensional data with the physical factors of UAV flight operations. A simulated, holistic understanding of UAV usage in urban space emerges, enabling better informed decisions by planners around safe flight operations. The feasibility, applicability and benefits of the decision support system and associated policy implications for urban planners and UAV users are discussed scoping further development of this approach.

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Stakeholder engagement; decision support system; 3D simulation; urban planning; UAV operations

Introduction

The emergence of autonomous vehicles within urban environments has the potential to change the fundamental nature of transportation in society (Gavanas, 2019). This paper articulates and seeks to address some of the major challenges stemming from these technologies. Autonomous vehicles are advancing at an exceptional rate and raise significant challenges and opportunities for policy and decision makers in relation inter alia to infrastructure, land use and social mobility (Campbell et al., 2010; Fraedrich et al., 2019, April; Gavanas, 2019). Such systems are growing in importance and are receiving considerable attention with extensive literature on the safe integration of autonomous vehicles into urban areas (see for example: Campbell et al., 2010; Fraedrich et al., 2019, April; Gavanas, 2019).

Advancements in unmanned aerial vehicles (UAVs) have resulted in a significant reduction in price, leading to accessibility by the general public (Albeaino et al., 2019; Braun et al., 2015; European Emergency Number Association (EENA), 2015; Radišić et al., 2018). However, UAVs differ from other autonomous vehicles not only due to the general mass availability of uncertified technology to an untrained, unaware and unregulated public (European Emergency Number Association (EENA), 2015), but are also airborne with 3-dimensional and temporal attributes not confined to surface operations (Balać et al., 2018; Bone & Bolkcom, 2003; Goel et al., 2018; Gupta et al., 2013). Most of the literature to date has focused on potential applications. As a result, the emphasis has been

on governance, technical capabilities such as safety and security measures (Ormand et al., 2014), and consequential impacts (Clarke & Moses, 2014). Examples of the potential impacts of UAVs in urban areas in recent times include major disruption at Heathrow Airport (January 2019)¹ and the Venezuela attack on a military parade (August 2018).² Despite this upsurge in activity and attention, and conversely to that of driverless vehicles, the scholarly knowledge base on UAVs has presented limited research that is focused on innovative approaches³ for the safe integration of UAVs in urban environments. UAVs are ubiquitous and will continue to grow in prominence as demonstrated by the increasing number of potential applications across a variety of uses including: sports event filming; infrastructural inspection; logistics; policing; and search and rescue (Balać et al., 2018; European Emergency Number Association (EENA), 2015; Gupta et al., 2013). UAV applications in the built environment are therefore, disparate, and as such this increases the complexity of managing and mitigating societal challenges that may exist.

The research presented in this paper proposes managing this complexity through flight planning of UAV operations in urban areas using an innovative platform that incorporates 3-dimensional data; technology and physics such as building information; and factors that influence flight operations such as wind velocity, UAV velocity, payload, altitude, and terrain. In the literature, it is apparent that methodological approaches have tended to rely on 2D tools including maps that are static and limited in level of immersion (Koziatek & Dragicic, 2017; Lange, 2011). This is problematic because of the complex 3D and temporal nature of urban areas (Chen et al., 2018; Luo et al., 2017); understanding the implications of decisions in 4D urban environments (Isaacs et al., 2010; Santosa et al., 2016); and difficulties in communicating 4D situations to stakeholders (Isaacs et al., 2011). In response, the paper proposes that a dynamic, 3D model of a city as used for urban planning (Biljecki et al., 2015; Isaacs et al., 2011; Luo et al., 2017), could be modified to incorporate flight operation characteristics thereby representing an innovative approach that has the potential to generate a holistic understanding of UAV usage in urban areas at any given point in time. The purpose is to enable decision makers to identify potential conflicts, issues, and impacts (Chan et al., 2016; Isaacs et al., 2011; Santosa et al., 2016), which is more effectively achieved in 3D rather than 2D (Ballentine, 2019). In turn, the visuals generated can be used to inform decisions around the safe use of UAVs in urban areas and assist in developing the necessary governance arrangements of emerging smart technologies (see for example: debates on smart mobility governance, Docherty et al., 2018).

This paper is structured as follows: firstly, an examination of the theoretical knowledge base on the challenges surrounding unmanned aerial vehicles within urban areas highlighting gaps in urban-UAV flight planning capability (Section 2); secondly, a conceptual methodology (Section 3) is proposed to address these challenges through development of a novel flight planning decision support system; thirdly, results from a case study (Section 4) are presented and discussed; the conclusion (Section 5) identifies further research and potential policy impacts.

Literature review

The Challenges of integrating unmanned aerial vehicles in urban environments

UAVs are defined as unconventional powered aerial vehicles that do not carry a human operator, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a payload (Bone & Bolkcom, 2003; Lele & Mishra, 2009); applications include those that are dull, dirty or dangerous (Beaudoin et al., 2011). Furthermore, UAVs effectively enable the deployment of small-scale systems on demand which are more economically efficient than manned aircraft (Braun et al., 2015; Shakhathreh et al., 2019). For example, Amazon has identified the potential of UAVs in logistics in urban environments (Yeonmin, 2014). There are numerous benefits in the emergency services arena; first aid; locating criminals; traffic policing; disaster management; searching vehicles and property (Gupta et al., 2013; Ormand et al., 2014); improving safety including on construction sites (Albeaino et al., 2019; Irizarry et al., 2012); and can be operated singly or as part of a larger group (Beaudoin et al., 2011). Aerial observation is also becoming less costly (Braun et al., 2015) and easier than before (Ormand et al., 2014). UAVs are a growing subject field in the unmanned aviation community and no matter the mission, are highly likely to grow in number with significant increase in usage in urban areas especially when considering their low cost (Albeaino et al., 2019; Gupta et al., 2013). Consequently, there is a push to integrate UAVs into urban airspace to avail of the social and economic benefits and the rate of integration appears to be accelerating (European Emergency Number Association (EENA), 2015; Labib et al., 2018; Schlag, 2013).

However, challenges exist regarding urban integration with the future of UAV flight operations progressing towards automation to overcome many inherent safety, technical and regulatory hurdles of operating small remote aerial vehicles within complex 3-dimensional and dynamic urban environments (Balać et al., 2018; Beaudoin et al., 2011; Boucher, 2014; Khan, 2014; Ormand et al., 2014; Radišić et al., 2018). For example, reliability, controllability, sensibility and navigation when in flight as well as coordination of multiple UAVs so that they do not enter prohibited locations accidentally or crash including into other UAVs (Beaudoin et al., 2011; Ormand et al., 2014). Increasing incidences of UAVs are accessing restricted areas and on occasions accidentally crashing into a physical asset, an example being the UAV that crashed into the Sydney Opera House in 2015⁴. The potential for harm and damage to people and property through moving parts, including causing fires, is high when a UAV fails in-flight and is further impacted by UAV capabilities, such as mass and velocity. Loss of control and collisions have in fact been more prevalent to-date compared with manned aircraft (Clarke & Moses, 2014). This is likely to increase and is caused by interference, technical failures, turbulence, operator-error or Acts-of-God. Harmonised regulations are now in place across Europe to govern how pilots operate UAVs.⁵

UAV regulations and policies are implemented with the aim of establishing privacy and legal boundaries and procedures to bring UAVs into line with other air regulations so that operators can be guided towards safe and legal operation in urban areas and be made accountable in the event of accidents or criminal activity (Ormand et al., 2014; Shakhathreh et al., 2019). However, such regulations appear to be at the lower end of the spectrum when compared with other forms of vehicle including manned aircraft (Clarke

& Moses, 2014) with more legal grey areas emerging as technology and use develops (Ormand et al., 2014). For example, licencing and registration is currently required in many countries including the UK and USA for commercial and emergency services operations; permission is also necessary for specialist civilian applications including research trials. In addition, operators are confined to rules of safe operation in many countries with the UK establishing safe operating distances from people, places and certain assets as well as technical confines such as maintaining line-of-sight. This includes prohibiting the flying of radio-controlled aircraft within specific distances of a structure or controlled airspace, and UAVs over 20 kg are generally not allowed without permission from the Civil Aviation Authority (Civil Aviation Authority (CAA), 2015). Regulations throughout the EU generally prohibit night-time flying and have a 400 ft maximum flight ceiling for civilian variants (Abbott et al., 2016).

Existing literature typically discusses the beneficial applications, resulting technical, regulatory and policy development of UAVs and associated infrastructure. In fact, a consistent theme throughout the literature is the requirement for more integrated management of UAVs at the local or urban level. For example, the National Aeronautics and Space Administration (NASA) is carrying out extensive research on Unmanned Traffic Management (UTM) systems as an enabler of safer low-altitude UAV operations integrating advanced technical and regulatory aspects.⁶ However, as a departure from existing application, technical and regulatory research narratives, there is little discourse surrounding the complexities of planning safe UAV flight operations with consideration for the complex multi-stakeholder, 3D topography and dynamic and potentially hazardous conditions of urban environments.

These, though, are not the only considerations when approaching this topic. Given the contemporary international attention placed on the smart city concept by public authorities, private enterprise and academia (see for example: Kitchin, 2015), it is important to ensure that technological discourse is not “blind” to urban political, social and environmental complexities (Bina et al., 2020, p. 115). With protagonists positing that urban dynamics and governance is perfected through the application of interactive ‘Big Data’ (Krivý, 2018, p. 9) and ‘techno-utopia’ (Pollio, 2016), balance is necessary to avoid making grand assertions that may eventually lead to dystopian realities that are, intentionally or inadvertently, to the detriment of individual rights and freedoms (Poole, 2014).

Managing UAVs in urban areas can be difficult due to the complexity of understanding their unconventional 3D spatial and temporal nature (Bugliarello, 2003; Goel et al., 2018; Yang et al., 2014) setting them apart from, for example, land-based vehicles which are 2-dimensional in a spatial context. There is thus a need to frame a mechanism to assess the risks during planning and aid in decision-making (Beaudoin et al., 2011; Lele & Mishra, 2009; McNeal, 2015). Planning for UAV flight operations requires understanding and consideration for numerous factors including complex 3D environments, conditions and operations with respect to time including flight path properties such as how altitude, direction, speed, range, endurance and flight objectives interact with already complex urban environments (Balać et al., 2018; Gandor et al., 2015; Shakhathreh et al., 2019). Due to the complexity of understanding and planning UAV flight operations within urban environments, it is suggested that future research could explore the development of some form of simulation that considers the urban environment, integration, stakeholder engagement, risk and mitigation (Balać et al., 2018; Beaudoin et al., 2011; McNeal, 2015).

Towards an Urban-UAV flight operations planning decision support system

From a historical perspective, visualisation of data and information is an inherent human communication preference and provides common ground for reporting regardless of racial, social, or language barriers, technical or non-technical background (Al-Kodmany, 2002; King et al., 1989). Traditional approaches to visualisation in urban planning include conversion of data and information into drawings, use of photography, physical models and 2D GIS. However, these approaches lack the ability to represent, manipulate, assess and communicate impact of change in respect to complex 3D features or dimensionality that are immersive representations of the real world across different spatial and temporal scales (Koziatek & Dragicevic, 2017; Lange, 2011). On a similar note, many existing UAV mission planners in fact focus on the UAV application, usually communicating with the UAV, and disregarding the complexities of urban environments such as buildings, usually reducing them to 2D feature or simple terrain maps (Gandor et al., 2015). Newly designed systems can also be impacted by a ‘disconnect’ between instrument developers and potential users, with the risk that technologies are not suitable as a ‘shared understanding of the needs and demands of specific planning contexts’ is missing (Te Brömmelstroet et al., 2016, p. 1178).

Developments in computational 3D modelling addressed the need to more accurately and realistically represent the real world with developments in 3D simulation seeking to visualise impact of changes or decisions made during planning through animated events relative to the 3D model (Isaacs et al., 2010; Luo et al., 2017; Santosa et al., 2016). Such systems are commonly known as decision support systems and are defined in the literature as stakeholder portable 3D simulation environments that enable evaluation of potential decisions during planning with consideration for impact (Chan et al., 2016). 3D animations are representative of decisions made to the fabric of the model (environment) or the dynamics (conditions) of the animation in respect to the underlying data and information (mathematical model or engine). 3D simulations represent real-world systems where the purpose is to obtain meaningful data and information output; to accomplish a pre-determined planning goal (Biljecki et al., 2015), such as an urban/neighbourhood masterplan.

3D simulation has many applications where visualisation of systems, engaging stakeholders and improving communication of impact of change, hazards or risks is required (Chen et al., 2018; Christensen et al., 2016; Isaacs et al., 2011; Koziatek & Dragicevic, 2017; Lange, 2011). This is representative of the potential of 3D simulation in addressing the safe flight planning of UAVs within urban areas including in engagement of built environment and operator stakeholders. That said, a review of literature indicates there is no discernible body of work on the use of decision support systems or 3D simulation in urban UAV flight operations planning; this highlights a critical capability gap. Addressing this gap would however, require consideration of 3D simulation limitations in respect to the UAV planning application. These include both pre-simulation limitations and post-simulation limitations (see Figure 1, derived from literature including Al-Kodmany, 2002; Isaacs et al., 2011; Lange, 2011; Luo et al., 2017).

Modern 3D simulation in urban planning stems from the field of geography which established the link between scientific visualisation and visualisation of spatial data in planning, improving the temporal and sensory experience, to elicit a very high level of

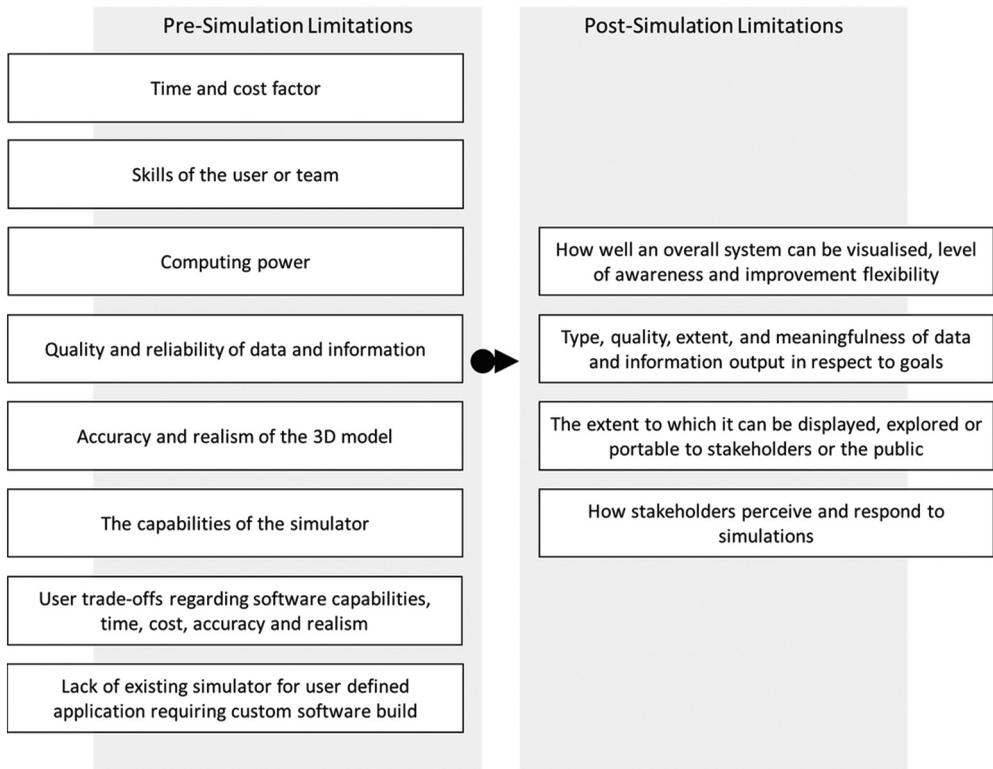


Figure 1. Pre and post-simulation limitations as derived from Luo et al. (2017); Isaacs et al. (2011); Lange, 2011 and Al-Kodmany (2002).

audience engagement (Al-Kodmany, 2002). 3D simulation in urban planning decision support consists of spatial and temporal data and information, and a highly realistic, accurate 3D urban or city model with 3D geometry of common urban objects and structures such as buildings (Biljecki et al., 2015; Isaacs et al., 2011; Luo et al., 2017). In urban planning, 3D simulation provides an enhanced user experience strengthening the understanding of the links between space, assets, hazards, time, events and impact so that strategies can be developed, evaluated and visualised to support decision-making in urban management including between policy makers and non-experts (Chen et al., 2018; Lange, 2011; Santosa et al., 2016). 3D simulation also takes into consideration key urban stakeholders' interests so that decision making is holistic and reinforced (Koziatek & Dragicevic, 2017) enabling legitimate prediction of the future of urban form (Luo et al., 2017). 3D simulation in urban planning decision-support has a wide range of existing specialist user applications and benefits (see Figure 2 as derived from Santosa et al., 2016; Biljecki et al., 2015; Al-Kodmany, 2002). Each of these applications are relevant to a UAV flight planning application and are illustrative of the ability of 3D simulation environments to incorporate and integrate identified urban factors with UAV flight operations factors and communicate such situations with stakeholders enabling better informed planning of safer urban flight operations.

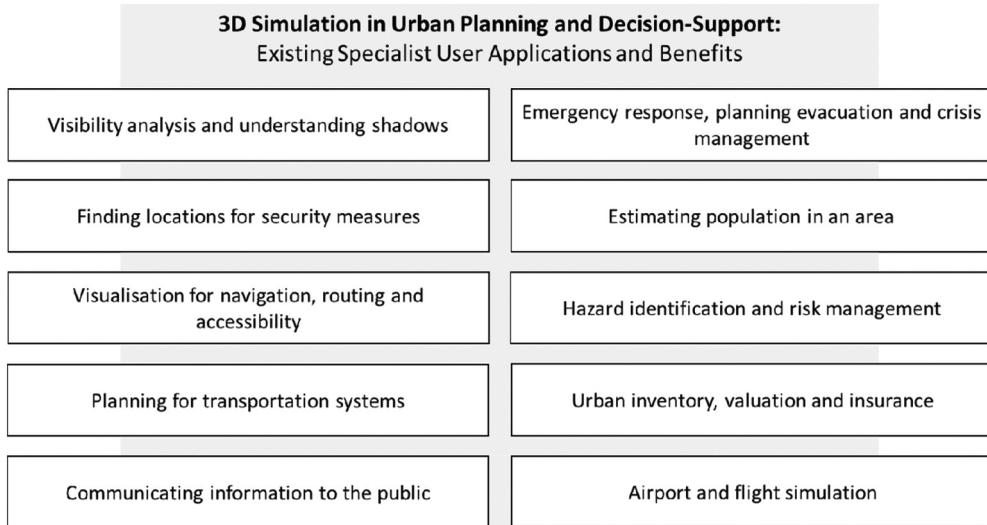


Figure 2. Existing specialist user applications and benefits of 3D simulation in urban planning and decision-support as derived from Santosa et al. (2016); Biljecki et al. (2015); and Al-Kodmany (2002).

However, there are many trade-offs that require consideration when developing a simulator including the motion and reaction of humans and other entities, weather dynamics, atmosphere and lighting. Accuracy, reliability and quality of underlying data and models also require caution when making-decisions, though, these can be updated as better data and models become available (Isaacs et al., 2011; Luo et al., 2017). The suitability of the 3D simulation approach as a communication tool in development planning and management, and stakeholder group preferences requires consideration and testing for any urban 3D simulation application. When developing a new simulation, it is critical to understand the nature of the problem to be modelled and simulated, the stakeholders, what the data and information requirements are, what needs to be modelled and simulated and what doesn't, with consideration for appropriate trade-offs regarding pre- and post-simulation limitations. These considerations form the basis for research questions surrounding the conceptual methodology, developed in Section 3 below, for prototyping an urban UAV flight operations planning decision support system.

Conceptual methodology

Five broad procedural stages in decision support system conceptualisation and development were adapted from theory to establish the research methodology underpinning this paper. These include: 1) accurate, reliable and quality data and information requirements; 2) realistic and accurate 3D urban model build or sourcing; 3) mathematical modelling and simulator development; 4) data and information output requirements; and 5) visualisation and stakeholder engagement requirements. These five adapted procedural stages are mapped to the UAV flight operations planning factors as emerged from the literature forming the basis for a conceptual framework for a decision support

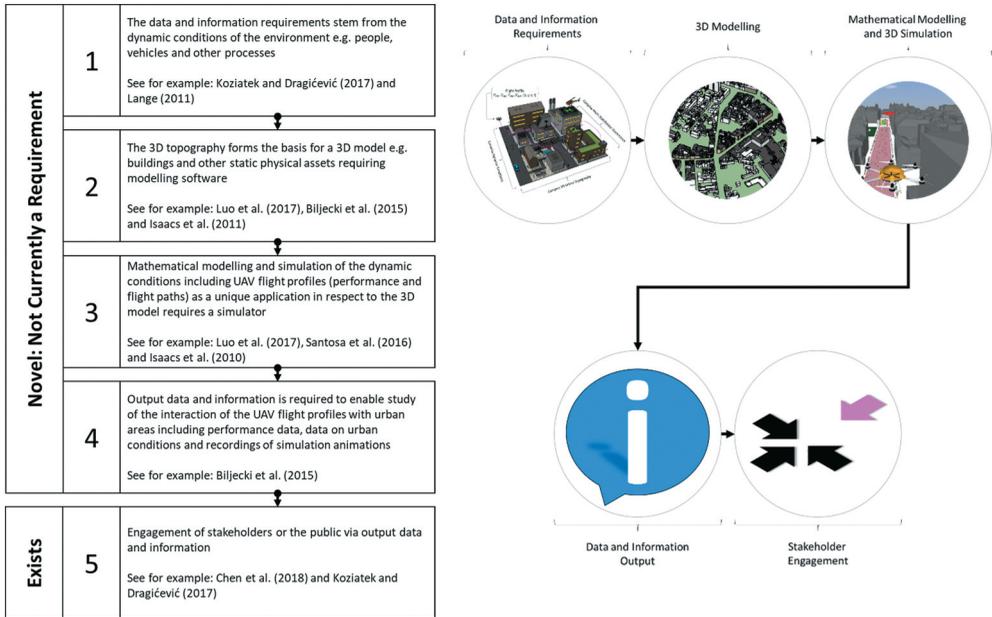


Figure 3. Procedural stages and conceptual framework for an urban UAV flight operations planning decision support system.

system and addressing this practical capability gap that is of relevance to a wide array of built environment professionals (see Figure 3).

Data, information and 3D modelling requirements

The initial focus is on stages 1 and 2 of the conceptual methodology as identified above. Data and information are required in relation to UAV profiles, such as device capabilities. There are various relevant capability data variables as discussed pertaining to payload, range, endurance and speed. Given the variability of these capabilities across UAVs a database is required that enables comparison and identification of specific UAVs based on optimisation of their weight and performance characteristics. A database was identified and sourced from a consultancy firm (DroneII⁷) that specialises in UAV industry insights and was the most comprehensive one available at the time (2018). The database was compared with manufacturer data to ascertain accuracy and reliability. Accuracy and reliability are critical to ensure that the data matched the real-world capabilities of UAVs. The maximum values for each capability aspect were provided in the database and can be considered reliable as they cannot realistically be improved upon in the real-world using the base-configuration of each UAV. In addition, the UAV models represented in the database provided adequate scope for study across a range of performance and weight capabilities. The database was filtered to 50 UAVs to focus on the most common variant likely to be used in the built environment for given regulatory and legal boundaries. Furthermore, data and information are required in respect to urban conditions. However, these are case study dependent. Data and information are also required to enable 3D modelling of a case environment. However, a very high accuracy model of a UK city was already developed and validated (Christensen et al., 2016),

and thus adapted for use in this methodology to reduce pre-simulation limitations such as cost and development time. Although a 3D model was available, it was in sections that required stitching together using a 3D modelling package which was also required to access and manipulate the model. Given the file type, Sketchup Pro was selected.

Mathematical modelling and 3D simulation requirements

Consideration turns to the requirements associated with stages 3, 4 and 5 of the conceptual methodology. Following Wolski and Narciso (2017) and Thiesing and Pegden (2015), Simio was identified as a suitable mathematical modelling and simulator package for decision support system prototyping purposes. Simio is a next-generation simulator designed for event-based simulation reducing development time and complexity due to its specially designed 3D model import, drag-and-drop interface, extensive object libraries, and easily calibrated properties (Abar et al., 2017). An important feature is compatibility with Sketchup Pro and the ability to run in-software analysis of a simulation, record simulations and provide different perspectives of a UAV profile. Simio has been widely used for similar research work including by large commercial organisations such as Vancouver Airport.⁸ The simulation process in Simio involves importing a 3D model, building and calibrating the mathematical model or simulation structure using input UAV and urban area parameters, running, observing, analysing the output data and information and conveying to stakeholders.

Scoping a case study

Moving the research forward, based on addressing the limitations identified earlier in this paper (see Figure 1) several research questions emerge regarding this conceptual methodology:

- (1) Can the conceptual framework successfully enable the visualisation and awareness of UAV flight operations in urban areas including the impact upon the complex urban system because of planning decisions and is the framework flexible regarding future improvements?
- (2) Does the conceptual framework provide meaningful data and information output that aids in urban UAV flight operations planning decision-support?
- (3) Is the conceptual framework portable across a wide stakeholder group and does it successfully engage and convey meaningful data and information that is perceivable and relevant to the urban-UAV flight operations group of stakeholders?

These research questions are used as a guide for applying the methodology, see Section 4 below.

Applying the methodology – city marathon case study

The conceptual methodological framework, established in Section 3, outlined the procedural stages (Figure 3) for applying the methodology to address the three research questions. Proprietary software, interestingly, is compatible with the conceptual

methodological framework, enables the implementation of the procedure, and is thus an ideal platform from which to pilot and test the framework in advance of any future upgrades and developments. The research therefore highlights the need for a novel urban UAV flight operations planning and decision support system, shown the potential of the 3D simulation approach, and established a pipeline for development, piloting and testing. Figure 4 illustrates the mapping of research questions to decision support system development, piloting and testing. Research question 1 requires development of a prototype decision support system. This then enables research question 2 to be addressed through appropriate case studies. Completion of case studies then allows for the testing of fitness-for-purpose of the system and addressing of research question 3. This process arises from the requirement to understand the extent of any development limitations. Given the availability of an existing 3D city model there is adequate scope for an initial or pilot case study thus enabling research questions 1 and 2 to be addressed. The city that the 3D model represents has been made anonymous to remove any direct association for confidentiality purposes. However, there is a wealth of data and information available on this particular city across a wide range of potential situations to enable the development, piloting and testing process to be initiated.

The case study makes use of UAV capability data analysis and 3D simulation of UAV flight plans. The research is derived from a study of civilian UAVs in the built environment with the case study modelled on a real urban space. The choice of case study environment arises from its typicality to other comparable urban areas as it is a complex and bustling urban centre with diverse crowds, places, assets, systems and processes that provide enough range and depth to the study. Furthermore, a marathon event was chosen given its nature as a large urban crowded event. A marathon event also provides the foundation for a wide range of UAV applications and for the investigation of flight operations in respect to complex urban topography, conditions and vulnerabilities or hazards. The chosen marathon for the case study is an annual event that is highly predictable in crowd numbers and a large wealth of information was available beforehand such as the running route. The nature of the marathon thus provides excellent basis for observation, data and information collection and analysis. The simulation of such

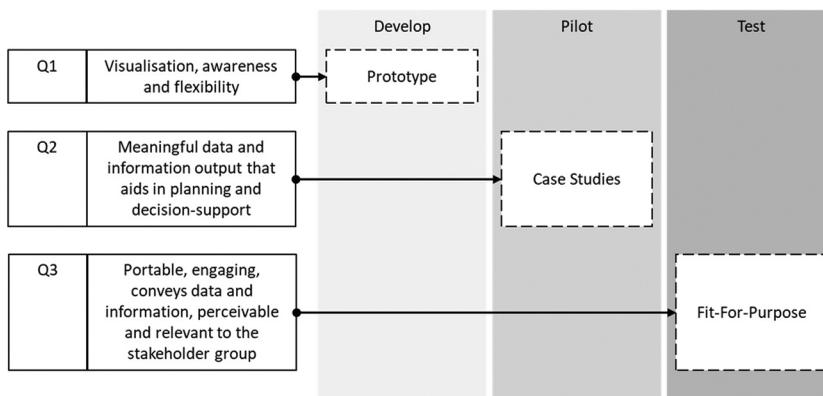


Figure 4. Urban UAV flight operations planning decision support system prototype development, pilot experiment and testing process.

urban crowded events removed the risk and liabilities associated with re-enactments of UAV operations in a real setting instead utilising UAV data and a 3D environment model.

UAV database analysis results

The three variables (max endurance, range and speed) were transformed into a single performance product variable. This enabled comparison of performance product against the maximum payload variable to establish payload weight-performance ratio of different UAV models. The greater the performance product value and maximum payload value the greater the payload, ability to travel further, for longer and faster in respect to other UAV models in the database. The performance product is thus used as a dimensionless reference scale. The performance product data variable (V_{Perf}) is given by Equation 1 (V_{ME} is the maximum endurance, V_{MR} is the maximum range and V_{MS} is the maximum speed).

$$V_{Perf} = V_{ME} * V_{MR} * V_{MS} \tag{1}$$

The performance product was calculated for each UAV in the database yielding a new dimensionless data variable. The resultant performance-maximum payload ratios are shown in Figure 5 where V_{MP} is the maximum payload variable. Figure 5 has four quadrants; low performance product, low maximum payload; high performance product, low maximum payload; low performance product, high maximum payload; and high performance product, high maximum payload. Thus, UAVs in the database with specific

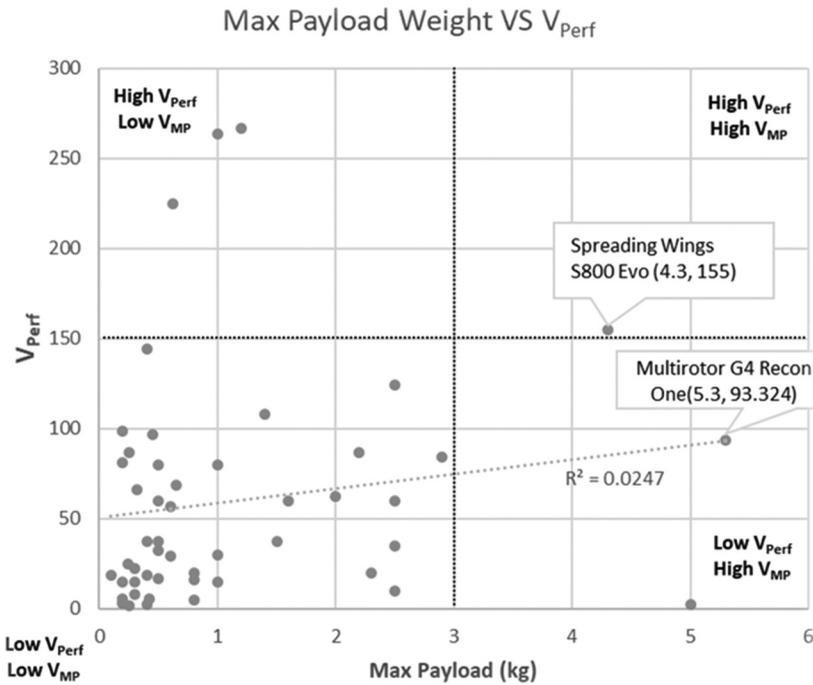


Figure 5. Max payload VS performance variable for a range of multicopter UAV models.

performance-maximum payload ratios could be easily identified. The Spreading Wings S800 Evo with a maximum payload of 4.3 kg fell within the high performance product, high maximum payload ratio quadrant – the only UAV to do so. It represents the best well-balanced UAV or in other words it has the best capability trade-offs.

The Spreading Wings S800 Evo UAV has a maximum speed at 25.83 m/s, 5,000 m maximum range, and a maximum endurance of 1,200s (Table 1) and clearly has the best balance of performance and weight capabilities of all UAVs assessed and hence was used in calibrating simulations in the prototype decision support system for the case study.

Prototype results

Images of simulations for the prototype decision support system and successful implementation of the case study including 3D model, conditions and UAV flight operations are shown in Figure 6(a–c). Figure 6c in particular demonstrates that multiple UAV operations can be incorporated simultaneously. As illustrated, the marathon event, situated within an anonymised city centre location, informed calibration of the UAV flight profile with a specific emphasis placed on the start/finish line. The marathon set parameters for the case study, taking into considerations the aforementioned UAV

Table 1. Performance and weight capabilities of the spreading wings S800 Evo.

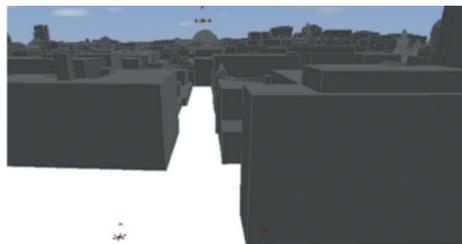
	Spreading Wings S800 Evo
Maximum Payload	4.3 kg
Maximum Speed	25.83 m/s
Maximum Range	5,000 m
Maximum Endurance	1,200s



a: Prototype stills for application 1 – payload delivery.



b: Prototype stills for application 2 – observation.



c: Prototype stills for application 3 – multi-UAV operations.

Figure 6. (a) Prototype stills for application 1 – payload delivery. (b) Prototype stills for application 2 – observation. (c) Prototype stills for application 3 – multi-UAV operations.

applications, surrounding urban topography, and users of spaces; that is, both urban (built environment) and operational constraints. The prototype results outlined below are not exclusive to a marathon or other sports event but reflect the complexities of UAV operational planning necessary for large gatherings in urban areas that are in close proximity to pre-existing and future urban structures.

After importing a 3D urban model, a particular scenario simulation could be set-up and calibrated within a few hours and quickly adjusted to explore alternative options. The prototype enabled the simulation of a UAV in real-time within close proximity to an urban environment including incorporation of complex building geometry (Figure 6a and b). In addition, the prototype enabled the UAV agent to be calibrated based on its capability range. Hence, it is possible to visualise, communicate and understand the implications of flight path and operational decisions in light of a particular profile's interaction with the 3D urban environment from any camera angle including first person or close-in perspective. The potential of such a decision support system for use in safe urban UAV flight operations planning is apparent in working with the prototype. However, as with any prototype there are limitations. Simio for example, lacked the ability to incorporate more complex environmental physics such as weather effects. In addition to the visual output of simulations, data were generated that depended on the application design and the calibration of the simulated UAV agent. The data output thus quantified the events being visually represented in the simulation. Simio outputted this data in complex spreadsheet form requiring the data to be reorganised into a dashboard (Figure 7), to improve ease and effectiveness of communication, including for example, time of flight, flight distance, speed, payload count and exposure (number of people that randomly passed through the simulated area over the course of the operation). The capability information for the Spreading Wings S800 Evo and Simio data output dashboard for three application flight profiles, namely: 1) payload delivery; 2) observation; and 3) multi-UAV operations respectively, is shown in Figure 7. The effective maximum sphere of operation is 5,000 m or 2,500 m fly-to-return range.

Having completed and tested the prototype, with verification of data and generation of visual outputs for analysis, focus now turns to discussing outputs from the marathon event-based simulation.

Discussion

Theoretical considerations

Application of this conceptual methodology addresses an identified gap in the literature regarding an urban UAV flight operations decision support capability, and the framing of such a decision support system in response. The literature revealed, through analysis of historical development, visualisation preferences and pre-existing urban applications, that decision support systems have the potential to be effective and beneficial in urban planning. Indeed, existing applications tend to be geared towards understanding and visualising the dynamic, spatial and temporal conditions of urban areas. The examples of urban 3D simulation applications are transferable to the simulation of urban UAV flight operations including incorporating the features of complex urban topography. For example, the simulation of flight within urban environments, and transport, hazard, safety, security and emergency planning are all indicative of the usefulness within a UAV

Spreading Wings S800 Evo			
Max Payload	Max Speed	Max Range	Max Endurance
4.3kg	25.83m/s	5000m	1200s
Application 1: Payload Delivery	Application 2: Observation	Application 3: Multi-UAV Operations	
Flight Distance	Flight Distance	Total 3x UAVs Flight Distance	
545m	1673m	1644m	
Flight Time	Flight Time	Max Flight Time VS Speed 1	
27s	335s	31s @ 20m/s	
Flight Speed	Flight Speed	Max Flight Time VS Speed 2	
20m/s	5m/s	125s @ 5m/s	
Flight Path Exposure	Flight Path Exposure	Total 3x UAVs Exposure	
653 †	2578 †	≈2500 †	
Payload Factor	Payload Factor	Payload Factor	
x1	x1	x3	

Figure 7. Application 1, 2 and 3 simulation data and information dashboard.

context as informed by analysis of the literature on the challenges of urban UAV operations integration. From an awareness and visualisation perspective, 3D simulation is already used for navigation, routing and accessibility planning including in respect to the dynamic conditions of urban areas (vehicles, people and processes), as well as for optimal location of new infrastructure (transportation systems or security measures). However, when considering UAVs in particular, there is a new 3D aerial spatial frame of reference unlike most ground-based vehicles with 2D spatial frames of reference confined to surface operations, and which unlike manned aircraft will move in respect, and proximity to the complex 3D urban topography. The results of the literature review show that this complexity is the basis for requiring a new level of situational understanding and communication so that effective and rigorous decisions can be made regarding safe UAV flight planning in urban areas with inclusion of all key stakeholders involved. In response to these findings, the prototype simulator was conceptualised and

prototyped yielding a novel outcome in the form of a decision support system and contribution to knowledge as further expanded upon below.

Methodological considerations

As demonstrated in the results, the prototype solution is capable of providing a level of awareness and understanding in respect to UAV flight operations, evidencing the potential success and aforementioned benefits of such a system. This includes the understanding and awareness of complex 4D situations involving single or multiple UAVs in close proximity to urban topography or other UAVs operating within the same urban flight space as demonstrated via the marathon case study representative of a typical urban event. Furthermore, the changeability of the camera perspective and user control of the simulated space enabled specific aspects of the UAV flight operations to be visualised and recorded. As a consequence, aspects that could not be shown in traditional 2D simulation methodologies, or via existing and much less detailed and informative UAV mission planners, are now covered.

The future of urban environments – form and function – and stakeholder governance relative to urban UAV flight operations and infrastructure systems also requires consideration as UTMs for example, are still largely developmental. Considering the issues surrounding urban UAV usage and integration in general, 3D simulation provides the basis for 3D spatial and temporal data and information retrieval that can be visually communicated to a wide range of stakeholders as demonstrated through the marathon case study simulations and output data dashboard. Furthermore, the communication benefits are not just relevant from a stakeholder point-of-view but also in providing evidence, communicable resources for public dissemination and potentially for use in investigation or insurance. Data and information reports, videos of animations, image stills, and virtual reality are all potential media formats that can be generated from 3D simulation. Such output could enable more immersive assessments of UAV operations planning decisions in urban areas to include actual flight operations-based-decisions and potentially, future multi-UAV operations and infrastructure-based-decisions.

In addressing research questions 1 and 2, the prototype as applied to the marathon case study successfully enabled the visual output of UAV flight plans in respect to complex 3D urban topography including other UAVs (see: [Figures 6 and 7](#)). The implications of decisions regarding flight plans can thus be investigated and communicated to stakeholders. Furthermore, data calibration, coupled with the output of the simulation data dashboard, enables flight plans to not only be visualised to stakeholders but also quantified in respect to performance across different application types. As shown in the results, the prototype based around the Simio platform provides a means for communication of complex spatial and temporal data and information via several modes including production of a data dashboard and various animation output modes such as stills and videos.

Thus, expanding upon the theoretical findings by evidencing the future flexibility and wide-ranging applicability of the decision support system concept. The potential for shared or joint communication, learning and complex decision-making is evidenced, concerning urban UAV integration across urban stakeholders. For example, bridging the gap between urban planners and UAV operators on safer flight path planning, or

corridor and supporting infrastructure development. However, the prototype requires further consideration and testing with stakeholders (research question 3); this is a potential pathway for further work in this area.

Policy considerations

The potential impact of this decision support system from a policy perspective is focused around urban UAV flight operations policies, in particular, safe and legal operation. The decision support system is geared towards improving urban management, planning, operator and policy stakeholder engagement on issues such as safer urban UAV flight operations and associated aspects such as the development of future UTM infrastructure. The Civil Aviation Authority for example, is the UK's specialist aviation regulator and has established policies regarding UAVs.⁹ In addition, government organisations including the Department for Transport have released policy documents such as *Taking Flight: The Future of Drones in the UK, Government Response*.¹⁰ These policies include information on organisational powers, industry statistics, commercial UAV operations guidance, UAV classification systems, permissions and licensing, rules and legal boundaries, and the drone code informing operators on safe and legal operation via the dedicated Drone Safe website.¹¹ In this regard, the decision support system would potentially improve upon such policies through more active and engaging planning practices. Existing policy offerings are largely based upon *guidance* rather than more *active measures* whereby planning systems are promoted to urban UAV flight operations stakeholders to enhance conformity to rules and legal boundaries and reinforce safety in advance of flying UAVs, including multiple UAVs, in close proximity to urban areas. Thus, there is an apparent gap in existing policy narrative surrounding the availability of such active measures, referring to 3D simulation-based decision support systems, to urban stakeholders, something that is potentially addressed by the developed decision support system.

Limitations

Some potential challenges do however exist particularly in relation to the availability of 3D models; data and information specific to particular urban areas; modelling or information and data capture; and the time and cost required to produce such realistic urban representations when not readily available. Although, the decision support system does allow flexibility for modelling and calibrating future UAV performance capabilities. As a consequence, it is clear that stakeholder governance and decision models which better organise, manage, encourage and guide cooperation among the UAV urban stakeholder group are needed to best utilise resources and prevent conflict of interest. Governance models would also foster the sharing of urban information across a multitude of locations and assets and associated urban activity for incorporation in the urban UAV flight operations planning decision support system. However, in parallel with this potential communication and cooperation challenge, UAV operations within urban areas will require stakeholders to cooperate at the local level as all will be mutually impacted by these operations potentially helping to naturally foster cooperation. Furthermore, the fundamental nature of the urban UAV flight operations planning decision support system is the encouragement of such cooperation. As a result, it is

important to integrate the decision support system with governance models at local level. In furthering this research to address research question 3, such governance models would be investigated, developed and set-up as a key part of testing the fitness-for-purpose of the system.

Conclusion

In conclusion, the methodological framework represents an innovative contribution to ongoing discourse on urban airspace UAV integration. As well as the planning of future individual and multi-UAV operations and UTM infrastructure, ensuring ongoing resilience and contributing towards sustainability, from a strategic urban development perspective this decision support system also has the potential to be used in debates on the future of urban environments in respect to UAV operations. It is highly beneficial to relevant stakeholder groups, fulfilling what can be perceived as a vital capability in future urban management given the outlook of increased and potentially mass UAV usage. Based on developments to-date, UAV flight operations and rapidly developing UTM infrastructures will increasingly interact with existing social dynamics (for example, perceptions of safety in urban spaces shared with UAVs) and future economic processes (such as the low-cost automated movement of goods). Consequently, we would propose that the methodology and tool outlined above would be of benefit in urban master planning and the consideration of new physical structures (buildings, bridges, towers, etc.), similar to (regulatory) land use planning processes in relation to airport public safety zones (Department for Regional Development (DRDNI), 2007).

Potential implications for built environment professionals include the realisation that better communication, insight and co-operation is required due to the extensive complexities of urban environments and inherent safety considerations when planning UAV flight operations. Clearly, there is a requirement for urban UAV flight operations planning governance models given the high proximity of physical assets within urban areas. Such models would focus on mitigating resistance to open discussion and break down communication and decision-making barriers including the sharing of information. Furthermore, the dynamic and variable nature of urban conditions and diverse stakeholder requirements surrounding different urban environments and individual assets, locations or systems makes planning and decision making a very complex process. It was indicated that urban UAV flight operations planning must be applied to each area, asset, location or system to take into consideration the dynamic and variable nature and unique requirements of each stakeholder involved.

As noted earlier, this research represents the initial stages of an innovative approach to mitigate the potential negative impacts from the ubiquitous use of UAVs. The next stage in the research would specifically involve governance model design, testing the portability, effectiveness and desirability of the decision support system in engaging stakeholders, and how stakeholders perceive the output data and information, per studies of transportation models (Te Brömmelstroet et al., 2017). Given the emergence of smart cities, UAVs and related infrastructure, such knowledge development is critical in ensuring effective UAV integration, whilst having stakeholder engagement and governance models as an integral component of urban planning.

Notes

1. Heathrow UAV disruption accessed via: <https://www.bbc.co.uk/news/uk-46803713>
2. Venezuela UAV attack accessed via: <https://www.bbc.co.uk/news/world-latin-america-45077057>
3. We acknowledge that not all innovation is 'positive' or necessarily 'beneficial' and can lead to 'unintended consequences' (see for example: Sveiby (2012).
4. Sydney Opera House drone accident via: <https://www.theguardian.com/world/2013/oct/05/drone-crash-on-sydney-harbour-bridge-investigated>
5. Drone users face new rules across Europe and UK via: <https://www.bbc.co.uk/news/technology-55424729>
6. NASA UTM's via: <https://utm.arc.nasa.gov/index.shtml>
7. DroneII via: <https://www.droneii.com/>
8. Simio via: <https://www.simio.com/index.php>
9. Civil Aviation Authority <https://www.caa.co.uk/Our-work/About-us/Our-role/>
10. Taking Flight: The Future of Drones in the UK, Government Response https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/771673/future-of-drones-in-uk-consultation-response-web.pdf
11. Dronesafe <https://dronesafe.uk/>

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