Collegiate Aviation Review International

Volume 40 | Issue 1 Peer Reviewed Article #3

2-21-2022

Airspace Deregulation for UAM: Self-organizing VTOLs in Metropoles

Hüseyin Önder Aldemir
Ozyegin University

Çağlar Üçler
Ozyegin University

Small-scale aviation has been driven extensively by recent technological developments. Distinct micro/small scale mobility modes are being interlined, where automated Vertical Take-Off and Landing Aircraft (VTOLs) are being conceptualized for Urban Air Mobility (UAM) in the form of air taxi, cargo, disaster relief, or medical help. This implicates many simultaneous flights over cities, which is a significant challenge. Traditional air traffic control is customized for commercial aviation, and it is not suitable for the dynamic variation in the flight routes of UAM. Consequently, a literature review is conducted firstly for air traffic management subject to UAM. Then, as a critical finding, a self-organizing model integrating particularly micro/small scale UAM is proposed utilizing the swarm concept to leverage the autonomous behavior of VTOLs. Rules for self-organization are set, which are then discussed in conjunction with available technologies such as Global Positioning System (GPS) and Traffic Alert and Collision Avoidance System (TCAS). Finally, the basic concept definition is elaborated to determine challenges and future research.

Recommended Citation:
Aldemir, H. Ö, & Üçler, Ç. (2022). Airspace deregulation for UAM: Self-organizing VTOLs in metropoles. *Collegiate Aviation Review International*, 40(1), 40-62. Retrieved from http://ojs.library.okstate.edu/osu/index.php/CARI/article/view/8377/7729

Developments in energy storage and electric propulsion empower a new era for aviation (Al Haddad et al., 2020). New innovative Urban Air Mobility (UAM) applications are being deployed as an alternative to traditional mobility solutions (Rothfeld et al., 2018). Micro-/ small-scale mobility is being interlined in cities in the form of automated electrical vertical take-off and landing vehicles (eVTOLs). These are being conceptualized for urban transport in the form of air taxis (Rajendran et al., 2021), cargo, or personal air vehicles (Rothfeld et al., 2019). Consequently, UAM refers to all flight operations within geographical limits of cities with the perspective of carrying persons or cargo subject to the vision of "Anyone, Anywhere, Anytime" (Cotton & Wing 2018, p.2).

There are already many technology firms focusing on UAM with different platform designs such as eHang 216, 116, 184, Volocopter 2x, VC200, Lilium Jet, Airbus Vahana, CityAirbus, Pop Up, Boeing Aurora, Bell Nexus, Kitty Hawk (+Boeing): Cora, Flyer, Joby Aviation S4, S2, (eHang, 2020), Neva AirQuadOne, Joby S2, Opener Blackfly (Straubinger et al., 2020), NASA Puffin, Rolls-Royce eVTOL, Agustawestland Convertiplane, Kitty Hawk Cora, Terrafugia TF-2 (Zhou et al., 2020), Sikorsky, JetBlue, Amazon, Google and Toyota (Cotton & Wing, 2018). Uber predicted that 27,000 flights with 300-500 eVTOLs per day per city will be carried out over many cities of the USA by 2025 (Moore, 2017).

UAM is substantially expected to improve individual mobility that the arising transportation modality can potentially overcome urban surface transportation (Lowry, 2018). Incorporating new modes of transportation with VTOLs (Rothfeld et al., 2018) is becoming crucial. UAM can reduce travel time, disrupting travel patterns (Fu et al., 2019). It is a new transport mode within or between cities (Straubinger et al., 2020), and only the air taxi utilization is estimated to reach up to 10,000 commuters per day in peak times (Rajendran et al., 2021). Consequently, a market with more than 23,000 automated aircraft is estimated with a volume of $32 Billion by 2035, and various companies such as Uber have already included air taxi income in their business plans (Al Haddad et al., 2020). The drone volume of the airspace and the value of the drone industry are unpredictable in the future. However, according to the European Drones Outlook Study (SESAR JU, 2016), it is estimated that approximately 400,000 drones will be providing services by 2050, and the total market value will be over 10 billion Euros by 2035.

Rothfeld et al. (2018) applied the agent-based traffic simulation framework MATSim for UAM by using the same case scenario improved by Hörl (2016) for self-driving cars. A simulation for the economic feasibility is provided for 100 UAM vehicles at a 500 m (1640.42 ft.) cruise level with a speed between 10 and 150 m/s (22.4 and 335.5 mph) distributed around 10 UM stations resulting in only three times the price of a car.

Autonomous aircraft are already being used in search and rescue, surveillance, localization and mapping, military (Sargolzaei et al., 2020), monitoring, inspection, data collection, logistics, and recreation (Merkert & Bushell, 2020). UAM solutions are also conceptualized for disaster relief and medical help besides individual usage. Japan Airlines aims to deliver medical care in remote areas using eVTOLs (Sumitiomo Corporation, 2020). More than one million small drones are registered in the USA, and many well-established large organizations are focusing on UAM solutions (Cotton and Wing, 2018). The European Union defined the importance of such systems with the Warsaw Declaration as “Drones as a leverage for jobs and new business opportunities” and decided to invest in this field with the SESAR Joint Undertaking (2016).

Antcliff et al. (2016), Garrow et al. (2018), Lowry (2018), and Haddad et al. (2020) indicated that the market is ready to adopt UAM despite psychological and ethical concerns based on automation. The willingness to fly can be further enhanced by implementing remote control mechanisms or safety devices such as parachutes (Ward et al., 2021). The acceptance criteria for UAM are travel time, travel cost, and safety, where a certain price increase for this service is already accepted (Fu et al., 2019). Socio-economic factors, safety perceptions, and modality patterns have an impact on the adoption, but it is inevitable that UAM will be the reality of tomorrow (Fu et al., 2019), and feasible VTOLs can find usage easily with technology advancements (Rothfeld et al., 2019).

Currently, the assumptions for the application of UAM are mainly consisting of an on-demand travel model (Rothfeld et al., 2018). This situation yields a high travel frequency without any schedule in advance, which is also highly dynamic. Lowry (2018) assumes that pilotless aircraft in UAM will have a density of 100 aircraft per square km in 2035. Therefore, the safe integration of UAM into the airspace appears as a major issue (Katz, 2019). The challenges within a city are particularly difficult, i.e., “maintaining safety under all failure conditions while flying over people and property is daunting” (Cotton & Wing 2018, p.2).

Such a complex environment requires an intelligent system with a high level of perception (Floreano and Wood, 2015) integrating many stakeholders simultaneously. The frequency of the interactions among these stakeholders is simply too high that decentralized systems are preferred instead of centralized control (Airbus, 2018).

Air traffic management and infrastructure are key for UAM (Straubinger et al., 2020). There is a need for low-altitude airspace management to support drone usage (Merkert & Bushell, 2020). Current research focuses on decentralized multi-agent-based architectures used for coordination, mission management, collision avoidance, formation, and path planning (Mualla et al., 2019). This means a decentralized “self-” management of the air traffic. There, swarms are the highest level of autonomous capability (Gao et al., 2016), which theories were applied to air traffic management as well (Torres, 2012).

However, UAM is more than a collection of distinct vehicle concepts or singular technology applications. It requires an operational concept within an infrastructure connecting to existing transportation systems (Rothfeld et al., 2018) that “new regulations and air traffic control systems are needed” (Fu et al. 2019, p.428). Consequently, the following research questions do arise:

Q1: What are the challenges and requirements subject to ATC and UAM?

Q2: What are the appropriate rules for setting up a model for traffic organization in UAM?

Consequently, ATC for small and medium VTOLs in metropoles is discussed here, and a model is proposed facilitating the concept of a self-organizing swarm for urban air mobility. The structure of this paper is as following: Firstly, literature research was made for UAM traffic management, where the requirements were set. Secondly, the method is explained. Then, based on the literature, a model was conceptualized, which was then discussed in relation to set requirements. Finally, conclusions and future research areas were defined.

Literature Review

Air Traffic Management Attempts for UAM

The lesson learned by the fatal mid-air collision of two commercial flights in 1956 over the Grand Canyon leading the way to the Air Traffic Management (ATM) is also indicating the need for the regulation of future low-altitude small unmanned aircraft systems (UAS) (Kopardekar et al., 2016). There is already research about the infrastructure and regulations for UAM operations by Cohen (1996), Lowry (2018), Cotton & Wing (2018), Fadhil (2018).

Then, governmental bodies are also working on the Concept of Operations (Kopardekar et al., 2016) on the regulative side. FAA and NASA are working together closely on UTM research through a joint Research Transition Team (RTT) collaborating with other governmental institutions focusing on low altitude safe operation of small UAS also supporting beyond visual line of sight conditions (Kopardekar et al., 2016).

Particularly, NASA is involved in the management of UAM under the UAS Traffic Management (UTM) initiative, while FAA is only concerned with safety issues of UAS regulating remotely piloted aircraft, and their vision of Technical Capability Level (TCL) 4 is by far not pacing with the progress of the industry (Cotton & Wing, 2018). According to the NASA UTM Technical Capability Levels, UAM operations will be authenticated at the fourth level, which denotes beyond the line of sight, high density, autonomous, vehicle-to-vehicle, in-flight deconflicted (Bijjahalli et al., 2019) and internet-connected operations over metropolitan cities for miscellaneous purposes (Koperdekar et al., 2016).

Then, the Drone Helsinki Declaration in 2017 with the participation of EU institutions - EC, EASA, EUROCONTROL, SESAR concluded in support of Urban Space services for more autonomous vehicles in denser traffic adopting new digital technologies from all sectors and uses (EASA, 2017). This is an important milestone, indicating that solutions beyond traditional aviation concepts are required and supported by authorities as well.

Furthermore, Airbus and Singapore Civil Aviation Authority (CAAS) also signed an agreement on 12 February 2020 to develop unmanned traffic management (UTM) system to support the initial stage of urban air mobility by delivering a framework for safety, operating standards, and public acceptance while Japan Airlines and Sumitomo Corporation signed a corporation agreement with Bell Textron Inc. in 2020 to search out business opportunities for air mobility services, deploying Bell's eVTOL in Japan and Asia, which addresses the studies for UAM, its infrastructure, and regulations of the environment by centering on the use of Nexus 4EX eVTOL (Aviation Week, 2020).

U-Space: The first official deregulation attempt

EASA released an Opinion (2020) in U-Space, a set of services and procedures for drones. The airspace for both manned and unmanned aircraft are orchestrated for safe operation, preventing collisions and reducing the air and ground risks. Due to the local legislations of European countries, the harmonization across Europe is still being assessed, but in short U-Space airspace is below 500 ft. outside the urban airspace and below the minimum height within the urban environment or around the airport. U-Space authorities provide services to UAS like network identification, geo-awareness, flight authorization, traffic information, tracking, weather information, and conformance monitoring services (Annex to EASA Opinion 01, 2020).

Accordingly, air navigation service providers are designated to support manned as well as unmanned aircraft in the controlled air space and to provide flight information services only to manned aircraft in U-space territories, while *U-space service providers* are in charge of the U-space airspace. Although being still under development, this is particularly of interest because it leads the way to the establishment of private or governmental organizations for the management of the urban airspace.

So, U-Space is aiming to enable high-density operations accessible to all parties in a scalable manner (SESAR, 2017), but it relies on ATC for flight planning approval and tracking and is far away from setting up a model for unmanned aircraft in urban environments; in the short term, it aims to regulate the registration and drone missions of human-guided unmanned vehicles over an online system. In the long term, U-Space aims to figure out conflict detection and resolution and large-scale UAV management by 2027 and to achieve full integration of UAVs with manned aircraft by 2035.

Requirements of UAM Applications

The regulation is complicated by the variety of urban applications such as transportation, monitoring, and urban management. Different business models are being discussed for UAM, particularly focusing on ownership models, on-demand services, and commercial air taxi solutions such as UBER (Rothfeld et al., 2018). According to current regulations, the presence of a pilot is required for safety purposes, and UAV flights in urban areas are restricted (Lancovs, 2017). Then, there is also a lack of validated rules for airspace operations and integration requirements, which can cope with the projected future densities (Kopardekar et al., 2016).

The future applications of UAM implicate a high number of simultaneous flights over cities, which is a major challenge. However, air traffic control is mainly dealing with commercial flights, and their capability is restricted. UAV integration to the air traffic is enabled by small transponders (Lancovs, 2017), but only in regulated airspace. Then, there is a high variation in the flight routes of UAM, which also have a dynamic character, i.e., they can change during the flight. Furthermore, the traffic density and the interactions with other traffic modes or with the urban properties contribute to the risk of UAM. Consequently, unmanned flight in urban airspace requires new methods for traffic management (Balachandran et al., 2018).

Decentralization and UAM: Rules of operation

There are no explicit regulations related to the dense traffic requirements of fully automated aircraft subject to UAM. Cotton and Wing (2018) came up with the idea of UTM applying a decentralized approach by using airborne surveillance, self-separation, and a minimized *design separation* approach to provide the optimization and safety of each flight in very high traffic densities and close proximities. Today's technology is rapidly developing, and particularly collision avoidance for UAM applications has to be worked on (Lancovs, 2017).

Considering that landing and take-off are to be done on rooftops, car parks, or other urban structures (Cotton & Wing, 2018), the resulting dense traffic definitely requires a collision-avoidance system (Katz, 2019). Airbus (2018) relies on a system with a mix of managed separation and detect and avoid (DAA). Consequently, UAM operations in the urban environment will lead to new airspace concepts, which include stacked layers, dynamic 4D tubes, designated zones, and urban air corridors. UAVs in this new, smart urban air space access depend on some capabilities like accurate, precise, and reliable trajectory tracking and conformance and robust DAA systems (Bijjahalli et al., 2019).

Considering that UAM systems will operate within 3,000 ft of the ground, they will be in close proximity to one another, or obstacles that existing ATC systems neither support them adequately nor there are any clear plans for how to integrate them (Vascik et al., 2018). So, this makes low altitude airspace management a requirement (Merkert & Bushell, 2020). There has to be cooperative decision-making in the traffic regulation (Gillissen & Schultz, 2018) across the UAM participants because the scalability of Air Traffic Control (ATC) is limited and constrains UAM depending on traffic workload (Vascik et al., 2018). This means that the self-managed separation is a must, which implies communication among all stakeholders and the reporting routines to the air traffic control.

Collaborative Traffic Management

Lancovs (2017) proposed a collision avoidance system used in manned aircraft for small, commercial UAVs operating in unregulated airspace since the UAV technology in UAM lacks a reliable collision avoidance system. Lancovs (2017) concluded that a cooperative, infrastructure-independent solution, like ADS-B, regardless of the sizes and attributes of UAVs, was required. The focus of this approach for all potential collision avoidance scenarios is to design a system maintaining the required level of P, which demonstrates the failure probability $P<10^{-9}$ (Won Keun Youn et al., 2015). This collision avoidance system is classified as a Level A system due to the possibility of human injury and death. Experiments were finalized by showing different minimal safe encounters which did not end in a crash. Thus, the system is guaranteed to provide the failure probability $P<10^{-9}$.

Balachandran et al. (2018) proposed an approach for the collaborative behavior of the UAVs in UAM to enable merging and spacing by using a combination of scheduling and distributed consensus. UAVs approaching an intersection schedule their arrival time independently and maintain a safe separation to safely merge at and coordinate passage through the intersection in a decentralized manner. For this common intersection, UAVs consist of a network, and each of them broadcasts its arrival time. Distributed consensus algorithm elects a leader from the UAVs approaching the intersection. This leader synchronizes the information gathered from the UAVs. The required minimum separation time for the UAVs was 10 seconds, and each of them adapted its trajectory to cross the intersection safely by applying the separation constraints. For this application, Dedicated Short Range Communication (DSRC) and Cellular V2V technologies seem the most operable tools.

The Route Management

According to the Blueprint for Airspace (Airbus, 2018), which outlines a roadmap for the integration of autonomous air vehicles into the airspace, four routing strategies exist: (i) basic flight with the freedom to select the shortest route which is open to conflicts, (ii) free routing coordinated and deconflicted with others involving a central authority, (iii) corridors as the best option to separate dense traffic, and (iv) (dynamically) fixed route with full control by the authority. For unmanned aircraft, the concept of Airbus (2018) assumes the provision of basic traffic information by the authority that pilots and autopilots can facilitate self-separation and collision avoidance. Furthermore, it also assumes a networked collection of services within distributed authorities instead of centralized control, which also leads to the privatization of the service.

A conceptual architecture for high-density UAM with over a million aircraft operations per hour is given by Lowry (2018), where different streams of traffic can be merged. There, the ascend and descent planning is designated with airspace construct, and vertiports are planned as stations. To achieve flight safety, the need for surveillance sensors is underlined there, and to tighten spacing and sequencing, the computation is planned to be ground-based and vehicle-based. The UAM is planned there to separate over 400 ft. from UAS and below 4,000 ft. from the regular traffic. Then, the short travels are separated from long-distance travels over 10 nautical miles at below 2,000 ft. The system has free planning across territories, i.e., free direct point-to-point flights below 2,000 ft. that the aircraft are not following any roads or other geographical features. Between 2,000 ft. and 4,000 ft., long-distance travels are on enroute highways, nonintersecting with other travelers at a similar height. This also requires a centralized control mechanism, but there is no information about this in the paper. It is only mentioned that parallel corridors in cardinal directions are fixed, and either a centralized system or inter-vehicle communication can be facilitated. Over 4,000 ft., the flights are channelized in the classical ATC manner. To prevent interactions, the UAM traffic is planned (Lowry, 2018) to be below the commercial traffic or on the side of commercial flight corridors that only general aviation airports are accessible for UAM. The system predicts over 5,000 vertiports for operation for an area such as the San Francisco Bay to enable walking distances for the UAM beneficiaries. Vehicle-to-vehicle communication and mutual spacing, and de-confliction are planned there as well, avoiding collisions and conflicts. Then, aircraft are separated with a 30-second distance in general and a minimum of 10 seconds by monitoring the vehicle ahead. The paper also mentions bilateral control but makes no information available, whether and how it shall be used or not.

Cotton & Wing (2018) proposed Airborne Trajectory Management (ABTM) concept, which evolves UTM using a decentralized approach in very high traffic and close vicinities by applying self-separation, a minimized *design separation*, and airborne surveillance. The conflict resolution modes of horizontal, vertical, and speed are facilitated together along with comprehensive traffic operating rules. Consequently, flights are planned independently, and the concept manages the angular velocity of a passing vehicle and perceives the hazard of very close UAM operations by autonomous, tactical separation of the vehicles, which enables flexible navigation plans. The decentralizing rather than ground-based trajectory management is preferred there for its economic applicability and robustness against catastrophic failure potential of ground-based systems (Cotton and Wing, 2018).

Then the "best-equipped, first-served" model was proposed by Vascik et al. (2018, p.5) to replace the *first-come, first-served* model used currently by ATC. The scalability of ATC is designated as a constraint and concern for the UAM high-density low altitude operations that safe and efficient airspace management with current ATC methods is a challenge (Vascik and Hansman, 2017). Traditional voice-based communication, existing navigation and surveillance (CNS) technologies, and separation minima regulations are not appropriate for UAM. Free Flight Operations allowing manned and unmanned aircraft dynamically to define their trajectories require Vehicle to Vehicle (V2V) communication and self-separation. Besides, some navigation technologies are expected to develop to support this decentralized and flexible concept for the integration of the UAM vehicles into the airspace (Vascik et al., 2018).

Separation in UAM

Katz (2019) proposed a new collision avoidance system (CAS) by utilizing the Partially Observable Markov Decision Process (POMDP) according to the expected behavior of UAM vehicles operating at low altitudes. Therefore, the proposed collision avoidance system extended the previous methods (Kochenderfer et al., 2012; Olson, 2015) to provide safe integration of these UAVs into the airspace. Monte Carlo simulations were executed to assess the performance of the algorithm by simulating it on a set of 1,000 pairwise encounters. Since many obstacles exist at low altitudes, lateral deviations are undesirable. This collision avoidance system just makes the UAVs use the vertical maneuvers called Resolution Advisories (RAs). However, since these UAM vehicles fly close to the ground, the descent is prohibited. Actions in the airspace used in this system similar to the Airborne Collision Avoidance System Xa (Kochenderfer, 2015) are clear of conflict (COC), do not climb (DNC), do not descent (DND), climb (CL250), strong climb (SCL450). The foremost assumption in the case of two aircraft's encounter is that a UAM vehicle with CAS reacts with vertical acceleration while the intruder (any aircraft) keeps its current path. There is also a reward model balancing safety and alert rate in this collision and avoidance system. Since there is no lateral movement defined in this model, just vertical separation is defined 100 ft. as a near mid-air collision (NMAC) variable. Alerts, which are the actions, not COC, are penalized while the COC action deserves a reward.

Besada et al. (2019) defined three layers in the air space as time/height constraints calculation (lower layer), terrain avoidance (middle layer), no drone zones avoidance, and incorporation of airspace constraints (upper layer). It is aimed to analyze the integration of the planning phases into traffic management solutions. Two types of operations are assumed: 1.

Automated flight, following 3D waypoint by applying open-loop control approach which is dependent on trajectory prediction tools by drone dynamic models; therefore, the operation is not dependent on the information received from drone. 2. Manual/autonomous flight dependent on the data provided by drone sensors in real-time, which autopilot or human pilot takes decisions on the trajectory.

The consolidated report of SESAR JU (2020) over nineteen projects, launched in 2017 and 2018, with numerous stakeholders demonstrates that Europe steps forward to implement safer UAM operations on metropole cities and to lead full integration with manned aviation. Although all nineteen projects are valuable, CORUS (Concept of Operation for European UTM Systems), DroC^{2}om (Drone Critical Communications), PODIUM (Providing Operations of Drones with Initial ATM), and TERRA (Technological European Research for RPAS in ATM) projects, more relevant to this research, stand out and are mentioned here. CORUS developed a Concept of Operations (CONOPS) for very low-level airspace operations of drones. CONOPS elaborated drone operations in uncontrolled, very low airspace and in/around controlled and/or protected airspace. After identifying airspace types, services, and technical development as an initial architecture, this consortium quantified the levels of safety and performance by applying scenarios for contingencies and emergencies. DroC^{2}om project validated LTE C2 (Long Term Evolution Command and Control) performance in urban areas. It concluded a hybrid cellular-satellite architecture combining low latency and coverage of cellular including 4G/5G specifications on LTE usage by aerial vehicles. PODIUM project paid attention to U-space solutions to ease the flight authorization of drone flights. PODIUM demonstrated a web-based UTM system including an open cloud-based solution and a secure gateway solution using tracking systems based on ADS-B 1090 MHz, UNB-L Band, and mobile phone networks for the drones operating in low-level airspace. TERRA project concluded that current communication, navigation, and surveillance (CNS) technologies are sufficient to support U-space services in simple environments with a low density of drones. However, new technologies like 5G, Galileo, and EGNOS v3 will be necessary for complex environments.

All in one, it is obvious that the integration of UAM into the airspace must be done by air traffic regulations (Mualla et al., 2019). This requires specific procedures for origin/ destination route planning, separation management, etc. For micro/ small scale UAM, i.e., the rules of UAM have to be written. Then a system complementing the existing air traffic control has to be defined to manage this traffic. At this stage, it is foreseen that it will be a separate system, which has the self-organizing capability, preferably within the swarm behavior of VTOLs.

Method

The challenges of urban air traffic management made this research required, where self-managed separation of unmanned aircraft is leveraged without the interaction of any external control authority. Consequently, a literature review was first conducted in scientific databases by using the keywords as ATC, UAV, RPA, and VTOL in conjunction with UAM. Then, TCAS, ADS, and urban keywords were added to further increase the scope. Consequently, 45 journal and conference papers were isolated. In addition to that, grey literature research was conducted as well: the commercial websites of urban autonomous aircraft producers, magazines, and similar sources were searched for by Google with the same keywords to trace technological enhancements on the technology push side. Also, FAA, EASA JARUS, NASA, and European Union publications were searched to include the regulatory input. Then, literature not delivering any explicit VTOL, UAM, or airspace control concept was excluded ending up in 12 reports, declarations, drafts, and regulation opinions. After that, the swarm concept in unmanned aircraft was looked at by the keywords swarm, VTOL, and unmanned aircraft resulting in 36 papers, where only 16 were selected after excluding the remaining papers which were not related to the concepts of air traffic management.

The literature review delivered the challenges and requirements subject to ATC and UAM, which were isolated as constructs for an air traffic management model in a deregulated airspace. In other words, based on the requirements and technological solutions presented therein, an appropriate model was conceptualized by the function-based synthesis method (Wood & Greer, 2009) for the regulation of the air traffic for UAM. There, the function is what the system has to do, i.e., the requirements are set with it. The synthesis is then focusing on structural elements enabling these functions constituting the model. These elements were set here as the rules of the urban air traffic guiding the self-organization as described next.

The Model: Self Organizing Swarms

UAM is embedded in a complex environment, which requires perceptual intelligence and reactive forms of control autonomy for coordination (Floreano & Wood, 2015). For this reason, the problems of regulation and collision avoidance have to be resolved (Mualla et al., 2019). This means that individual autonomous UAM systems, i.e., agents, have to operate together safely, leading to a multi-agent problem. In multi-agent systems, multiple interacting computing systems autonomously take actions in the coordination of other agents to achieve specific goals (Wooldridge, 2009). Such cognitive, decentralized multi-agent systems are used today in UAVs, particularly for coordination, mission management, collision avoidance, formation, and path planning, with urban planning as a common application domain (Mualla et al., 2019).

Since sight is limited in UAM, continuous use of radar to track neighboring aircraft is impossible. A multi-agent coordination framework is required, such as in the Vehicle to Vehicle (V2V) communication proposals of autonomous driving in the automotive industry (Balachandran et al., 2018). For this purpose, centralized as well decentralized attempts find a place where distributed consensus algorithms are safer. (Balachandran et al., 2018).

A multi-agent system can be used to form a swarm of aircraft acting as autonomous collaborative robots for spatial tasks, whereas model predictive control can be used for collision avoidance (Tahir et al., 2019). So, cooperative UAVs have challenges in collision avoidance, velocity matching, and cohesion due to the nonlinear dynamics, where existing technologies are capable of addressing these challenges by using cooperative algorithms for consensus, guidance-law, and flocking in a swarm (Sargolzaei et al., 2020; Luo & Duan, 2017). Cooperative algorithms have to be distributed that complex tasks are divided into simpler tasks and assigned to each member resulting in collective performance such as bird’s flight behavior as in nature (de Mendonca et al., 2016).

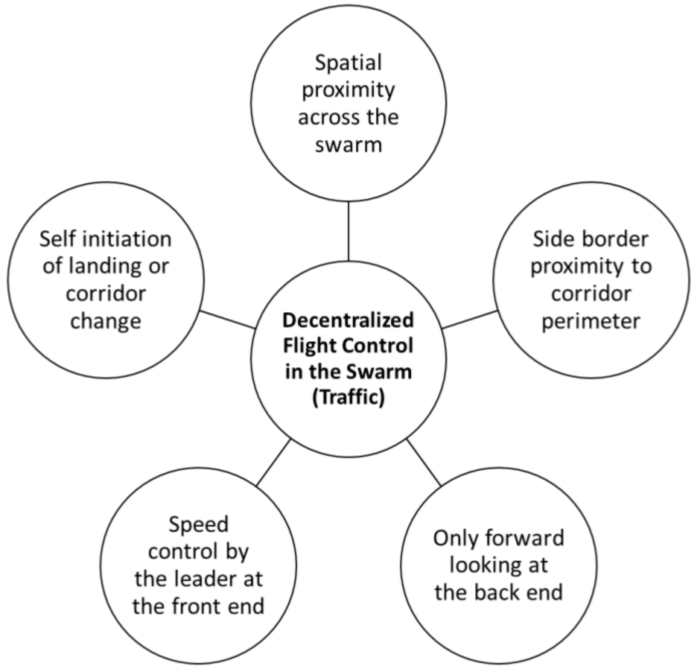
Such swarms are the highest level of autonomous capability in UAVs (Gao et al., 2016), where the dynamic task allocation can also be done with a distributed approach. Then, each member can operate only with limited information. It is also possible to have a task swap within the swarm (Wang & Rubenstein, 2020), e.g., two agents can change their positions. There are many algorithms from robotics that perform efficiently in systems with limited storage and processing power (de Mendonca et al., 2016). Each member of the swarm can operate alone or as a part of the swarm, where self-organization is achieved (Gao et al., 2016) in a resilient network (Jakaria & Rahman, 2018).

Torres (2012) applied the swarm theory in air traffic management, where airline pilots were designated as agents for optimizing the separation. Here, a distributed system is taking over the control enabling self-organizing swarms. Consequently, dense local traffic forms a swarm that each UAM system becomes a member of the swarm as soon as it goes into the traffic zone. Then, the UAM systems shall be capable of having distinct swarm and stand-alone states, and distributed algorithms control the individual agents controlling the traffic.

Biologically inspired by the birds, relative spatial proximity can be used in swarm state instead of explicit control of position and distances that a decentralized aircraft control can be realized on the trajectory tracking trying to remain in the middle of the surrounding members (Garcia & Keshmiri, 2016). Unlimited agents can be members of the swarm. Here, the stacked corridors over each other are utilized, which simply outline physical air volumes over streets or rivers with defined flight directions and minimum and maximum speed limits. These corridors are managed dynamically by the ground control unit, which most probably is assumed to be parts or subcontractors of a municipality.

Members on the side border of the swarm are controlling their distance to the flight corridor perimeter in addition, and those at the end only look forward, while those in front are adjusting their speed according to the limitations of the corridor. One of those on the front is also to be assigned as the leader that it can assign a task such as immediate deceleration in emergencies or upcoming obstacle warnings at certain points. The leader selection does not have to be optimal and can be done with submodular algorithms (Chung et al., 2018). All members, including the leaders, can also communicate that they want to initiate a landing or a corridor change (See Fig. 1).

Figure 1
Means of Control within a Flight Corridor

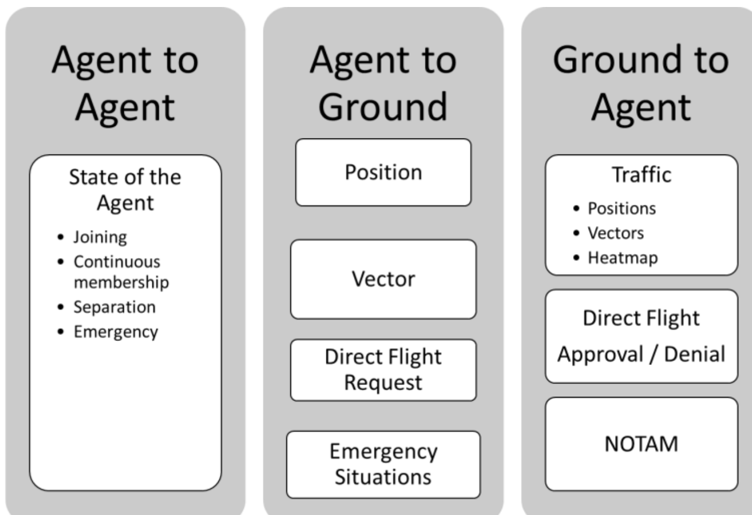


Just following the surrounding traffic, members of the swarming process only limited information from their neighbors. This requires a communication infrastructure for push notifications from agents to agents or for mission assignments (Rosalie et al., 2016). Here, the position and the flight vector do not have to be broadcasted to the swarm because the safe distance, which might be determined as a minimum as five times the span of the larger one among the neighboring UAM vehicles, is being used for the control within the swarm. Besides, going and returning courses should be separated by different flight corridors, one under the other, unlike the car roads side by side, since one-way swarm movement provides safer operations. The widths of these air corridors will be the same as those of the car roads followed. The depth/altitude of these flight corridors will be two-fold the width due to the need for extra vertical movement area. The interconnectivity allows distributed algorithms to change the state of the agent, which can be broadcasted as well, i.e., continuous membership, joining/ separation to/ from the swarm towards the stand-alone mode can be communicated that surrounding swarm enables a safe passage zone. Furthermore, a member of the swarm can also declare an emergency to have a safe passage as well.

As of today, distributed algorithms might be slower (Chung et al., 2018) than centralized algorithms, but they enable collision-free navigation. Then, the attacks to the network can be prohibited by aggregate signatures and associated algorithms (Hong et al., 2020) that safe operation requires further resources. However, considering the progress in hardware technology and the upcoming 5G cellular technologies for connectivity (Campion et al., 2018), it is simply just a matter of time that such a swarm approach involving a high number of stakeholders will be a reality soon. Therefore, new technologies mountable to the UAVs are needed to preclude the airborne collisions of these swarm operations.

To prevent such incidents and accidents, the position and the flight vector, including speed and acceleration data, is broadcasted to a local ground station, where the operator of the ground station only has the job of consolidating received information from all members to broadcast consolidated local traffic notifications. Then, the ground generates 3D heat maps indicating dense traffic zones to enable a better selection of flight corridors for economic and safe flight. Finally, the ground station can also send Notifications to Airman (NOTAM) to define restricted zones such as temporarily closed corridors (see Fig. 2), which enables a further safe environment.

Figure 2
Communication routines within the system

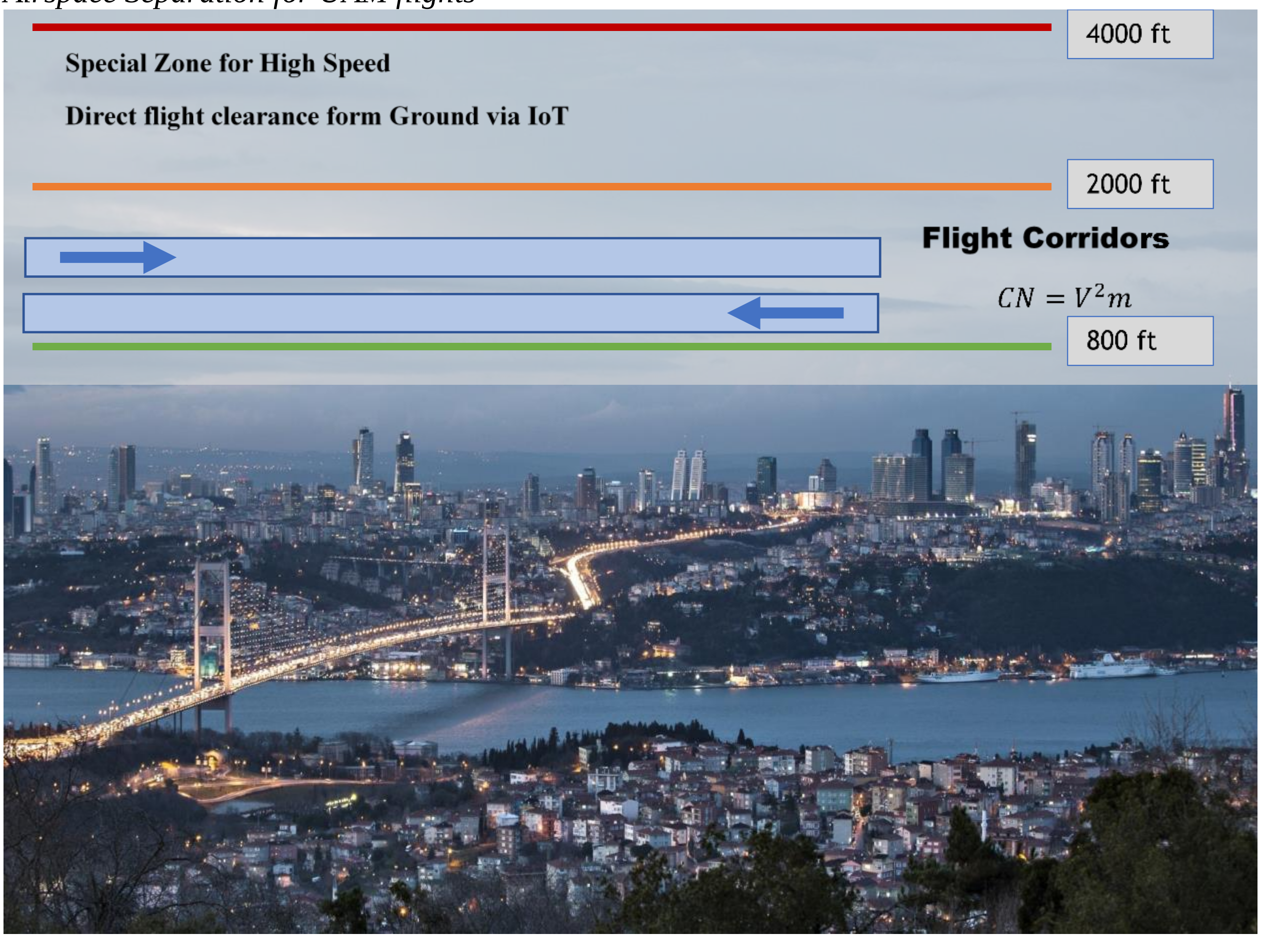


When flying alone, an aircraft is then free to choose any speed and height within the allowed interval of the corridor. Within a swarm, these limits are also applied in addition to the surrounding interaction. If a member of the swarm wants to get faster, this is possible depending on the proximity of the traffic: having a free passage ahead, the aircraft can move there with only a 10% speed increase until it is out of the traffic. This means that overtaking on any side is allowed by a set of rules similar to car traffic. This is possible only if there is no swarm formation but a free flow of traffic. In the case of existing swarm formation, members can separate from the swarm to a higher altitude to overtake. However, the required navigation performance (RNP) is a challenge. If RNP 0.001 can be enabled, approximately 5 m distance between aircraft can be realized, particularly in lower flight corridors.

Considering that existing VTOL concepts have a cruise speed up to 630 km/h with a capacity generally of up to six passengers (Rothfeld et al., 2018), there will be a high difference between small and large UAM participants. If the maximum speed of an aircraft is not suitable for a corridor, then it is not allowed to go in there. So there are unidirectional stacked air corridors over streets to fly through, such as utilized in RNP AR of NextGen. This means, in general, that slower aircraft remain low while faster aircraft will eventually climb to higher corridors, and to address privacy and security concerns of low altitude UAM (Kopardekar et al., 2016), the conceptualized model is intended to use the airspace above the streets and rivers. This new categorization for altitude separation is made with a category number (CN) as $CN = v^2 m$ where v is velocity and m is mass. The higher the CN, the higher the flight corridor that can be chosen. These flight corridors are designated between 800 ft. and 2,000 ft. (see Figure 3). Considering this attitude gap, 2 or 3 pairs of flight corridors (each pair accounted for one going and one returning corridor due to the one-way swarm movement) might take place in this designated altitude. After this maxima, up to 4,000 ft. is a special zone for high-speed UAM vehicles, where direct line routes can be flown from A to B rather than following street patterns. However, this requires a direct flight clearance from the ground control by Internet of Things (IoT) connectivity subject to special handling and fee, which is compatible with the height separation schema of Lowry (2018). If only the aircraft is certified to land in regular airports, then a further climb over 4,000 ft. is allowed, where a flight is carried out according to regular civil aviation rules with ATC communication.

Figure 3

Airspace Separation for UAM flights



When not in a swarm operation, the UAV will simply fly in the middle of the corridor in the horizontal plane and separate linearly in height by the ratio of their speed and the allowable speed minima and maxima of the given corridor. This means simply that the faster aircraft will be higher compared to the slower ones. Then, if the CN is large enough, overtaking up to the slower UAV after climbing will also be acceptable. If there is any proximate traffic, all acceleration and deceleration limits are within those defined for the given corridor. Then, the aircraft can be commanded to take off from a vertiport at point X to fly via a charging station Y to a final destination Z.

However, due to having a control based on the swarm logic and having the possibility of fuzzy mistakes, there is no predictive coverage of all possible aircraft maneuvers, which makes escape maneuvers inevitable. To enable this, there are designated zones that can be used. There are already zones, such as for waiting, charging, and landing at vertiports, defined within the corridor maps, but in emergencies, all airspace over the private ground, i.e., gardens or houses, can be temporarily used. Then, the penetration into this private zone shall be kept at a minimum and as short as possible. In certain cases, landing in emergency areas such as some rooftops parks are also allowed, where the aircraft have to be equipped with sensors to check the existence of humans and other living creatures in these areas.

Due to the low altitude flight profile of the UAM vehicles over the cities, there is a line of sight (LOS) limitation problem, but since these vehicles are intended to total autonomous flight, this is not expected to be a problem. Different sensors and systems are going to be used within the system that detects and avoid systems are all on board (Kopardekar et al., 2016). There, traditional navigation systems (VOR, DME, etc.) might not be reliable, ADS-B might be susceptible to jamming, signal insertion, and deletion. Standard GPS might not be dependable because of signal multipath and urban canyon impacts at low altitude operations. All these are challenges of Performance-Based Navigation (PBN) (Vascik et al., 2018). A remedy for that is the usage of 5G technologies as proposed by Besada et al. (2019) together with Global Navigation Satellite Systems (GNSS) (Biijahalli et al., 2019) and inertia navigation. Then, all aircraft have to have TCAS and ADS-B/C capability of NextGen for interlines in airport regions. Furthermore, there will be a proximity sensor enhancement requirement for the TCAS, which is subject to further research, which could facilitate the Airborne Collision Avoidance System X (ACAS X) for quadcopters (Katz, 2019).

Discussion

The application of the self-organizing swarm system for the regulation of UAM is promising. While the rules are delivered to organize the swarms within high-density traffic, the same rules are also capable of guiding the traffic. The separation schema, confirmed by Lowry (2018), enables performance-based navigation according to ICAO PBN Manual (Doc 9613) and supports required escape maneuvers (Lowry, 2018).

Similar to the UTM ConOps scope class G (Kopardekar et al., 2016), a separation is made here with respect to auto-regulated operations in an uncontrolled area. Then, a transition to operations in controlled airspace is also allowed. Gillissen and Schultz (2018) introduced a System-of-Systems (SoS) concept for cooperative decision making, which is a formal integration attempt of the regular aircraft/ air traffic control for en route and airport operations. The same applies here: the decision-making during flight shall be cooperative and, in fact, also collaborative across the UAM systems within the swarm. However, due to the high traffic density, the control of the UAM traffic cannot be centralized. This is contrasting Straubinger et al. (2020), which relies on ATMs, but there it is also mentioned that drones can be assessed as networked cyber-physical systems. Furthermore, unlike regular traffic, the UAM systems can change their destination during the flight. Thus, all systems shall have a certain degree of freedom, collaborating during maneuvers by adjusting their speed and altitude, which is also strived by the industry (Merkert & Bushell, 2020).

Katz (2019) discussed the use of the Airborne Collision Avoidance System X (ACAS X), which relies on complicated Markov decision processes instead of the heuristic rules of TCAS in order to comply with NextGen. This is compatible with the approach here.

According to Rothfeld et al. (2018), UAM concepts have to include emergency landing areas, charging stations, vertiports for boarding, which are all included by the proposed system as well. This also can enable the usage of air taxis, as indicated by Rajendran et al. (2021). Lowry (2018) indicated that a VTOL such as the Volocopter can only deliver a 0.1 g acceleration envelope, while a car like the Tesla can achieve an acceleration up to 1.0 g on the ground that due to this difference in maneuverability, the existing roadways cannot be simply lifted up to virtual roads. However, it is obvious that these performance characteristics are not subject to be used in regular traffic. When a car is driven smoothly in traffic, the accelerations are by far lower, and we believe that with the correct speed limitations on the air corridors and the correct deceleration prior to direction changes, the aircraft can cope with the elevated air corridors over the streets.

eHang believes in a “centralized remote command-and-control platform to perform multiple tasks autonomously” (eHang 2020, p.9). Contrary to eHang, the model in this study proposes decentralized and uncontrolled air space for UAM. It is anticipated here that the traffic control system is only regulating the maps and enabling the transition from free flight zones towards regulated airspace because the workload at a centralized system would be simply too expensive, and such centralization is not necessarily required. The approach of eHang is partly based on the belief that “advanced avionics, weather-sensing equipment, and terrain avoidance capabilities remain too expensive or too heavy” (Kopardekar et al. 2016, p.5) to be included in UAM. However, technology has advanced so fast that even small UAVs can have radars anymore, and peer-to-peer communication devices are affordable as well. This can also be simulated in further research: There are distinct multiple demand modeling tools suitable for urban air traffic such as PTV Visum and TransCAD, but due to a high number of integrated stakeholders, an activity-based open structure with free licenses shall be preferred, such as in MATSim (Rothfeld et al., 2019) with an extension for autonomous vehicles (Bischoff and Maciejewski, 2016) based on the Dynamic Vehicle Routing Problem of Maciejewski’s (2016).

As of today, free flight in UAM is particularly enabled by “Global Positioning Systems (GPS), data link communications like Automatic Dependence Surveillance-Broadcast (ADSB), Traffic Alert and Collision Avoidance Systems (TCAS), powerful onboard computation, and automated conflict detection and resolution tools” (Bertram et al. 2019, p.1), which are utilized by the proposed system. Here, the ADS-C compatibility is also given since the aircraft can contact Air Traffic Service Unit by IoT requesting clearance for the high-speed zone. Furthermore, emergencies are also broadcasted to the air traffic controller. This is in line with the low-altitude airspace management system approaches (Merkert & Bushell, 2020).

Then, the communication among participants of the swarm is a key point. Collaborative algorithms with respect to consensus control have to be developed (Sargolzaei et al. 2020), particularly assigning the leader, which is a further research area. Markov Decision Processes (MDPs) can be used to solve collision avoidance in urban mobility (Bertram et al., 2019). Consequently, it seems possible for UAM to be realized with existing technology and appropriate development efforts.

At this point, security concerns might arise, which can result in costly disruptions (Merkert & Bushell, 2020). Al Haddad et al. (2020) points out this with respect to information sharing cyber-security. Furthermore, the smart city concept involves many IoT devices whose interrelations with UAVs have not been widely researched (Mualla et al., 2019). For instance, the emerging trend of mobility as a service (MaaS) and on-demand mobility (ODM) (Fu et al., 2019) can be addressed with this system as well. Such approaches will become a reality soon, which further complicates the safety assurance. However, it is too early to discuss the impact since this ecosystem is just being shaped; thus, it is a future research area.

Environmental considerations (Kopardekar et al., 2016) can be taken into consideration, particularly the noise and visual impact of UAM (Al Haddad et al., 2020) can be discussed. While the UAM application enabling new operations increases the environmental load, on the one hand, the electrified traffic enabling micro-mobility will provide a better load balancing preventing the circulation of empty vehicles on the other hand. Moreover, UAM is inevitable, and the scope should be rather how to enable it in a safe and efficient manner by the appropriate integration of UAM into airspace.

The focal point of this study is to determine an altitude separation among UAM vehicles moving in a swarm manner by applying the proposed category number (CN), which is a function of velocity and mass. While moving in a swarm, each UAV/agent might need individual movements to change their positions, like leaving the swarm, joining a different swarm, or overtaking the other UAVs in case of new tasks and any emergency situations. Therefore, it needs some different algorithms considering collide and avoidance from each other under these possible circumstances. Then, UAVs may have communication problems in low-altitude corridors of the air space when solely relying on satellite-connected GPS. Therefore, UAVs might be gained some specialties like feature extraction, certain point recognition algorithms, artificial intelligence (AI), and machine learning algorithms to carry out their tasks without GPS. Furthermore, ground stations to support the GPS resolution can be examined and improved. These are indeed hot research topics in the literature and are totally in line with the requirements of the proposed deregulation attempt.

Since the proposed model obliged the UAVs to use main roads and rivers between 800 ft. and 4,000 ft. altitude, a high traffic potential might be expected. Consequently, the optimum number of the UAVs in the swarm must be determined by simulations; even if relative spatial proximity might allow unlimited agents in the swarm that the sizes and types of UAVs within the swarm should be regulated according to their maneuver capabilities. Then, minimum and maximum speed limits of these stacked corridors at each separation should also be determined even if the UAVs are supposed to choose any speed and height within the allowed interval of the corridor and participate in UAM swarms according to their category numbers. This particularly requires further categorization of UAVs, especially high-speed UAM vehicles, probably preferring direct line routes over 4,000 ft. rather than following street patterns shall be investigated further. On top of this, technical concerns for charging stations and take-off & landing points should be determined to further elaborate rules for the deregulation of the airspace.

Conclusions

Micro and small-scale mobility has become a reality of today. Automated VTOLs are being proposed in various applications for urban transportation. The increasing number of UAM applications will result in a high traffic load, which cannot be managed with a centralized system. As of today, there are many initiatives actively trying to develop solutions, but so far, there is no specific framework yet.

As a result, the deregulation of the airspace in urban areas is a promising approach for this challenge, requiring certain rules capable of guiding the adaptive nature of small stakeholders, which are given here in detail. The integration of UAM into the airspace is assured here by specific procedures that a self-organizing capability is provided in conjunction with the swarm formation for the autonomous behavior, which is the contribution of this work to the literature. Deregulated airspace over the streets is also utilized together along with direct flight possibilities over buildings in spite of the existence of larger manned vehicles.

The main contribution of this proposed model is to create deregulated air corridors within determined altitudes (800-4,000 ft) over the main roads and rivers of the metropolitan areas and to assign each UAV to a corridor for UAM swarm movement by calculating their CN. Furthermore, this model also proposes communication routines for agent to agent, agent to ground, and ground to agent while it determines the control means of the UAM swarm within the corridor. This model undoubtedly tries to regulate the deregulated airspace without authorized air traffic control. Besides, this study also demonstrates the need for the most recent sense-and-avoid, navigation, and communication technologies and improved AI algorithms for the UAM integration into airspace.

The proposed model is successfully discussed but certainly has some challenges and limitations, which might also be considered as future studies. Particularly, collision avoidance and positioning are the challenges where the proposed model assumes that they are solved by the UAV community. Nevertheless, the realization of this model requires that robust swarm algorithms using AI and machine learning are developed to satisfy the needs of the proposed flight formation. While improving some mathematical models and algorithms for the emergent and early UAM operations by using recent technologies, all aviation stakeholders should also cooperate and improve the necessary concepts and regulations for airspace integration of high-density, high-speed, and safe UAM by utilizing the miscellaneous proposed models. In the end, the architecture of the airspace will inevitably undergo a new transformation.

References

Airbus. (2018). *Blueprint for Airspace: The roadmap for the safe integration of autonomous aircraft.*

Al Haddad, C., Chaniotakis, E., Straubinger, A., Plötner, K., & Antoniou, C. (2020). Factors affecting the adoption and use of urban air mobility. *Transportation Research Part A.* 132, 696-712.

Aviation Week. (2020, 12 February). Singapore Links with Airbus On UAM. [online] https://aviationweek.com/shownews/singapore-airshow/singapore-links-airbus-uam

Balachandran, S., Munoz, C., & Consiglio, M. (2018). *Distributed Consensus to Enable Merging and Spacing of UAS in an Urban Environment.* International Conference on Unmanned Aircraft Systems (ICUAS), June 12-15, Dallas, TX, USA.

Bertram, J., Yang, X., Brittain, M. W., & Wei, P. (2019). *Online Flight Planner with Dynamic Obstacles for Urban Air Mobility.* In AIAA Aviation 2019 Forum, 3625.

Besada, J., Campana, I., Bergesio, L., Bernardos, A., & Miguel, G. (accepted in 2019). Drone flight planning for safe urban operations- UTM requirements and tools. *Personal and Ubiquitous Computing*, in press.

Bijjahalli, S., Sabatini, R., & Gardi, A. (2019). GNSS Performance Modelling and Augmentation for Urban Air Mobility. *Sensors*. 19, 4209, 1-24.

Bischoff, J., & Maciejewski, M. (2016). Autonomous Taxicabs in Berlin - A Spatiotemporal Analysis of Service Performance. *Transportation Research Procedia*, 19(June), 176–186. Available at: http://dx.doi.org/10.1016/j.trpro.2016.12.078.

Campion, M., Ranganathan, P., & Faruque, S. (2018). *A review and future directions of UAV swarm communication architectures.* 2018 IEEE International Conference on Electro/Information Technology (EIT), 0903-0908.

Chung, S. J., Paranjape, A. A., Dames, P., Shen, S., & Kumar, V. (2018). A survey on aerial swarm robotics. *IEEE Transactions on Robotics*, 34(4), 837-855.

Cohen, M. M. (1996). The Vertiport as an Urban Design Problem. *Technical Report SAE Technical Paper.*

Cotton, W. B., & Wing, D. J. (2018). *Airborne Trajectory Management for Urban Air Mobility.* AIAA Aviation Forum, Aviation Technology, Integration, and Operations Conference, June 25-29, Atlanta, Georgia.

Draft Annex to EASA Opinion No 01/2020. (2020). Commission Implementing Regulation (EU) of High-level regulatory framework for the U-space.

EASA Opinion No 01/2020. (2020). *High-level regulatory framework for the U-space*.

eHang. (2020). *The future of transportation: White paper on Urban Air Mobility Systems*. [online] https://www.ehang.com/app/en/EHang%20White%20Paper%20on%20Urban%20Air%20Mobility%20Systems.pdf

EU. (2016). *Warsaw Declaration: Drones as a leverage for jobs and new business opportunities*. Warsaw, 24 November 2016 [online] https://ec.europa.eu/transport/sites/transport/files/drones-warsaw-declaration.pdf

EU. (2017). *Drones Helsinki Declaration*, 22 November 2017 [online] https://ec.europa.eu/transport/sites/transport/files/2017-drones-declaration-helsinki.pdf

Floreano, D., & Wood, R.J. (2015). Science, technology and the future of small autonomous drones. *Nature*, 521(7553), 460–466.

Fu, M., Rothfeld, R., & Antoniou, C. (2019). Exploring Preferences for Transportation Modes in an Urban Air Mobility Environment: Munich Case Study. *Transportation Research Record*, 2673(10), 427–442.

Garcia, G.A., & Keshmiri, S.S. (2016). Biologically inspired trajectory generation for swarming UAVs using topological distances. *Aerospace Science and Technology*, 54, 312-319.

Gao, C., Zhen, Z., & Gong, H. (2016). A self-organized search and attack algorithm for multiple unmanned aerial vehicles. *Aerospace Science and Technology*, 54, 229-240.

Garrow, L. A., Ilbeigi, M., & Chen, Z. (2017). *Forecasting Demand for On Demand Mobility*. 17th AIAA Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, Denver, doi:10.2514/6.2017-3280.

Gillissen, A., & Schultz, M. (2018). *Formal Modeling of Air Traffic as System-of-Systems- Air Traffic as Systems of Interdependent Operational Decision-Making Processes*. 8th International Conference for Research in Air Transportation, June 26-29, Barcelona.

Guterres, M., Jones, S., Orrell, G., & Strain, R. (2017). *ADS-B surveillance system performance with small UAS at low altitudes*. AIAA SciTech Forum.

Hong, W., Jianhua, L., Chengzhe, L., & Zhe, W. (2020). A provably secure aggregate authentication scheme for unmanned aerial vehicle cluster networks. *Peer-to-Peer Networking and Applications*, 13(1), 53-63.

Hörl, S. (2016). *Implementation of an Autonomous Taxi Service in a Multi-Modal Traffic Simulation Using MATSim*, doi:10.13140/rg.2.1.2060.9523.

International Civil Aviation Organization (ICAO). (2013). *Performance-Based Navigation Manual* (Doc 9613), 4th edition.

Jakaria, A.H.M., & Rahman, M.A. (2018). *Formal Analysis of k-Resiliency for Collaborative UAVs.* 2018 IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC), 1, 583-592.

Jung, J., D'Souza, S.N., Johnson, M.A., Ishihara, A.K., Modi, H.C., Nikaido, B., & Hasseeb, H. (2016). Applying Required Navigation Performance Concept for Traffic Management of Small Unmanned Aircraft Systems. *Proceedings of the 30th ICAS 2016 Congress of the International Council of the Aeronautics Sciences*, Daejeon, Korea, 25–30 September.

Katz, S. M. (2019). *Collision avoidance for Urban Air Mobility vehicles using Markov decision processes.* Stanford University Project Report: Physical Sciences.

Kochenderfer, M. J., Holland, J. E., & Chryssanthacopoulos, J. P. (2012). *Next generation airborne collision avoidance system.* Massachusetts Institute of Technology-Lincoln Laboratory Lexington United States, Tech. Rep.

Kochenderfer, M. J. (2015). *Decision making under uncertainty: Theory and application*. MIT Press.

Koperdekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., & Robinson III, J. E. (2016). *Unmanned Aircraft System Traffic Management (UTM) concept of operations*. 16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA 2016-3292, Washington D.C.

Lancovs, D. (2017). Broadcast transponders for low flying unmanned aerial vehicles. *Transportation Research Procedia*, 24, 370–376.

Lowry, M. R. (2018). *Towards high density Urban Air Mobility*. AIAA Aviation Forum, Aviation Technology, Integration, and Operations Conference, June 25-29, Atlanta, Georgia.

Luo, Q., & Duan, H. (2017). Distributed UAV flocking control based on homing pigeon hierarchical strategies. *Aerospace Science and Technology*, 70, 257-264.

Maciejewski, M. (2016). Dynamic Transport Services. In A. Horni, K. Nagel, & K. W. Axhausen, eds. *The Multi-Agent Transport Simulation MATSim*. London: Ubiquity Press, 145–152.

de Mendonça, R.M., Nedjah, N., & de Macedo Mourelle, L. (2016). Efficient distributed algorithm of dynamic task assignment for swarm robotics. *Neurocomputing*, 172, 345-355.

Merkert, R., & Bushell, J. (2020). Managing the drone revolution: A systematic literature review into the current use of airborne drones and future strategic directions for their effective control. Journal of Air Transport Management, 89, 101929.

Moore, M. (2017). Uber elevate: eVTOL urban mobility. Rotorcraft Business & Technology Summit, Rotor&Wing International, Ft. Worth, TX.

Mualla, Y., Najjar, A., Daoud, A., Galland, S., Nicolle, C., & Shakshuki, E. (2019). Agent-based simulation of unmanned aerial vehicles in civilian applications: A systematic literature review and research directions. *Future Generation Computer Systems*, 100, 344-364.

Olson, W. A. (2015). *Airborne collision avoidance system X*. Massachusetts Institute of Technology-Lincoln Laboratory Lexington United States, Tech. Rep.

Rajendran, S., Srinivas, S., & Grimshaw, T. (2021). Predicting demand for air taxi urban aviation services using machine learning algorithms. *Journal of Air Transport Management*, 92, 102043.

Rosalie, M., Danoy, G., Bouvry, P., & Chaumette, S. (2016). *UAV multilevel swarms for situation management.* Proceedings of the 2nd Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use, 49-52.

Rothfeld, R., Balac, M., Ploetner, K. O., & Antoniou C. (2018). *Initial analysis of Urban Air Mobility's transport performance in Sioux Falls*. AIAA Aviation Forum, Aviation Technology, Integration, and Operations Conference, June 25-29, Atlanta, Georgia.

Rothfeld, R., Balac, M., & Antoniou C. (2019). Modeling and evaluating urban air mobility – an early research approach. *Transportation Research Procedia*， 41, 41–44.

Sargolzaei, A., Abbaspour, A., & Crane, C. D. (2020). Control of cooperative Unmanned Aerial Vehicles: Review of applications, challenges, and algorithms. In *Optimization, Learning, and Control for Interdependent Complex Networks*. Springer, Cham, 229-255.

SESAR JU. (2016). *European drones outlook study- Unlocking the value for Europe*. Publication Office of the European Union, Luxembourg.

SESAR JU. (2017). U-space: Blueprint. Belgium: The European Commission. doi:10.2829/335092

SESAR JU. (2020). *Supporting safe and secure drone operations in Europe- Consolidated report on SESAR U-space research and innovation results*. Publication Office of the European Union, Luxembourg.

Straubinger, A., Rothfeld, R., Shamiyeh, M., Büchter, K. D., Kaiser, J., & Plötner, K. O. (2020). An overview of current research and developments in urban air mobility–Setting the scene for UAM introduction. *Journal of Air Transport Management*, 87, 101852.

Sumitomo Corporation. (2020). https://www.sumitomocorp.com/en/jp/news/release/2020/group/13020

Tahir, A., Böling, J., Haghbayan, M. H., Toivonen, H. T., & Plosila, J. (2019). Swarms of Unmanned Aerial Vehicles–A Survey. *Journal of Industrial Information Integration*, 16(100106).

Torres, S. (2012). Swarm theory applied to air traffic flow management. *Procedia Computer Science*, 12, 463-470.

Vascik, P. D., & Hansman, R. J. (2017). *Constraint identification in on-demand mobility for aviation through an exploratory case study of Los Angeles*. 17th AIAA Aviation Technology, Integration, and Operations Conf.

Vascik, P. D., Balakrishnan, H., & Hansman, R. J. (2018). *Assessment of air traffic control for Urban Air Mobility and unmanned systems*. 8th International Conference for Research in Air Transportation, June 26-29, Barcelona.

Wang, H., & Rubenstein, M. (2020). Shape formation in homogeneous swarms using local task swapping, Early Access, *IEEE Transactions on Robotics*. DOI: 10.1109/TRO.2020.2967656

Ward, K. A., Winter, S. R., Cross, D. S., Robbins, J. M., Mehta, R., Doherty, S., & Rice, S. (2021). Safety systems, culture, and willingness to fly in autonomous air taxis: A multi-study and mediation analysis. *Journal of Air Transport Management*, 91(C).

Wood, K.L. & Greer, J.L. (2009). Function-based synthesis methods in engineering design. In: *Formal Engineering Design Synthesis*. Publisher: Cambridge University Press, New York. DOI: 10.1017/CBO9780511529627.009

Wooldridge, M. (2009). *An Introduction to Multiagent Systems*, John Wiley & Sons, 2009.

Youn, W. K., Hong, S. B., Oh, K. R., & Ahn, O. S. (2015). Software Certification of Safety-Critical Avionics Systems: DO-178C and Its Impacts. *IEEE Aerospace and Electronic Systems Magazine*, 30(4), 4-13.

Zhou, Y., Zhao, H., & Liu, Y. (2020). An evaluative review of the VTOL technologies for unmanned and manned aerial vehicles. *Computer Communications*, 149, 356-369.