

Received July 15, 2021, accepted August 6, 2021, date of publication August 16, 2021, date of current version August 25, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3104963

The Rise of Drones in Internet of Things: A Survey on the Evolution, Prospects and Challenges of Unmanned Aerial Vehicles

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This work was supported by the Joint Research Program University of Luxembourg (UL)/Interdisciplinary Centre for Security, Reliability and Trust (SnT) – L’Institut luxembourgeois de la normalisation, de l'accréditation, de la sécurité et qualité des produits et services (ILNAS) on Digital Trust for Smart-Information Communication Technologies (ICT).

ABSTRACT The recent years have seen a rise in the incorporation and integration of new smart connected devices and platforms such as Unmanned Aerial Vehicles (UAVs) to the ubiquitous network of Internet of Things (IoT). UAVs not only offer new means of delivering value-added IoT services through a wide range of applications ranging from monitoring and surveillance to on-demand last-mile delivery and people transport, but they also promise a pragmatic solution to the limitations of fixed terrestrial IoT infrastructure. Owning to their potential, UAVs are expected to soon be an integral part of our cities, dominating the shared low-altitude airspace. This introduces new research challenges in privacy, security and most notably in the safe management of UAVs' operation under high traffic demands. To this end, this work presents a holistic study on the current state-of-the-art of UAVs and low-altitude airspace traffic management. This work additionally explores the technical standardisation landscape and highlights synergies between scientific research and standardisation efforts towards enabling safe UAV operations, while taking into consideration additional IoT inherent challenges such as security, data protection and privacy.

INDEX TERMS Internet of Things, traffic management, autonomous unmanned aerial vehicles, low-altitude airspace, security, privacy, technical standardization.

I. INTRODUCTION

The Internet of Things (IoT) may be described as a network of uniquely addressable and interconnected devices, built on standard communication protocols, the point of convergence of which is the internet [1]. IoT hence enables a vast array of services that otherwise could not be realised. Although IoT, as explained in [2], [3], can be seen as part of the next generation internet, IoT has its unique vision that expands beyond the confinements of internet to enabling an inter-connected world of "things", both, physical and virtual. To this end, the technologies of IoT catalysed the growth of data-driven applications as well as encouraged the integration of new connected devices, in turn, creating new value-added services in almost every market sector and unleashing a magnitude of new opportunities for businesses, individuals and society [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Chien-Ming Chen .

The economic impacts of IoT are, therefore, beyond doubt. Nevertheless, apart from the buzz-term and the idea of interconnected things, IoT is a complex technological paradigm [5]. IoT can be seen as a system of systems while it is not a single technology, but rather a composition of various technologies working together in tandem. The fundamental building block of IoT is the device, commonly referred to as "thing". Devices can be broadly categorised as sensors, actuators or a combination of both. Sensors are devices that gather information from the environment, while actuators are devices that reach out and act on the world. These devices connect directly or indirectly to the internet using wireless and wired technologies.

Over the recent years the rapid development in communication technologies as well as the miniaturisation of sensors and actuators, encouraged the integration of new connected devices and platforms to the ubiquitous IoT network [5]. One promising set of devices and platforms that

have quickly found their way into IoT, as connected “things”, are Unmanned Aerial Vehicles (UAVs). Commercial UAVs not only promise new means of interacting with the world, to collect and deliver new value-added services through a wide range of application domains ranging from monitoring and surveillance to on-demand last-mile delivery as well as people transport, but they also present a potential solution to the challenges of solely relying on fixed terrestrial IoT infrastructure. Owing to their potential, UAVs are expected to soon become an integral part of modern aviation, dominating the low-altitude airspace over populated cities. This foreseeable future introduces new research challenges such as autonomous UAV safeguards [6] and efficient operations management under high traffic demands. In response to this, the scientific community, industry and standardisation bodies initiated a handful of constructs for the management of the low-altitude airspace; however, to the best of our knowledge there is no study that addresses the lack of harmonisation between the different actors and combines the state-of-the-art in technical standardisation, scientific research as well as industry.

To this end, the successful realisation of UAVs’ potential does not rely on a single technology but a multitude of interconnected systems building on international standards, regulations and novel approaches. In this context, the main contribution of this work is to present a holistic study on the evolution of UAVs within IoT, exploring:

- how digitisation led the transformation of UAVs into smart, connected devices and platforms;
- challenges obstructing the deployment of UAVs within cities from of safety, security, data protection and privacy perspectives;
- current state-of-the-art of low-altitude airspace traffic management in the scientific literature;
- current development in UAV technical standardisation landscape.

The structure of the paper is as follows. Section II provides an overview of the conceptual and technological UAV landscape, highlighting UAVs’ key definitions, notions and evolution as they find their way into IoT. Section III presents current state-of-the-art of UAVs’ role within IoT and devises a taxonomy for some predominant commercial UAV applications found in literature. The section additionally explores the inherent challenges of IoT introduced as UAVs become part of the connected ubiquitous network. Section IV presents current state-of-the-art of the low-altitude airspace traffic management with focus on UAVs. The paper investigates the concept of UAV Traffic Management constructs followed by a compilation and classification of their key functionalities with respect to safety and operational support. The section follows with a comparison of predominant UAV Traffic Management constructs in literature, namely, the NASA UTM and the EU U-Space concepts of operations as well as other national constructs. Section V explores the current state-of-the-art in UAVs technical standardisation. Finally, section VI concludes the work.

II. UNMANNED AERIAL VEHICLES

As industries continue to embrace digitisation, catalysed by IoT, the aerospace sector witnesses the rise of a new generation of UAVs as smart mobile IoT-connected devices and platforms with applications extending beyond the confinement of military use-cases.

This section explores the conceptual and technical landscape of UAVs, highlighting key definitions, notions as well as predominant commercial applications found in literature. The section then outlines the challenges introduced as UAVs become part of the IoT network.

A. CONCEPTUAL OVERVIEW

While the term UAV emerged in the late twentieth century to include any robotic aircraft, the concept of such aerial robots has its origins back in the beginning of the nineteenth century, specifically before manned aviation ever occurred. Unmanned aviation was popularised with models designed by Sir George Cayley, John Stringfellow, Felix Du Temple, as well as a few other aviation pioneers, as precursors to their attempts at manned flight in the first half of the twentieth century [7]. However, the idea of unmanned aviation can be linked back to Nikola Tesla’s proposals and patent *“Method of and apparatus for controlling mechanism of moving vessels or vehicles”* [8] published at the beginning of the nineteenth century. Tesla not only deserves credit for founding the concept of unmanned aviation, but also for envisioning a future where they would have unprecedented commercial applications. Nevertheless, due to insufficient technology at the time [7], it was only a decade later when the first experiments took place, specifically after Elmer Ambrose Sperry [9], the father of modern day navigation, invented the gyro-compass [10]. The development of unmanned aircrafts hinged on the confluence of four critical technologies which are further explored in Section II-B and include: flight propulsion, automatic stabilisation, remote control, and autonomous navigation.

As the technology rapidly evolved, the terms used to refer to aerial robots, in turn, evolved over time. It was not until after the Vietnam War that the term UAV came to replace “Remotely Piloted Vehicle (RPV)”, a term previously used by the US military [11]. The US Department of Defence, therefore put out a definition of UAVs as “any powered aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide a vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles” [11]. The International Organisation for Standardisation (ISO) [12], on the other hand, has a broader definition where the term UAV refers to any aircraft that is designed to operate remotely or autonomously. For the purpose of clarity, throughout the remainder of this work, we use the ISO definition to refer to UAVs. Figure 1 summarises some of the key changes in

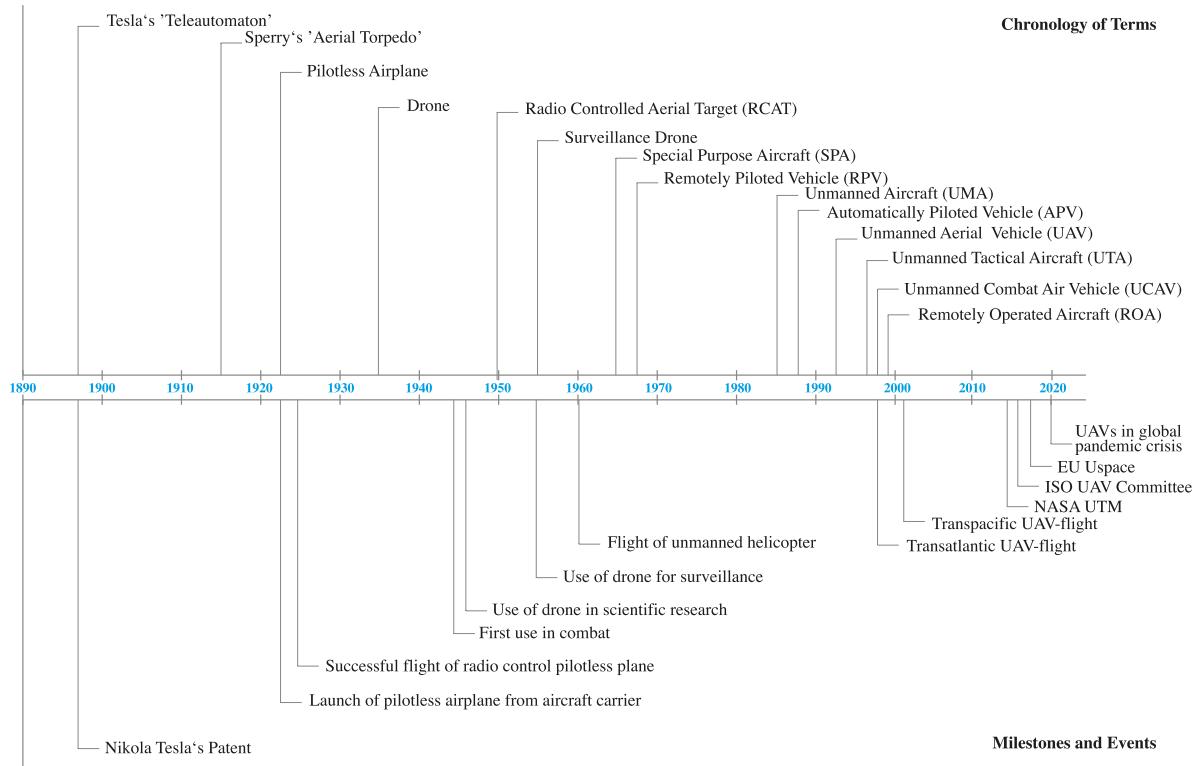


FIGURE 1. Chronology of terms used to refer to aerial robots adopted from [7] (top) key milestones and events (bottom).

terminology as well as showcases a non-exhaustive list of key dates and milestones related to unmanned aviation.

B. TECHNICAL LANDSCAPE

While the origins of UAVs are decades old and their development may be seen as an evolution rather than a revolution [13], given the accelerated rate at which new disruptive UAV-based applications are evolving, it becomes safe to envision a future where such smart, connected UAVs are an integral part of smart cities. As explained in subsection II-A the early development of UAVs critically depended on the convergence of the four following critical technologies:

- flight propulsion,
- automatic stabilisation,
- remote control, and
- autonomous navigation.

These technological challenges, that hindered the development of UAVs for over a decade since the conception of the idea, can broadly be translated to today's main UAV subsystems, namely, actuation and propulsion, orientation and control, communication and navigation. These, in turn, rely on three main building blocks that make the main UAV architecture which are sensors, actuators and software as illustrated in Figure 2.

While a detailed explanation and thorough analysis of such systems fall out of the scope of this work, the interested reader can refer to [14] where the authors present a comprehensive overview of each of the underlying concepts of UAVs'

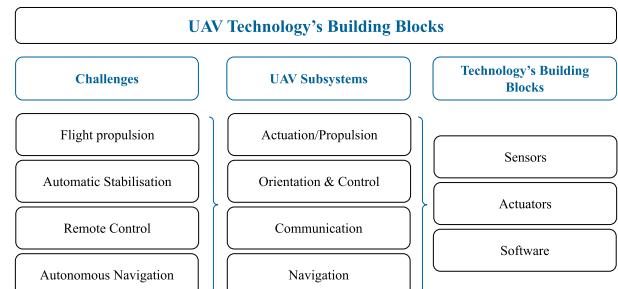


FIGURE 2. UAV technology's building blocks.

key subsystems in more detail, describing how they interact. However, as seen in Figure 2, what is to our interest is that despite whether it is attitude and orientation control, communication and navigation or propulsion, they all share the same core technologies of sensors, actuators and management software. It is hence easier to comprehend the correlation between UAVs developments and sensors/actuators advancements.

One of the main factors that led to the drastic change and development of UAVs, from the first successful radio-controlled pilotless aircraft in 1924 (c.f. Figure 1) to the role UAVs play today in fighting the global COVID-19 pandemic [15], [16], is the great advancement in sensors technologies. The evolution in sensory systems, introduction of intelligent wireless sensors networks, and battery

improvements have led to an increase in reliability and a drop in price which in turn contributed to moving the UAV development to the second and third stages of the technology cycle [17] as shown in Figure 3.

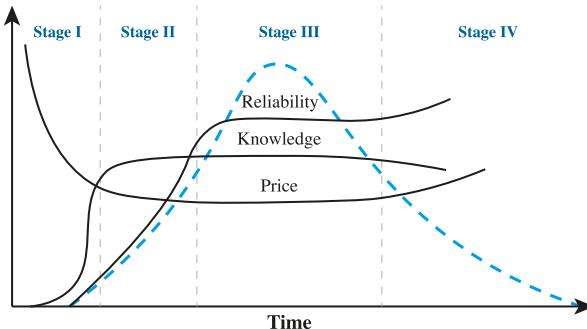


FIGURE 3. The four stages of the technology cycle based on [17].

As emerging computer paradigms continue to evolve, so does the autonomy capability of UAVs, relying on smarter algorithms and analysis. Ranging between 0 to 10 levels of autonomy, the authors in [18] compile an analysis of the various autonomy levels of UAVs, from a remotely piloted vehicle to a fully autonomous UAV capable of independent tactical (short-term actions) and strategic (longer-term or higher-level actions) mission planning.

III. STATE OF THE ART OF UAVS WITHIN IoT

UAVs have quickly found their way into IoT, becoming more than solely aircrafts, but a promising category of connected devices and platforms to this ubiquitous network. The multitude of application scenarios and use cases for UAVs within the IoT found in scientific literature can broadly be categorised under two classes, UAVs as part of the IoT infrastructure, and UAVs as smart connected “Things” as illustrated in Figure 4 - left-hand side.

Within this context, the following section presents a study of the current state-of-the-art of some predominant use-cases of UAVs within the context of IoT followed by a discussion on the challenges hindering the full realisation of the UAV potential, including operational safety risks as well as limitations of UAVs as IoT devices and platforms with the main focus on data protection, privacy and security.

A. THE PROSPECTS

UAVs not only offer a pragmatic solution to overcome possible connectivity limitations caused by only relying on fixed terrestrial IoT infrastructure, but also offer new means of delivering value-added services through a wide range of IoT-enabled applications. Figure 4 (right-hand side) as adopted from [5], uses the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission’s (IEC) generic architecture of Internet of Things first proposed in ISO/IEC 30141 [19] to illustrate some of the application scenarios of UAVs within IoT, that will later be explored in detail.

1) PRAGMATIC SOLUTION TO TERRESTRIAL INFRASTRUCTURE LIMITATIONS

Today, UAVs present a feasible dynamic and pragmatic extension to fixed IoT infrastructure, mainly in cases when having terrestrial infrastructure would not be economically feasible or would not be sufficient to guarantee communication coverage with an acceptable level of quality [20]. This, in turn, making UAVs equipped with the appropriate telecommunication payload, a potential solution to overcoming such limitations by offering wider aerial-based communication coverage, improved availability and enhanced resilience as explored in [21], [22].

With the increasing demand for network coverage and the envisioned unprecedented loads on the current infrastructure, research has quickly found new uses for UAVs in telecommunications as aerial gateways and base stations to deliver emergency and on-demand telecommunication services.

Since the early 90s research in the military context has investigated the use of UAVs for telecommunication scenarios. In [23] authors discuss the possibility of using UAVs to provide Beyond Line of Sight communications (BLOS) capabilities within an area of military operation without using scarce satellite resources.

Nowadays, with the introduction of commercial UAV applications, the scientific community, inspired by the ambitious idea announced by Google back in 2011 of providing internet using high-altitude balloons [24], [25], continuously research innovative ways of utilising the use of UAVs in heterogeneous telecommunication networks.

Initially, most research focused on disaster relief and temporary communication infrastructure using UAVs. With advancement in communication technologies, the work presented in [26], [27] emphasises the importance of incorporating UAVs in multi-tier heterogeneous networks to extend network coverage and capacity in disaster-struck areas. To this end, literature provides multiple use-case scenarios, for example, in [28] authors use the 2011 great earthquake and tsunami in Japan as a use case to illustrate that communications infrastructure can be damaged during such disasters. The paper presents a UAV-based Software Defined Radio (SDR) platform that could be deployed rapidly for emergency communication use-cases. The authors explain that, in this scenario, UAVs act as aerial base-stations to provide cellular network coverage to users on ground within UAVs’ vicinity. Additionally, the work in [29]–[31] discusses the interaction between UAVs and terrestrially deployed wireless sensors networks. The aforementioned papers emphasise the challenges related to energy management and UAV placement as well as provide possible solutions for maintaining a connected aerial mesh during handoff between UAVs, taking into consideration UAV-specific, security and energy challenges.

Besides disaster relief and short-term, temporary emergency networks, the introduction of 5G and the growing communication demands of the vast heterogeneous IoT devices, call for new ways to utilise UAVs on continuous and

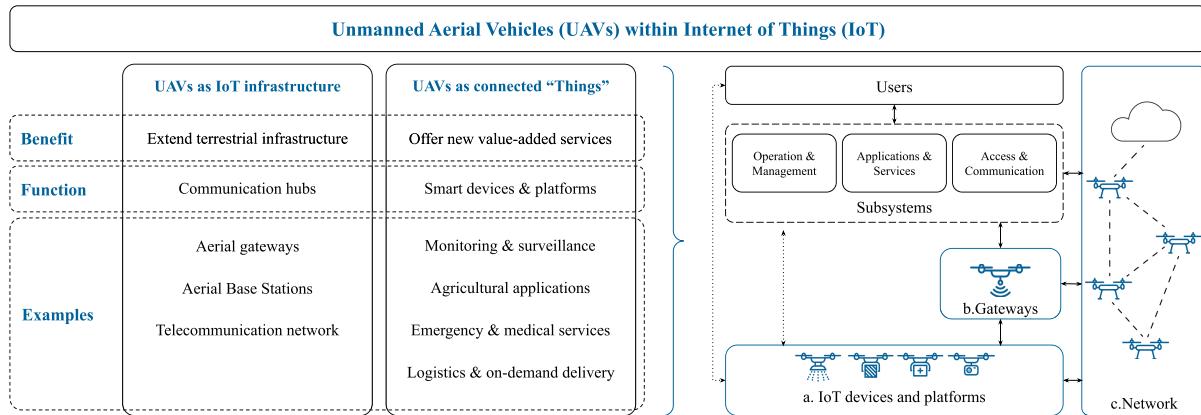


FIGURE 4. Left: Benefits, function and examples of UAVs as part of IoT infrastructure & UAVs as connected “Things”. Right: Illustration of UAVs within the context of IoT as, (a) terminal IoT-devices that interact with the physical world; (b) aerial base stations & gateways; (c) telecommunication network connected to IoT cloud.

regular basis within hybrid aerial–terrestrial network infrastructures [32], [33] to deliver IoT services [34], [35]. Recent work presented in [20] argues that the fifth generation of mobile communications would catalyse further applications where latency and quality of service cannot be compromised, the authors then present UAVs as a potential solution to foreseeable ground–based infrastructure limitations. Furthermore, the work in [36] presents supports the argument of the strain on cellular networks due to the inefficiency in handling the large traffic demands driven by the ever growing increase in users continuously requesting more data and services. The paper provides a viable solution utilising multiple UAVs to act as aerial–nodes connecting the macro and small cell tiers for improving coverage as well as increasing capacity. The authors investigate the problem of user demand–based UAV assignment over geographical areas subject to high traffic demands, formulating a neural-based cost function approach in which UAVs are matched with a specific geographical area. The results presented in [36] illustrate that utilising multiple UAVs on one hand provides long range connectivity but also improve load balancing as well as traffic offload. The authors support their models by extensive simulations that demonstrate significant improvements of up to 38% and reduction in delays of up to 37.5% when compared to solely ground–based networks. This is further supported in [37] where the authors propose a novel hierarchical architecture of UAVs with multi–layer and distributed features in order to facilitate smooth integration of different mainstream UAVs into the next–generation wireless communication networks. The paper additionally unveils the critical comprehensive design trade-offs, in light of both communication and aerodynamic principles. The authors present empirical models and satellite measurement data to conduct numerical analysis of the meteorological impacts of UAV enabled, 5G high bands communications. Additional complementary research presented in [38] provides experimental review on ray-tracing simulation for a UAV–aided 5G networks where the authors main objective was to assess the usage of UAV

in next-generation wireless networks. Moreover, a recent survey [39] emphasises the importance of UAVs in assisting 5G as well as beyond 5G (B5G) mobile networks. The authors provide comprehensive discussions the technologies and analyse use-cases to highlight pressing challenges and future research directions.

2) FROM AIRCRAFTS TO SMART CONNECTED PLATFORMS

Supported by the miniaturisation of sensors, actuators, processors and developments in wireless connectivity and energy storage systems as well as rapid advancements in IoT, UAVs are quickly finding many new uses in enhancing our everyday life as smart terminal devices. With the observed rate in development of innovative use-cases, it becomes safe to envision UAVs as important tools for people, businesses and governments alike. They will not only be used for disaster relief operations, but myriads of commercial services. From assisting in search and rescue missions, homeland security and border control to monitoring of traffic, construction sites to delivering medical supplies, to name a few examples.

Given the expected wide usage of UAVs in different sectors and scenarios it becomes challenging to introduce all possible use cases; therefore, for the purpose of this work, we outline some predominant civil commercial applications found in scientific literature. Besides the classification presented in [40] of UAVs in manufacturing, there is no study, to the best of our knowledge, that presents a detailed taxonomy for commercial UAV applications. Building on the proposed classification of [40], we devise a novel categorisation of UAV applications into three broad categories based on the main role of the application, namely, *Perceive*, *Act*, *Perceive & Act*. Figure 5 presents the three categories of UAV applications and illustrates how Stages 1–4 representing “see”, “sense”, “move” and “transform” based on the classification of [40] respectively, develop in correlation to improvement in UAVs’ sensing, actuation & analytical capabilities where *Stage 1* indicates basic data collection applications, while *Stage 4* indicates more complex applications where UAVs are able to

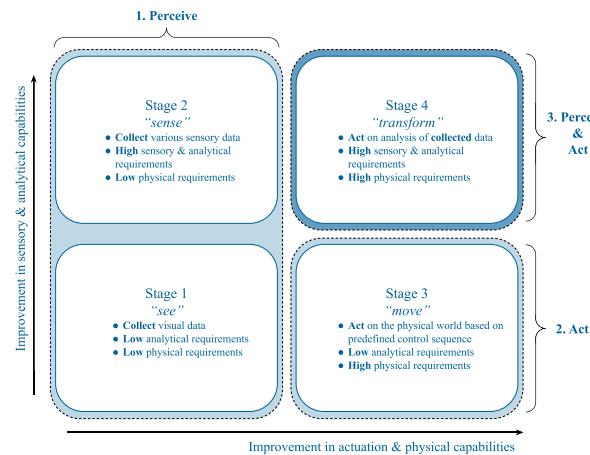


FIGURE 5. The three categories of UAV applications: **Perceive**, **Act**, **Perceive & Act**, illustrating the development from Stages 1–4 [40] governed by improvement in UAVs' sensing, actuation & analytical capabilities.

perceive the physical environment and act based on a higher degree of autonomy.

In this context, this section explores each of the three categories then outlines some of the predominant applications in scientific literature followed by a summary in Table 1.

1) **Perceive:** applications where the main objective is data collection and perceiving the physical world. Such applications cover systematic, continual, and active or passive observation of places, things, persons or processes or in addition to use-cases consisting of targeted monitoring of activities for specific evidence of faults, crimes or other wrongdoing. This category includes Stage 1 and 2 in Figure 5, where the former includes applications where the UAV does not require high analytical and computational capability while the latter requires UAVs to be able to collect and analyse multiple sensory data types. Some examples falling under this category include:

- Asset and Traffic Monitoring
- Persons and Crowd Monitoring
- Environmental Monitoring
- Agricultural Monitoring
- Security and Surveillance
- Infrastructure Inspection
- Search and Rescue

2) **Act:** applications where the main objective is acting upon the physical world. Such applications compromise of logistics and supply activities. This category includes Stage 3 in Figure 5 requiring high actuation and physical capabilities but not necessarily high analytical and computational capabilities. for example:

- Logistics and On-demand Delivery
- Emergency and Medical Services

3) **Perceive & Act:** hybrid applications requiring higher degree of autonomy where UAVs are able to perceive

TABLE 1. A summary of UAV application domains and corresponding illustrative use-case examples based on the devised categorisation.

UAV Application Taxonomy		
Category	Application domain	References
Perceive	Telecommunications <i>Examples:</i> -Temporary & emergency networks -Hybrid aerial-terrestrial infrastructure	[20], [23]–[37]
Stages 1-2	Asset and Traffic Monitoring <i>Examples:</i> -Monitoring car traffic patterns -Monitoring traffic densities	[41]–[48]
Perceive & Act	Persons and Crowd Monitoring <i>Examples:</i> -Monitoring safety of staff & personnel -Monitoring pedestrian traffic	[49]–[53]
Stage 3	Environmental Monitoring <i>Examples:</i> -Air quality & climate diagnosing -Mapping & land surveying -Wildlife monitoring	[54]–[58]
Stage 4	Agricultural Monitoring <i>Examples:</i> -Multi-spectral imagery and crop monitoring -Precision farming -Mapping pesticides	[59]–[63]
Stage 3	Security and Surveillance <i>Examples:</i> -Moving target detection & tracking -Security border control -Parameter surveillance	[64]–[70]
Stage 4	Infrastructure Inspection <i>Examples:</i> -Hazard identification & detection -Automated infrastructure inspection	[71]–[73]
Stage 4	Search and Rescue <i>Examples:</i> -Relief operations -Search & identify disaster victims	[74]–[77]
Act	Logistics and On-demand Delivery <i>Examples:</i> -Last-mile delivery -Logistics & cargo transport	[78]–[84]
Stage 3	Emergency and Medical Services <i>Examples:</i> -Blood sample & medicine transport -Emergency response in remote locations	[85]–[91]
Perceive & Act	Other Autonomous Applications <i>Examples:</i> -Warehousing & product sorting -Pest detection & spraying -Search, detect & extract -Autonomous UAV safeguards	[6], [92]–[95]

their environment and act based on informed decisions. This category includes Stage 4 in Figure 5. Applications falling under this domain, while limited in comparison to previous categories, compromise of demanding application scenarios, for example:

- Autonomous Urban Mobility
- Detect and Extract

a: ASSET AND TRAFFIC MONITORING

With regard to asset and traffic monitoring, an interesting review on the subject focusing on advantages and disadvantages of main methods found in scientific literature can be found in [41] and [42]. In these reviews, applications on traffic monitoring are organised thematically identifying the novelty and state-of-the-art. One of the first projects - WITAS [43], [44] was dedicated to the development of

a fully autonomous UAV able to navigate at different altitudes and conduct several tasks including identifying, tracking and monitoring specific vehicles and assets. In [45], [46] the authors discuss the potential of collecting traffic data from aerial video footage; several key parameters were able to be extracted, according to the study, including car traffic densities, travel times, turning counts and queue lengths. Another more recent work [47] investigated the use of UAVs for asset and traffic monitoring applications by proposing and testing a complete traffic monitoring system using rotary-wing UAVs equipped with on-board cameras. The authors use video and data processing algorithms to detect vehicles based on the Haar cascade model. The results obtained conclude that the designed system can monitor traffic with high accuracy and flexibility. This complements the argument presented in [48] where the authors highlight the limitations of stationary ground-based traffic information collection methods and propose an alternative aerial traffic monitoring system using autonomous UAVs.

b: PERSONS AND CROWD MONITORING

For crowd monitoring, various research projects were proposed over the past few years, such as in [49] where the authors describe the use of collaborative micro-drones for people tracking in disaster situations. In [50] the authors present a novel airborne based high-performance crowd monitoring framework for estimating crowd density and motion using video data based on custom object detection techniques. Another application that has gained the interest of the scientific community is finding innovative means of collecting data of pedestrian traffic as it has been demonstrated to be complex and labour-intensive [51]. The authors argue that using conventional techniques, such as manual observers and on-site video records or the use of survey questions and qualitative questionnaires to investigate pedestrian flow characteristics and behaviour may be restrictive. To this end, the recent years have witnessed an increase in novel methods incorporating the use of UAVs. In [51], the authors present a feasibility analysis of UAV technology in persons and crowd monitoring and show that UAVs can be an alternative viable technology in monitoring pedestrian traffic characteristics in outdoor pedestrian zones. More recent studies propose novel large scale crowd monitoring systems [52] that take into consideration the privacy and security challenges of using UAVs for crowd monitoring [53].

c: ENVIRONMENTAL MONITORING

Over the past two decades researchers have investigated innovative uses of mobile robotics in various monitoring applications. In [54] the authors explore emerging research trends for achieving large-scale environmental monitoring, including cooperative robotic teams and wireless sensor network interaction. The authors emphasise that these trends offer efficient and precise measurement of environmental processes at ultra-large scales, in turn, furthering the frontiers of natural sciences. In a more recent study [55], the authors stress on

the constant need for monitoring the environmental features changes. The paper proposes guidelines for the design of a lightweight and low-cost UAV platform for environmental monitoring. As environmental monitoring plays a central role in diagnosing climate and managing impacts on natural and agricultural systems [56]; the research community continuously develops new systems and proposes new projects to address such needs. In [57] the authors propose AQNet, an aerial-ground wireless sensor network (WSN) system, for fine-grained air quality monitoring and forecasting in urban three-dimensional areas. The proposed system compromises of hundreds of programmable on-ground sensors, working in tandem with UAVs, to monitor air quality at various heights. The paper proves the scalability of the system through demonstrated experiments. This is further complemented by a comparable proposal in [58].

d: AGRICULTURE MONITORING

Another emerging field with great potential for UAVs usage is agriculture. For instance [59] provides an improved remote sensing system based on an autonomous UAV. Equipped with a multi-spectral cameras, the authors demonstrate that their UAV-based system was capable of monitoring turf grass glyphosate, in turn, indicating the flexibility and reliability of UAVs in precision agriculture (PA). This is further supported in the comprehensive survey in [60]. The latter emphasises that images taken by low altitude remote sensing UAV platforms have potential given their low cost of operation in environmental monitoring, high spatial and temporal resolution, and their high flexibility in image acquisition programming. The survey further outlines recent studies in the application of UAV imagery for PA. Indicating that, to provide a reliable end product to farmers, advances in platform design, production, standardisation of image geo-referencing and mosaicing as well as information extraction workflow are required. This is further supported in the recent review [61]. The paper focuses on current and potential applications of thermal remote sensing in PA as well as some concerns relating to the PA application such as spatial and temporal resolution, atmospheric conditions, and crop growth stages. Supporting it, is [62], where the authors discuss how UAVs play a great role in transforming the farming sector. This, in turn, has led to a rise in a new domain known as *precision farming* that is quickly gaining attention of the scientific communities, one recent example is in [63] where the authors propose a narrow-band IoT UAV-aided network to study various soil parameters which were previously not feasible to investigate.

e: SECURITY AND SURVEILLANCE

Taking off from military to now more commercial and public sectors, UAV security and surveillance applications have recently emerged to be a predominant domain falling under Stage 2 in Figure 5. From target following and tracking [64] to border control [65], [66], the scientific community is continuously working on utilising the mobility and agility of UAV platforms for security applications. In [67] the

authors present a resource-usage management scheme called Adaptive Multi-scale Optimisation (AMO) for UAV surveillance operations. The paper demonstrate AMO's benefits and trade-offs through a series of simulator runs, covering multiple use cases. Moreover, the authors in [68] discuss their designed frameworks for UAV surveillance and security systems for smart cities and marine applications emphasising on the potential such applications would have on the benefit of the society. In [69] the authors propose a new cooperative network platform and system architecture of multi-UAV surveillance. First the paper elaborates on the design concepts of a multi-UAV cooperative resource scheduling and task assignment scheme, then explains the small target recognition technique as well as the localisation and tracking model, using the fusion of multiple data sources. In addition, this article discusses the establishment of suitable algorithms based on machine learning, due to the complexity of the monitoring area. The authors support their work by conducting real world detection and tracking experiments of multiple moving targets using the proposed multi-UAV systems. A complementary recent study [70] presents a novel surveillance optimisation and a distributed navigation algorithm for UAV network in applications of ground vehicle tracking.

f: INFRASTRUCTURE INSPECTION

One additional domain that gained a lot of attention from both the research and commercial communities is infrastructure inspection. The use of UAVs offers the flexibility of reaching to places and taking measurements that were considered near impossible for their hazardous nature to human labour. The work presented in [71] provides a comprehensive review on robotic infrastructure inspection systems. The paper aggregates these studies in an effort to distil the state of the art in inspection robotics, as well as to assess outstanding challenges in the field and possibilities for the future. [72] gives a possible solution to the overcome the infrastructure inspection challenges in Japan using UAVs. The authors develop a light weight manipulator on UAV system for ageing infrastructure inspection where people cannot. Another recent paper [73] describes a mission definition system and implementation for automated infrastructure inspection using airborne sensors. The paper's main aim is improving planning efficiency with respect to state-of-the-art way point-based techniques. The obtained results for a set of representative infrastructure inspection flights, show accuracy of flight prediction tools in actual operations using automated flight control.

g: SEARCH AND RESCUE

Search and Rescue (SAR) includes operations led by emergency services, to locate and identify assets in distress in remote or difficult to access areas. Since the early 20th century global organisations have put efforts in establishing international Search and Rescue (SAR) plans to ensure the coordination of missions. As technology developed over time, researchers have found new tools and

methods to optimise SAR missions. This in turn led to exploring the potential of integrating UAVs in such SAR networks. In [74] the authors introduce small UAV systems to provide essential support to on-ground task forces in situation assessment and surveillance. As external infrastructure for navigation and communication is usually not available, such UAV systems should be able to operate with some degree of autonomy in turn classifying such applications between Stages 2 and 4 in Figure 5. This is further supported in [75] where the authors present an integrated data combination and data management architecture that is able to accommodate near real-time data gathered by a fleet of UAVs. The paper validates the system by illustrating two experiments. First, in the controlled environment of a military testing base, a fleet of UAVs was deployed in an earthquake-response scenario. Second, on an actual mission to aid with the relief operations after major flooding in Bosnia in 2014. After the success of multiple similar scenarios, research such as in [76] and [77] explore the use of complete autonomous UAV systems for SAR missions.

h: LOGISTICS AND ON-DEMAND DELIVERY

One of the segments and key market sectors where UAVs are increasingly becoming popular is logistics. Logistics can be defined as the management of the flow of things between their point of origin to their point of consumption in order to meet predefined requirements. They are a very cost effective solution for warehousing, container terminals and many others. December 1st 2013 marked the beginning of a new era of commercial package delivery when Amazon announced plans for Prime Air [78]. In early 2014, the work presented in [79] discussed the potential of package deliveries using small UAVs after Amazon's promotional video exceeded 14 million views. However, at the time, not many studies have implemented practical applications in this area since several challenges needed to be addressed first. The authors in [80] highlight the potential and challenges for UAV-enabled Intelligent Transportation Systems for next-generation smart cities. With more researchers investigating the topic, [81] as well as the NASA technical report [82] present a good example of such work. Here the authors discuss different approaches to the typical notional small package delivery UAV concepts giving an indication where future research trends are. While the origins of use cases have been first researched in military logistics applications [83], the current global health crisis triggered a shift to more commercial and specifically more efficiency-critical medical deliveries [84].

i: EMERGENCY AND MEDICAL SERVICES

Another application group that has recently emerged and is continuously attracting more researchers is UAV for e-Health. One example is [85] which discusses the potential UAVs have in this segment. Furthermore, [86] examines the use of drones in Swiss hospitals. The work shows the areas in which Swiss hospitals can benefit from integrating UAVs in

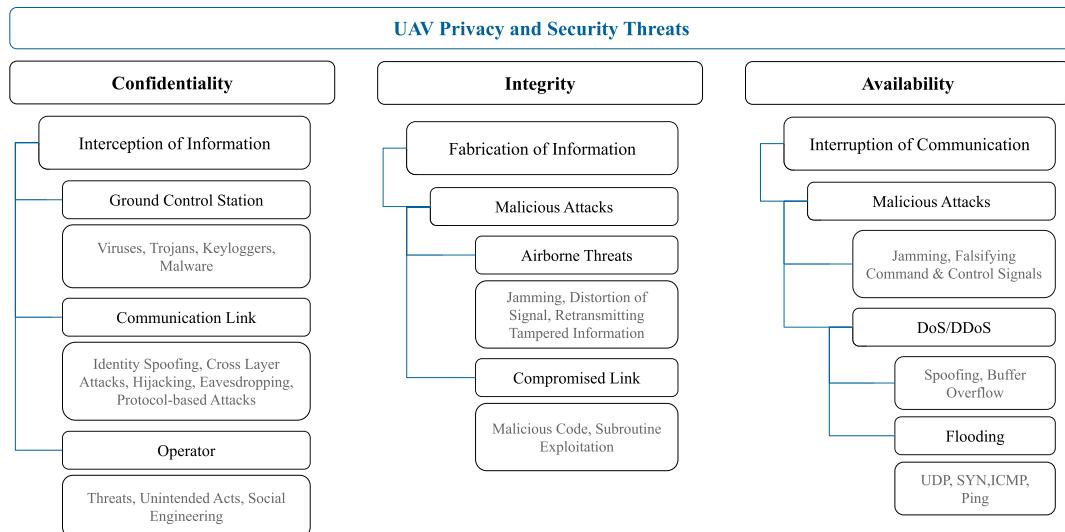


FIGURE 6. Taxonomy of UAV privacy and security threats based on [96].

order to create cost saving as well as process optimisation possibilities to manage increasing cost pressure and technological progress. This is further supported in [87] and [88] where the authors discuss UAV-aided delivery and pickup planning of medication and test kits for patients with chronic diseases who are required to visit clinics for routine health examinations and refill medicine in rural areas. In another recent work, presented in [89], the authors stress on the time-critical optimisation of such emergency service. This is further supported in [90] where the authors present a design process of unmanned vertical take-off and landing aircraft (VTOL), developed by the High Flyers team from Silesian University of Technology, who decided to participate in the Medical Express UAV Challenge competition. During the past year marked by the global pandemic of COVID-19 numerous applications within the e-Health domain have been introduced in addition to governmental initiatives like EU AiRMOUR [91].

j: OTHER EMERGING HYBRID APPLICATIONS

As analytical and computational capabilities of UAVs improve combined with the rapid development in sensory and actuation as well as communication and other IoT technologies, we witness a shift to Stage 4 for the aforementioned UAV applications. Relying on a higher degree of autonomy and the ability to perceive & act UAVs can be used to in varied domains. Some potential future examples include pest detection and control within agriculture, UAVs for pick up and drop off as an extension to logistics and on-demand delivery, autonomous UAV safeguards such as malicious-UAV detection and escort presented in [6], [92] and cargo as well as people pick up and drop off [93]. Within this context, researchers explore key enablers to such applications ranging from mobility and swarming behaviours for complicated tasks requiring multi-UAV operations [94]

and automating the design of autonomous UAV swarms as a disruptive approach to tackle the problem of designing swarming behaviours to novel automated algorithm selection approaches [95].

To this end, the preceding subsections attempted to compile some predominant conceptual application domains under the main three devised categories of *perceive*, *act* and *perceive & act*, illustrated in Figure 5. Additionally, for each of the predominant application domains some empirical use-cases were highlighted from scientific literature. This is summarised in Table 1 below.

B. THE CHALLENGES

The value and benefits that UAVs can bring to our everyday lives and to our future cities is undeniable, however, being part of the next generation IoT, UAVs face the inherent vulnerabilities and threats of other smart IoT devices. The unprecedented connectivity combined with foreseeable large number of data being exchanged by IoT-enabled UAVs operating in the low-altitude airspace present a set of security and data related challenges [2] let alone the physical and operational safety risks.

1) SECURITY, DATA PROTECTION AND PRIVACY CHALLENGES

As UAVs become more connected they naturally inherit from the security privacy and data protection challenges in IoT. Over the recent years, these challenges have been continuously addressed in scientific literature [96]–[100]. The authors in [96] present a summary of some of the main UAV privacy and security threats, illustrated in Figure 6. Based in the work in [96] the figure presents the devised taxonomy of security threats, categorised under *confidentiality*, *integrity* and *availability* threats.

Besides the security challenges that obstruct the full realisation of connected UAVs, are the inherited data protection and privacy related threats of being mobile IoT-connected devices and platforms. Most UAVs' commercial applications and specifically those in cities, require a lot of sensory as well as location and other critical data to be collected and transmitted over the internet hence posing a set of threats in addition to direct violations to General Data Protection Regulation (GDPR) [1] such as lack of transparency, data quality, profiling and data security. Nevertheless, UAVs extreme mobility and modes of operation pose additional physical threats to both people and property within cities.

2) OPERATIONAL MANAGEMENT CHALLENGES

The majority of UAV applications in literature require the operation of single as well as swarms of UAVs in the low-altitude airspace [101]. This in turn introduces a new set of challenges in safely let alone efficiently managing the operation of such agile, mobile aerial vehicles over populated cities. Moreover, the lack of consensus on airspace structure, not to mention the lack of technical standards and minimum requirements for things like collision avoidance, remote identification as well as the non-existent unified data model for communication add further complexity to an already convoluted problem.

One initial step towards tackling these challenges is understanding the associated risks and establishing some tools to aid in their modelling. The authors in [102] introduce a set of risks that need to be quantified or qualified and mitigated. Similarly, in [103] a comprehensive risk assessment model based on collision probability is proposed for UAV operation in urban environments. Three risk categories are considered, namely property, people and vehicles. As the topic of UAV risk assessment continues to gain more attention in the scientific community, more novel approaches are proposed that take further external arguments into consideration such as flight conditions [104]–[106]. However, one limitation in most approaches is that they do not consider the operational status of the various internal UAV subsystems for example, time to maintenance or battery level when conducting flight-related risk assessments. While from a macroscopic perspective simplifying UAVs to mass points within a flight environment can arguably suffice, UAV operational risk assessment should be more comprehensive as UAVs are a complex system consisting of multiple subsystems operating in tandem, each with their own fault tolerances and accuracy levels. In [107], for instance, the authors develop a novel data-driven fuzzy comprehensive evaluation approach to monitor the condition of the various UAV subsystems and incorporate them into the risk assessment model.

IV. LOW-ALTITUDE AIRSPACE TRAFFIC MANAGEMENT

The significance of UAVs of all categories is growing exponentially ranging from small off-the-shelf recreational UAVs, commonly referred to as drones to large aircrafts potentially capable of transporting cargo and people. Previously,

section III outlined and discussed possible applications and use-cases for UAVs ranging from goods infrastructure monitoring to on-demand delivery and search & rescue. However, the shared airspace utilisation of such promising systems remains a crucial challenge obstructing the full deployment of UAVs. To the best of our knowledge, till this day, there is no complete and operational regulatory framework or established traffic management infrastructure to enable and securely manage the widespread use of general airspace for UAVs [108].

This section firstly provides an overview of low-altitude airspace structure and its impact on traffic followed by a conceptual and technical overview of UAV traffic management (UTM) systems highlighting the key functionalities of such constructs. Additionally, the work explores state-of-the-art of different concepts of operations of predominant UTM systems in the scientific literature.

A. LOW-ALTITUDE AIRSPACE

After a series of tragic midair collisions as air traffic increased in mid 20th century along with the advent of the jet era [109], the Federal Aviation Act of 1958 was passed as a first step towards regulating the airspace. One of its key outcomes was the creation of the Federal Aviation Administration (FAA) [110] in the United States of America. This in turn marked the beginning of a more complex system of airways, however it was not until 1993 [111] when major adjustment to the airspace structure took place leading to the current system of airspace classes known today. The ever so slightly modified version of the international system divided the usable airspace vertically into a three-dimensional horizontal segments denoted as classes labelled from A through G, based on altitude and flight rules including visual - VFR - and instrument - IFR (c.f. Figure 7). The interested reader can refer to [112] for definitions from international standards and from the International Civil Aviation Organisation. However, it is worth noting that whereas Classes A–E represent regulated and controlled airspace, Class G - extending up to 700ft above ground level (AGL) - is completely uncontrolled. It is additionally crucial to emphasise that most current and foreseeable UAV applications are and will be mostly taking place within this low-altitude airspace class, concurrently with other manned aircrafts like rescue helicopters para-gliders and others.

B. INFLUENCE OF AIRSPACE STRUCTURE ON TRAFFIC

Whether for manned or unmanned aviation, air traffic performance is not only subjected to traffic demands but also dependent on the given airspace structure. The flow characteristics of the airspace including traffic volume, mix of aircraft types, flight activity, climbing and descending traffic including Vertical Take Off and Landing (VTOL), best angle, best rate, recommended climb for visibility and engine cooling, cruise, glide and powered descent to name a few, all influence airspace complexity, which in turn can influence the probability of safety occurrences [113]. In other words, all

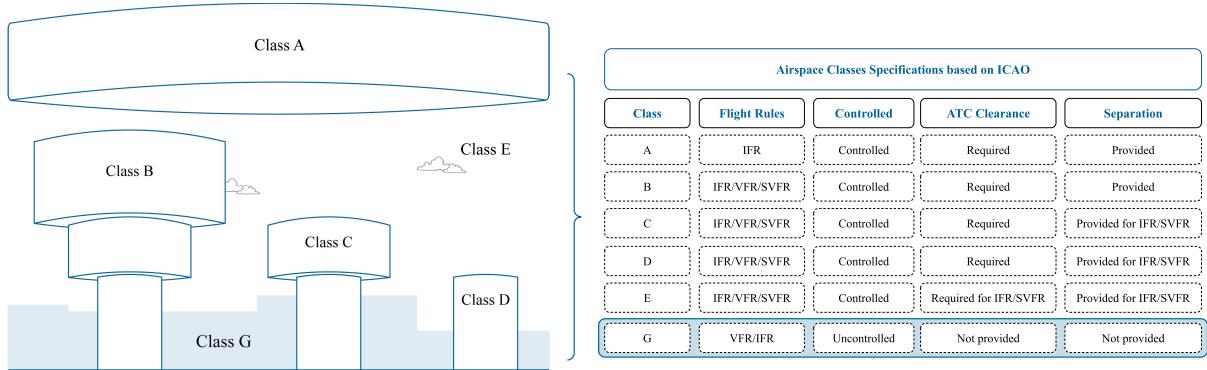


FIGURE 7. Illustrative taxonomy of airspace structures.

these dynamic and static complexity components potentially have an impact on the safety of the air traffic management system or UTM in our case.

As the number of UAVs continues to grow and given the nature of the major application domains, the demand for utilising the low-altitude airspace will only be expected to expand. In [114] the authors argue that the difficulty of safely separating a large number of UAVs can be reduced through careful design of airspace structure. However, in contrast to manned aviation, there is no clear consensus on how the low-altitude airspace should be structured. The topic has gained attention of the scientific community over the recent few years in turn leading to several studies presented on the topic. On one hand, some emphasise that a well-defined, structured approach is necessary to account for the expected high traffic densities [115], [116] and on the other, there are arguments for free flight systems without any structure would enable UAVs to take user-preferred direct routes at the cost of higher risk of conflict or collisions under high traffic demands [114].

For the former approach, studies state that it is required that UAVs have pre-planned conflict free routes negotiated and pre-approved between the UAV or UAV operator and Air Navigation Service Providers (ANSPs). In addition to the three-dimensional (3D) paths that aircrafts are required to follow, the negotiated and approved trajectories include fixed time constraints for arrival at the different way-points along the pre-approved route. In such approaches, the position-related uncertainties of aircrafts can be minimised, in turn, allowing for minimising the safety distance required between different trajectories, hence, enabling an increase in traffic capacity levels. On the contrary, free flight studies have found evidence of the opposite. The concept of having free flight UAVs has been shown to allow for higher traffic densities by reducing traffic flow constraints and structure according to [117], [118]. In such approaches, UAVs are allowed to fly on operator-preferred, often direct air routes, while separation responsibility is delegated to each individual UAV by means of on-board collision detection and resolution systems. As a result, the authors argue that

traffic would be evenly distributed over the airspace, thus reducing the number of potential conflicts while increasing capacity [119], [120]. However, this free flight mode comes with multiple challenges of its own when considering the ripple effect of rapid unexpected changes in flight paths within large traffic densities possibly due to rogue behaviour. On one hand, as illustrated in Figure 8, a free flight system without any structure would enable UAVs to take user-preferred direct routes at the cost of higher risk of conflict or collisions under high traffic demands similar to civil manned aviation prior to 1958 and on the other, an extremely structured airspace could lead to poor operational efficiency [121] specifically when UAVs follow predefined routes following ANSP defined way-pints [114].

To this end, one potential solution that is further explored in though-out the remainder of this work is a dedicated UAV Traffic Management (UTM) system [122] to complement the conventional manned Air Traffic Management (ATM) systems by facilitating the exchange between UAVs and operators on one hand and the various other stakeholders with the aim of mitigating operational risks.

C. UAV TRAFFIC MANAGEMENT

The inception of UAV traffic management systems in the recent years is a result of the need of having a clear framework at national, regional and international levels to guide the rapidly evolving UAV technologies and to enable as well as catalyse the creation of a market for UAV services. UTMs will facilitate the growth of this new promising sector of the economy, on one hand, while ensuring public safety on the other.

However, since its conception [123], [124] the definition of the term UTM remains fuzzy. While most acknowledge that a UTM is a specific aspect of air traffic management responsible for the operational safety of UAVs as defined by ICAO [125], many fail to see that similar to IoT, a UTM is a system of systems that functions by facilitating collaborative integration of people, information, technology as well as services by incorporating heterogeneous air, ground and space-based communication technologies and standards.

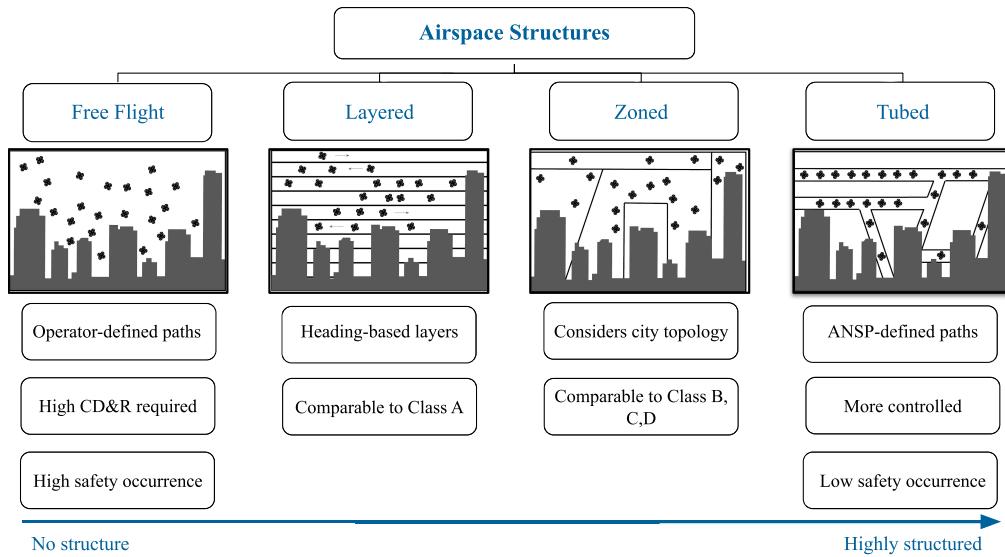


FIGURE 8. Illustrative taxonomy of low-altitude airspace structure.

It can be therefore deduced that the main goal of a UTM system is to facilitate data and information exchange between stakeholders as well as manage and monitor UAVs with diverse characteristics safely, together while ensuring safe integration with other airspace users including helicopters, gliders, and para-gliders for a future fully-integrated manned and unmanned airspace. It becomes apparent that a UTM is a multi-stakeholder system of systems where every actor group has different needs and incentives. On one hand industry service providers and operators want to simplify bureaucratic procedures and have the ability to fully utilise the potential of UAVs to bring value-added services, and on the other authorities, administrators and regulators want to ensure safe operation and compliance. This in turn emphasises the level of complexity of a UTM system.

The expected complexity of a successful traffic management system can be abstracted to spatial and time-related interactions between aircrafts, whether manned or unmanned, operating in a given airspace during a defined period of time. Consequently, such presumably high complexity may be reduced at both the strategic and tactical levels.

On the strategic level, the UTM system is responsible for efficiently planning and segmenting the available low-altitude airspace with the main goal of making optimal use of the shared resource. Such efficient airspace management builds on a suitable airspace structure [101] to avoid a permanent segregation between different users of the airspace [126]. This proactive approach can be achieved by a dynamic allocation of airspace taking into consideration performance and flight requirements to efficiently utilise airspace and optimise the planned traffic in order to ensure safe UAV operations even in dense traffic scenarios.

Subsequently, complementing the proactive strategic stage of airspace management is the dynamic tactical stage.

The main aim of this stage is to maintain separation and mitigate collision risks therefore a reliable underlying information management systems is crucial. This underlying information management system collects traffic data including 3D positions, heading and velocities in order to provide situational awareness and to be able to issue traffic alerts or geo-limitation warnings to airspace users when needed.

The past few years have shown a growth in interest in UTM and UTM-related topics from the research communities which is evident through the increased number of publications as explained in [127]. While initially, the models and approaches presented in scientific literature only focused on specific domains, the recent years have witnessed an increase in publications following more holistic approaches that account for the benefits and challenges experienced by the different UTM stakeholders. According to [127], one of the first proposals for a UTM construct - “*Internet of Drones*” [128] - emphasised the importance of such interdisciplinary approaches by combining best practices in air traffic control networks, cellular networks as well as the internet to devising one of the first UTM constructs in scientific literature. Since then we have witnessed a clear interest in such holistic research as seen in [5], [102], [127], [129]–[136] on UTM systems, in addition to domain-specific research on airspace design in [101], [111], [113]–[120], collision avoidance and risk mitigation in [103]–[106], [137]–[146] and communication and cybersecurity including counter-UAV systems in [96]–[100], [147]–[159] as summarised below in Table 2.

D. KEY FUNCTIONS OF A UTM

To this end, the term UTM in scientific literature is used as an overarching umbrella term to represent the infrastructure encompassing all systems that assist UAVs to depart

TABLE 2. Non-exhaustive list of recent contributions from the UTM perspective.

UAV Traffic Management Development	
Area of Contribution	References
Airspace Structure & Design	[5], [101], [111], [113]–[120]
Communication & Cybersecurity	[96]–[100], [147]–[159]
Collision & Risk Mitigation	[103]–[106], [137]–[146]
Development of UTM Systems	[5], [102], [127], [129]–[136]

from a vertiport or aerodrome, transit airspace, and land at a destination aerodrome or vertiport, safely, including traffic services, airspace density and traffic flow management, integration with manned aviation, authorities as well as others by facilitating data exchange between the different stakeholders as explained above. In this subsection we highlight the key functions of a successful UTM system as compiled from industry proposals, scientific literature and standardisation organisations. The devised proposal categorises UTM functions as either *safety critical (SCF)*, *safety related (SRF)* or *operational support (OSF)* where,

- *SCF* are those that if lost or degraded as a subsequent to any incorrect would result in total service disruption and collateral damages;
- *SRF* on the other hand are functions that have the potential to contribute to the violation of or achievement of a safety goal, but whose loss or degradation would not on its own be sufficient to cause catastrophic consequences;
- finally, *OSF* include any web-based tools and information provided by service providers to UAV operators with the aim of supporting safe and efficient planning and execution of a UAV mission.

With this broad categorisation in mind, the key UTM functions can then be further classified based on compiled definitions and functional descriptions of ICAO's Core Principles for Global Harmonisation [125], Concept of Operation for EuRopean UTM Systems (CORUS) [160] and Federal Aviation Authority (FAA) Concept of Operations [161], into the following five main function classes shown in Figure 9 and are further explored below in subsections IV-D1-IV-D6.

1) REGISTRATION FUNCTION

The registration function provides a mechanism to register as well as share authorities' certified UAV records in order to ensure a safe operation within the airspace. The registration functions are therefore classified as pre-flight Security Critical Functions (SCF) and information provided through this function should be managed by the national authority or other appropriate third entity and regulated in each country according to their specifications of airspace laws and regulations. The registration function hence, encompasses - however not limited to - the following:

- *Remote Pilot Registration* – register information about certification as well as skills of the operating pilot.



FIGURE 9. Classification of UTM main functions as *safety critical (SCF)*, *safety related (SRF)* or *operational support (OSF)*.

- *UAV Registration* – register information about UAVs such as type of aircraft, specifications, on-board equipment and remote identification.
- *UAV Identification* – provide individually assigned referral ID to UAVs and remote pilots.
- *Operator Registration* – register information about UAV business operators including information such as name of operator, authorisation information and fleet identification.

2) FLIGHT INFORMATION MANAGEMENT FUNCTION

The flight information management function is a SCF and aims to ensure the safe operation of UAVs as well as manned aircrafts operating within the same airspace. Such function is responsible for handling the exchange of traffic and aeronautical information with air traffic management systems within the shared airspace. The flight information management function hence, encompasses - however not limited to - the following:

- *Aeronautical Information Management* – facilitate the exchange of aeronautical information necessary for safe UAV operation.
- *Traffic Information Exchange* – exchange UAV and manned aviation information with ATM.
- *Interface with Air Traffic Control (ATC)* – provide UAV operators and pilots with means to communicate with ATM services within controlled airspace.
- *Flight Plan Exchange* – facilitate the exchange of UAVs' operation and manned aircrafts' flight information between UTM and ATM.
- *Airspace Organisation and Capacity Management* – design the structure of airspace and manage the usage thereof to achieve safe and efficient UAV operations through by:
 - defining where UAV activity should be prohibited or restricted within the airspace and to define the routes where UAVs can fly safely.
 - controlling UAVs access to predefined airspace and monitoring UAVs in controlled airspace according to national regulations.
 - managing airspace capacity limits and coordinates operations with operators to maintain safe traffic flow.

3) OPERATION PLAN MANAGEMENT FUNCTION

The operation plan management function is a SCF which aims to aid in the flight route plan authorisation to ensure UAV operations are carried out safely and efficiently. The function also supports necessary plan changes when flight conditions such as weather change during operation.

- *Operation Planning* – support operators in pre-flight planning taking into consideration constraints on the flight path such as geo-limitations, interference with terrain, severe weather conditions and UAV as well as pilot capabilities.
- *Operation Plan Approval* – authorise or deny filed operation plans and return the result to the operator. The function additionally confirms that the operation plans do not interfere with other UAVs or restricted areas of the airspace.
- *Operation plan sharing* – share minimum necessary UAVs' operation data upon operator's consent among UTM service providers.
- *Conflict Management* – ensure and maintain separation between UAVs as well as between UAVs and manned aviation.

4) POSITION DATA MANAGEMENT FUNCTION

The position management function is a SRF that aims to manage the position-related information provided by the UAV to confirm that the operation is executed correctly as per authorised plans.

- *BVLOS UAV Tracking* – securely track the location information of UAVs operating in controlled airspace or BVLOS.
- *Performance Monitoring* – monitor the operation status of the UAV as well as flag any inconsistency with operation plans like route of flight, altitude, proximity to no-fly zone, terrestrial structures and other UAVs, remaining fuel level.
- *Conflict Advisory and Alert* – notify UAV operators of any abnormal status of UAVs based on tracking data.
- *Flight Flight Log and Data Recording* – securely record UAV flight information data in case of operational incidents.

5) REPORTING FUNCTION

As a SRF, the reporting function collects and shares the incident or accident report on UAV operation from operators or third parties for analysis in order to prevent recurrence.

- *Incident and Accident Reporting Provision* – provide reports from operators and authorised UTM actors when an incident or an accident occurs.
- *Public Reporting Provision* – provide reports from third party persons when an incident or illegal operation is observed.

6) SUPPLEMENTAL DATA SUPPLY FUNCTION

As the name suggests, the supplemental data supply function is an OSF that provides UTM actors with supplemental data,

such as weather information as well as maps or other supplementary data to enable efficient operation. Some of these include the following provisions:

- *Geospatial Information* – provide UTM actors with geographic information, including terrain, buildings and obstacles for efficient UAV operation.
- *Navigation Coverage* – provide UTM actors with operating status and coverage area of navigation assistance equipment.
- *Population Density Information* – provide UTM actors with information on population density to estimate flight risk.
- *Weather Information* – provide UTM actors with meteorological information to plan and conduct safe and efficient operation.
- *Communication Information* – provide UTM actors with operating status, coverage area and signal strength of various communication means.

E. UTM USE-CASES

While the concept of UTM is still relatively new, the recent years have witnessed some initiatives and proposals from various governments most notably the NASA's UTM and EU U-Space project. This subsection presents an overview of the concept of operation of both constructs followed by some UTM demonstrations and use-cases found in scientific literature.

1) NASA UTM

NASA's conceptual framework for a UTM, one of the earlier concepts, first conceived in 2013 and was initially presented at a NASA–Industry workshop in 2014 [123]. In 2015, NASA hosted a UTM convention where NASA worked together with industry and UAV operators expressed the need for UTM system to manage the operation of UAVs at the low-altitude airspace [123]. In response to the convention, the Federal Aviation Authority (FAA) together with NASA formed a UTM Research Transition Team (RTT) in 2016 [62] to jointly undertake the development and eventual implementation of such UTM system [162].

The scope of the concept of operation (ConOps) of NASA's UTM focuses on UAV operations below 400 feet (122 meters) above ground level (AGL) and addresses the increasingly complex UTM operations within and across both uncontrolled (Class G) and controlled airspace environments. The ConOps additionally sets out the national UTM architecture as well as addresses scenarios where UAV operations take place BVLOS and in controlled airspace. The ConOps lists out a set of functions and roles of all of the UAV operators, UAV service suppliers (USS) as well as authorities and administrative bodies like the FAA as well as the corresponding level of responsibility of every actor. A summary adopted from [162] is presented in Table 3.

2) EU U-SPACE

Not much longer after the NASA UTM concept was initiated, the ConOps of European UTM known as U-space

TABLE 3. Summary of NASA's UTM functions and roles adopted from UTM ConOps [162].

Summary of NASA UTM Functions				
	Function	Entities [P]rimary / [S]upport Operator USS FAA		
Separation (B/VLOS)	UAV - UAV	P	S	
	UAV - Manned aircraft	P	S	
Hazard/Terrain Avoidance	Weather Avoidance	P	S	
	Hazard avoidance	P	S	
	Terrain avoidance	P	S	
	Obstacle avoidance	P	S	
Status	Operations status	S	P	
	Flight info archive	P	S	
	Flight info status	P	S	
Advisories	Weather info	P	S	
	Hazard info	P	S	
	Hazard alerts	P	S	
Planning, Intent & Authorising	Intent sharing	P	S	
	Intent negotiation	P	S	
	Authorisations		S	P
	Control of flight	P		
	Airspace allocation		S	P

was announced. U-space is defined in according to [163] to incorporate a new set of services as well as procedures designed specifically to support the safe, efficient and secure UAV operations within the European. Additionally, U-space takes into consideration conceptual elements introduced by the European Union's (EU) regulations, such as EU's classification of UAV operations and their corresponding requirements.

In contrast to the 400 feet UAVs operational limit set by NASA UTM, U-space considers UAVs operations up to 700 feet (213 meters) AGL. Furthermore, U-space divides the UAVs operations according to three broad operational classification namely, *open*, *specific* and *certified*. The definitions of the different categories were proposed by the European Union Aviation Safety Agency EASA and published in the 2019 regulations in [164].

Additionally, U-Space concept of operation divides the low-altitude airspace into three different volumes as explained in [160]. The devised classification is based on the following considerations:

- The numbers of expected UAV flights;
- The ground risk when flying over populated areas;
- The air risk based on the other operators in the shared airspace;
- Security, privacy as well as other factors such as public acceptance;
- Finally, the availability of mission-required U-space services.

The devised airspace volumes are distinct in terms of support service offered, types of operations allowed as well as their access and entry requirements. The 700 feet of available airspace is made up of these three volumes signified as X, Y and Z respectively. Where in X no conflict

resolution service is offered, in Y only pre-flight strategic planning support is offered, and in contrast in Z all strategic and tactical services are offered [165]. In contract to NASA UTM's 5 functions, the U-space concept of operation defines a set of 8 core functions for U-space ranging from UAV identification and tracking to the integration with manned aviation traffic management ATM. A summary of the main 8 functional categories each with the respective sub-functions is illustrated in Figure 10 adopted from [166].

3) UAV TRAFFIC MANAGEMENT DEMONSTRATIONS

Over the course of the past few years a considerable number of UTM constructs have been proposed by governments, standardisation committees and industries. This subsection highlights a few examples of these UTM systems found in literature.

a: SWISS U-SPACE

Within the context of EU's UAV traffic management, the Swiss U-space concept of operation presents Switzerland's vision for incorporating UAVs within one of Europe's busiest national airspace. The Swiss U-space describes the associated high-level requirements as well as outlines the national UTM architecture [167]. The architecture of the Swiss UTM adopts a federated set of services designed with the aim of facilitating safe, secure and efficient integration of multiple UAVs within the same airspace as manned aircrafts. The concept of operations emphasises that airspace and traffic flow management in addition to various monitoring services would represent the core functions of the Swiss U-space. Additionally, its architecture aims to support multiple service providers in operational data exchange and to manage the balance of demand and airspace capacity as well as facilitate authorisation requests, and provide directives and advice to UAV operators.

b: TAIWANESE UTM

Another example of UTM proposed as well as demonstrated is the Taiwanese UTM [131]. In [127] the authors analyse the Taiwanese UTM concept of operation and according to their work, The Taiwanese UTM relies in its core on the ability to track and monitor UAVs within the airspace. For the demonstration of the UTM - surveillance flight demo - Automatic Dependent Surveillance-Broadcast (ADS-B) was used. The UTM concept of operation proposes that it is the duty of ANSPs to alert pilots of any traffic within 600m radius. The concept of operation proposes a pre-flight process of flight scheduling and approval however, all collision avoiding decisions during flight are up to the operator [131].

c: OTHER DEMONSTRATIONS

Additional to what is presented in [129]–[131], [131], [137], literature provides other constructs and architectures as part of on-going U-space and UTM projects. Some of the most notable ones include China's Civil UAS Operation Management System (UOMS) or the Japanese UTM.

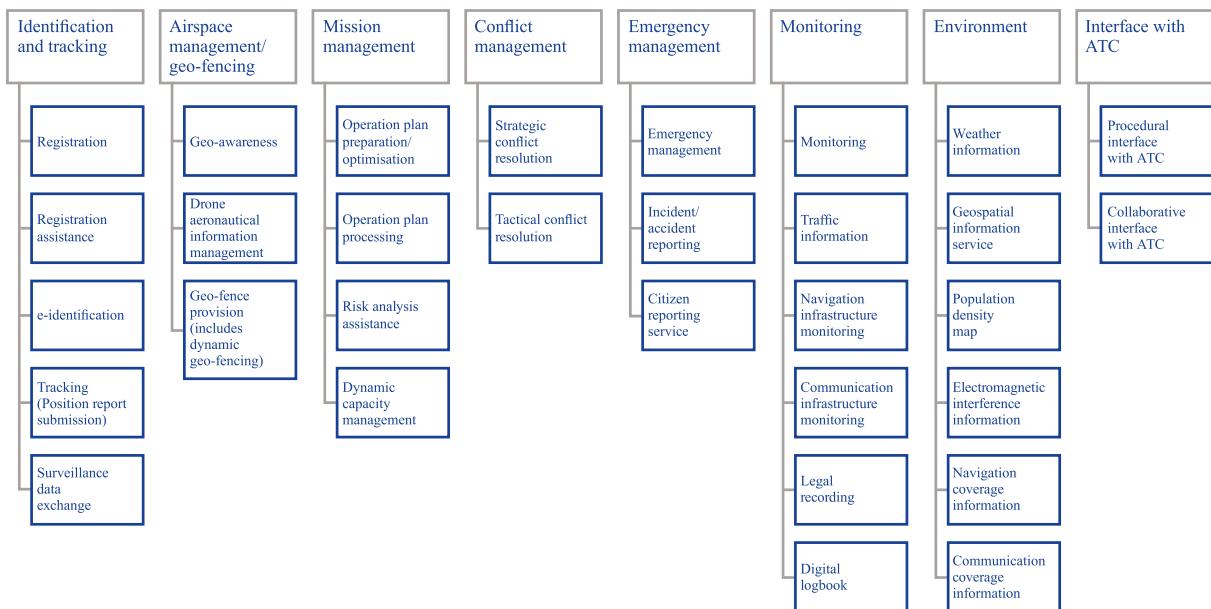


FIGURE 10. Summary of U-Space main 8 functional categories each with the respective sub-functions as adopted from [166].

Furthermore, the recent years have witnessed rise in UTM proposals from private industry including AirMap UTM and Unifly UTM as well as GuardianUTM by Altitude Angels. This is in addition to current standardised architectures being developed by Standardisation Development Organisations (SDOs) such as the on-going work at ISO TC20/SC16 on UTM development [12]. The interested reader can find an exhaustive list of commercial concept architectures and constructs in [168].

V. UAV TECHNICAL STANDARDS OVERVIEW AND DEVELOPMENT

Technical standardisation is the process of implementing and developing technical standards based on the consensus of different parties that include industry, users, interest groups, governments and other stakeholders. The main aim of technical standardisation is to help maximise interoperability, safety and quality as well as facilitate commoditisation of processes. The idea of standardisation is comparable to the solution for a coordination problem, a situation in which all parties can only realise mutual gains by making mutually consistent decisions.

This section gives an overview of UAV and UTM technical standardisation as well as the current efforts and developments within the relevant committees. UAV and UTM technical standardisation lies in the conjunction of the well-established aviation industry and the evolving Information Communication Technologies (ICT) standardisation. However, in contrast to IoT technical standardisation as one of the pillars of ICT, UAV standardisation is relatively recent with only a few published standards. Nevertheless, while the majority of the working groups and committees were only initiated in the past few years, the technical committees' efforts are picking up pace, benefiting from the well-established aviation standards, to correspond to the growing market needs.

On the regulatory side, the recent rapid growth in the commercial UAV market has encouraged authorities, regulators to collaborate with SDOs to form working groups and collaboratively address some of the pressing issues, some notable examples of regional SDOs include the European Organisation for Civil Aviation Equipment's (EUROCAE) working group (WG 73), the European Union Aviation Safety Agency (EASA) and EUROCONTROL Joint as well as international SDOs including International Civil Aviation Organisation (ICAO) [125], ISO TC20/SC16 [12] on Unmanned Aircraft Systems and IEEE-SA P1939.1 for Structuring Low Altitude Airspace for UAV Operation [169]. In response to the market, SDOs aim to reach consensus over guidelines and standards to safeguard the UAV economy and despite their geographical scope - local, regional or international - they all follow similar themes as explored below (c.f. Figure 11) from the more defined to the most recent, indicating that UTM technical standards build on all other sub-domains.

A. CLASSIFICATION AND TERMINOLOGY

Being the well-developed theme of UAV standardisation, standards under this theme are mainly focused around defining terms relating to UAVs that are widely used in science and technology. Additionally, they aim to specify requirements for the classification and grading of civil unmanned aerial vehicles with a wide enough scope to include heavier than air aircraft as well as lighter than air aircraft of any possible architecture. Such documents apply to the industrial conception, development, design, production and delivery of civil UAVs as well as their modification, repair and maintenance. Current efforts are to consider risk-based classification or categorisation of UAV operations within their scope mainly because risk-based classification could be prerogative of aviation authorities.

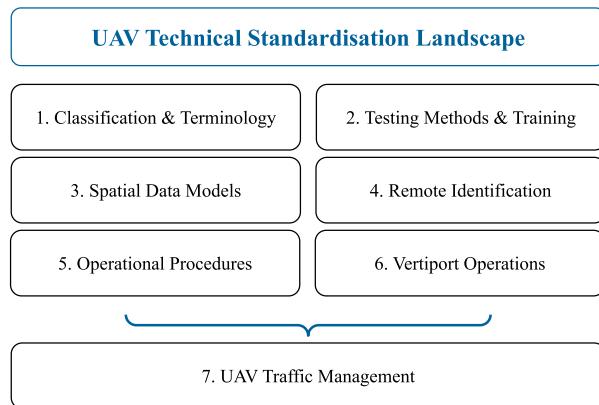


FIGURE 11. Summary of UAV technical standardisation activity domains from the more defined to the most recent, indicating that UTM standards build on all other sub-domains.

B. TESTING METHODS AND TRAINING

As for any new technology, quality plays a significant role in public acceptance. Standardisation committees therefore work alongside industry and governments to define various testing methods to ensure all manufacturers and operators use comparable benchmarks. Moreover, most of standards under this scope devise the minimum requirements for various systems and subsystems with UAVs. While having benchmarks and testing methods is a good initial step, it is far from enough without the accompanying training guidelines for personnel as UAVs are expected to operate within populated cities in the near future and hence, safety is paramount.

C. SPATIAL DATA MODELS

While the majority of allowed UAV flights are within the Visual Line of Sight (VLOS), the greater commercial benefit comes from applications that would inevitably require authorisation Beyond Visual Line of Sight (BVLoS). In order to facilitate such transition, standardisation organisations work on defining data structure and models to represent UAVs spatial environment. Such data models include static and dynamic obstacle representation in addition to other elements of the airspace.

D. REMOTE IDENTIFICATION

Identification systems for vehicles, let alone unmanned aerial vehicles, is essential for their safe operation and management. Hence, remote identification is a foundational component of integrating UAVs into the low altitude airspace of cities. With various companies in the market proposing different means of identifying UAVs remotely, SDOs are faced with the challenge of reaching consensus on a unified standardised means of identification.

E. OPERATIONAL PROCEDURES

The standards that follow this theme - mainly international standards, aim to specify the requirements for safe commercial UAV operations within the low-altitude airspace.

Such standards and guidelines include procedures of operation for various UAV scenarios including people-carrying.

F. VERTIPORT OPERATIONS

In contrast to manned aviation where airports are stationary and well-defined, to UAVs and specifically multi-rotor UAVs, every place is a potential airport. In line with this, SDOs are currently working on defining operational standards for UAV vertiports as vertical landing and take-off sites for UAVs.

G. UAV TRAFFIC MANAGEMENT

Finally, building on all the above standards as well as the established aviation and communication standards, UTM-dedicated working groups are the latest addition to most SDOs. UAV traffic management is crucial to ensure compliance and safe operation within the airspace by standardising foundational functions including registration, remote identification, UAV tracking in addition to communication systems and data models as well as geo-limitation and operational procedures. Some notable examples of technical committees include ISO TC20/SC16 WG4 on Unmanned Aerial Systems Traffic Management [12].

VI. CONCLUSION AND FUTURE DIRECTIONS

The recent years have seen a rise in market demand for commercial UAVs as smart IoT-connected devices and platforms. UAVs offer a magnitude of new value-added services through a wide range of applications ranging from monitoring and surveillance to on-demand last-mile delivery and people transport. This rapid growth in demand translates to a foreseeable growth in traffic demand in the near future. Owing to their potential, UAVs are expected to soon be an integral part of our cities, dominating the shared low-altitude airspace. This, in turn, introduces new research challenges in privacy, security and most notably in the safe management of UAV operations.

The main goal of this work was hence to contribute to scientific literature by presenting a holistic study on the current state-of-the-art of the low-altitude airspace and UAV traffic management. The work additionally explored the standardisation landscape in an attempt to highlight the synergies between research directions and standards developments, taking into consideration pressing inherit challenges of UAVs within IoT such as security, data protection and privacy.

One of the observations of the work was that the trends in scientific research show a clear correlation between the development in IoT and sensors technologies and the advancement in commercial UAV applications. Supported by the shift from solely data collection and sensory dominant applications to ones where UAVs interact with the physical environment. Additionally, it is also observed that with advancement in computing paradigms, UAV applications become more sophisticated and, in some cases, require swarms of heterogeneous UAVs to cooperate and hence exercise some degree of autonomy.

This is further supported by the vision of the Single European Sky ATM Research Joint Undertaking (SESAR) in [124] where it is argued that in the near future, most of the flights will be completely autonomous allowing more freedom to piloted aircraft and freeing manned ATC for specific and complex tasks that may with higher risk missions.

Although the promised benefits and added-value enabled by the adoption of IoT and development in UAVs is undeniable, in order to fully realise these conceptual models and proposals, a handful of key challenges need to be addressed.

On one hand, there are the security, privacy and data protection challenges of UAVs as connected smart devices and platforms and on the other, the challenges in their safe integration in the airspace over cities. Our analysis shows that until this day there is no consensus on the regulations, infrastructure nor standards that would govern the safe operation of UAVs within the low—altitude airspace. One other potential direction emphasised is the need of establishing a standardised risk assessment framework dedicated for IoT-connected UAVs, to complement existing risk assessment guidelines, in order to more accurately identify, estimate or quantify and prioritise risk strategies, as a first step in complying with GDPR but also insuring safe UAV operations.

Nevertheless, the recent growth in interest in the domain of UAVs over the past few years from various stakeholders shows promising potential towards the envisioned future where UAVs are an integral part of aviation.

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