Vehicle Configurations, Infrastructures, and Future of Urban Air Mobility: A Review

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Abstract. This paper studies the developments of urban air mobility by a focus on the configurations and flight mechanisms of the different vehicles in this field. This study contains twelve different common configurations in urban air mobility and reviews their advantages and disadvantages in order to provide a road map or prediction of the future of urban air mobility. It also reviews the major challenges in this field like infrastructure and future of urban air mobility along with considering these major issues. At the end of the paper, a summarization is provided to compare the advantages and disadvantages of each configuration considering urban air mobility concerns.

1. INTRODUCTION

Urban air mobility (UAM) is a new topic in the history of aerospace engineering and transportation. Many novel ideas have been introduced so far by many researchers and companies which are making aerial transportation faster and easier. UAM can accelerate the transportation rate, reduce the traffic and costs, and eliminate many of the current problems in transportation. Researches show that it is efficient even considering the emission. Regarding greenhouse gas emissions, under certain boundary conditions, VTOL aircraft for three or more passengers have been shown to produce fewer emissions than combustion engine-powered automobiles and even battery-powered cars. The emissions per passenger kilometer of a fully-loaded VTOL aircraft are stated to be 52% lower than the combustion engine-powered car, and 6% lower than the battery-powered car. In addition, their benefits in terms of travel time are also considerable [1].

Much research has been conducted in this area. Straubinger et al. have studied the developments of urban air mobility considering aircraft requirements, configurations, and their challenges like certificates, regulations and infrastructures [1]. Garrow et al. have also reviewed the urban air transportation, electric and autonomous vehicles (EV, AV). Their review includes eVTOL, vectored thrust, hybrid, wingless, multirotor, and rotorcraft vehicles. Based on their review which is based on about 800 papers, the demand for UAM may actually increase in the near future. Considering the popularity of UAMs, due to the fact that individuals can be more productive in an AV compared to a conventional car, the introduction of AVs into the market will decrease demand for commuter air taxis [2]. Rajendran and Shrinivas have also studied the developments and challenges of air taxi. Based on them VTOL technology can make air taxis be operational from sky ports retrofitted on building rooftops, which makes air taxi service (ATS) a suitable option for everyday travels of a single passenger or a small group of passengers. Like Garrow et al. they have also studied vectored thrust, hybrid, wingless and multirotor vehicles. They have concluded that on-demand aerial transport would be launched in coming years [3]. Liu et al. have also studied the developments of the personal aerial vehicles in the USA and Europe. They see the personal air vehicles (PAV) as a fast on-demand aerial mobility which is a game-changing innovation. Although, based on them it still has serious issues in infrastructure availability, performance, safety, regulation and public acceptance. They have introduced some fundamental concepts of the PAVs and studied related research in the USA and Europe [4].

The development of the UAM and its popularity is not something related to academics only. Investment of some big companies like Boeing and Porsche in this field is also another proof for their bright future. Today there are more than 100 vehicles in various stages of development all over the world and the UAM market will be worth tens of billions of dollars based on Boeing's flight path for the future of mobility report. Along with technical developments they are working on other critical issues like regulations and market acceptance [5].

Based on previous research in the field of aerial systems, the performance of an aerial system can be significantly influenced by its configuration and flight mechanisms [6]. Different configurations of aerial systems have their own advantages and disadvantages which make them suitable for specific missions and applications. Regarding the UAM, many different configurations are being used by different companies. This includes fixed-wing, morphing wing, helicopter, multirotor, and hybrid vehicles. Many rare configurations like gyroplane, magnus effect, cyclocopter, and autogyro are also being used in concepts and real designs. In Spite of a common belief, that considers the vertical takeoff and landing (VTOL) vehicles as the most common classification in the aerial urban vehicles (AUV), numerous horizontal takeoff and landing (HTOL) vehicles are also visible in the list of urban aerial vehicles. This paper reviews different AUVs, considering their configurations and flight mechanisms, to illustrate a comprehensive view of the current developments of the AUVs and study their benefits and challenges. Major challenges and the future of the UAM is also studied as a supplement of the topic to provide an updated discussion considering the latest developments.

2. AERIAL URBAN VEHICLE CONFIGURATIONS AND CONCEPTS

Different configurations of AUVs have been introduced so far. Considering the different missions and their requirements, different concepts and configurations are applicable [1]. Fig1 illustrates the classification of aerial urban vehicles.

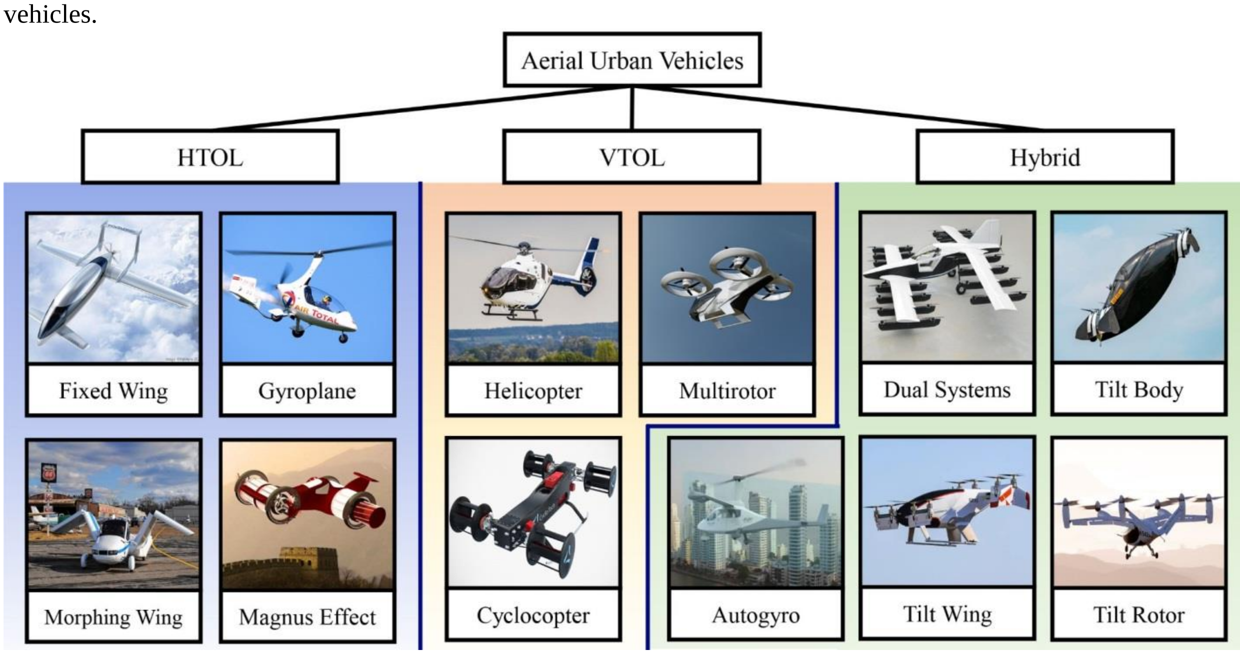

FIGURE 1. Classification of Aerial Urban Vehicles

The most popular configurations in aircraft design are fixed-wings, VTOLs, and hybrids. However, there are about 27 different configurations in aircraft design, including the Magnus effect, moving mass control [6,7,8], cyclocopter, flapping wing, Coanda effect, tail-sitter, lighter than air, and others[6]. In the following sections, we review different AUV configurations, the successful examples, their advantages, and disadvantages. We consider three main categories for AUVs; horizontal take-off and landing, vertical take-off and landing, and hybrids. Based on the currently available

AUVs, each category has been divided into some sub-categories in order to provide a comprehensive and cohesive review.

This classification is based on the flight mechanism and configuration of AUVs. We have tried to consider any available air taxis, personal planes, small aircraft, and conceptual designs of them in order to evaluate the role and importance of configuration in the design of AUVs. Based on published data, information, and companies' claims we have tried to summarize the advantages and disadvantages of each configuration in different aspects.

2.1. Horizontal Take-off and Landing (HTOL)

Although the most suitable configuration for urban applications seems to be VTOL vehicles due to the lack of enough space for runways, still some HTOL aircraft are being used in this area. One major benefit would be their higher capabilities to carry more passengers. Using currently available spaces for small airports, HTOL urban aircraft can be used for short and medium transportation.

2.1.1. Fixed-wing

A majority of AUVs are light and personal vehicles. They mostly can carry up to two passengers and are suitable for personal usage. A good example in this category is Cessna 172 which is considered to be the one of the most popular personal planes in history. As well as Cirrus SR22, Cessna uses a fixed-wing configuration, which provides a simple structure and manufacturing process for it. A fixed-wing configuration provides several advantages, such as the low operating cost, the ability to operate under adverse or hazardous conditions, and the high flight endurance. Generally, fixed-wing AUVs have longer endurance, their flight endurance is essentially up to the efficiency of their configuration[6]. . Fig2 illustrates views of some fixed-wing AUVs.

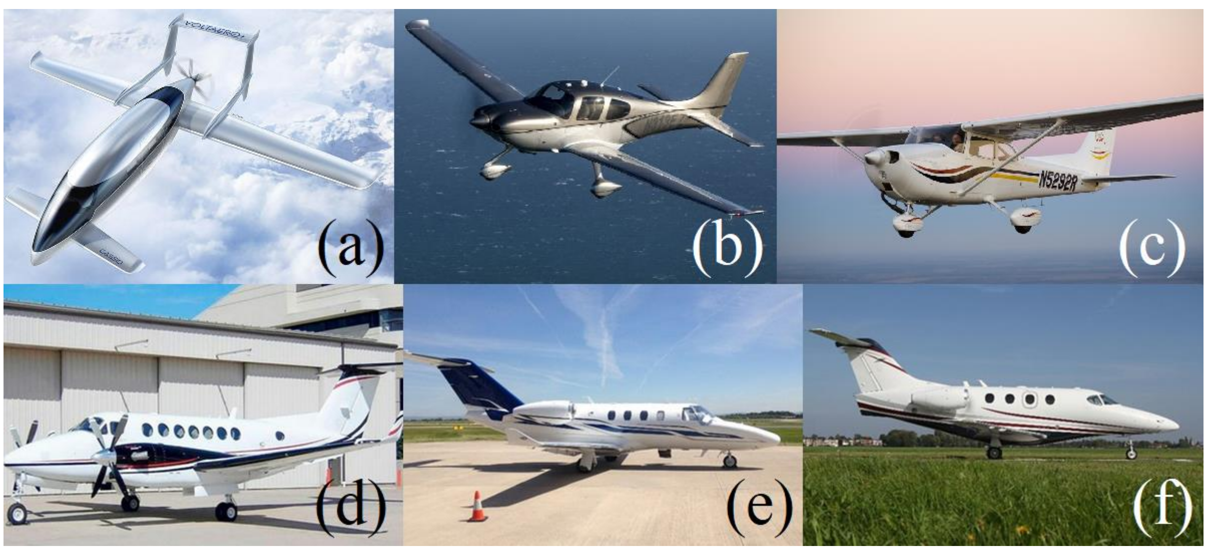

FIGURE 2. View of fixed-wing AUVs (a) VoltAero Casio, (b) Cirrus SR22, (c) Cessna 172, (d) King Air 350, (e) Citation M2, (f) Premier 1

One of the greatest challenges related to fixed-wing aircrafts is the lack of enough space for runways. As they are unable to vertically take-off and land, the applicability of using them in daily transportation would be a challenging problem specifically in big and dense cities. However, currently they are being used in UAM more than any other configuration and there are many small airports around big and small cities for small fixed-wing air taxis.

The family of Cessna (like 172, 182, 206, 208, and 408) and Cirrus are good examples of fixed-wing AUVs which are able to fly up to 2000km and 170km/h[9]. VoltAero's Casio is also a modern fixed-wing hybrid-electric airplane that is designed to carry four to ten passengers for about 3.5 hours. Its wing and canard along with twin tail boom are aerodynamically optimized to have a safe, quiet, efficient, and eco-friendly flight[10]. Other examples are very light jets (VLJ) or personal jets. Which are suitable options for low passenger solutions. Using jet propulsion provides higher speeds and range, and an increased number of passengers can cover their operational costs and make the flight more efficient. VLJs are comparatively popular in short urban air mobility. Fig2 illustrates views of some fixed-wing AUVs.

2.1.2. Flying Car (Roadable aircraft)

Flying cars or roadable aircraft are a category of airplanes that can transform into a car or are suitable to be used on road and as a car. Curtiss Autoplane, which was invented by Glenn Curtiss in 1917, is probably the first attempt to produce such an aircraft [11]. Convair Model 116 and 118 (Fig.3) are also some of the other tries in designing flying cars. Although they had several flight tests, they never experienced commercial success. Looking at the history of flying cars, we may see many other prototypes like Aerocar, Mizar, and Fulton FA-2 Airphibian. Some concepts use fixed-wing configurations, while others have foldable wings to make them compact enough for on road transportation.

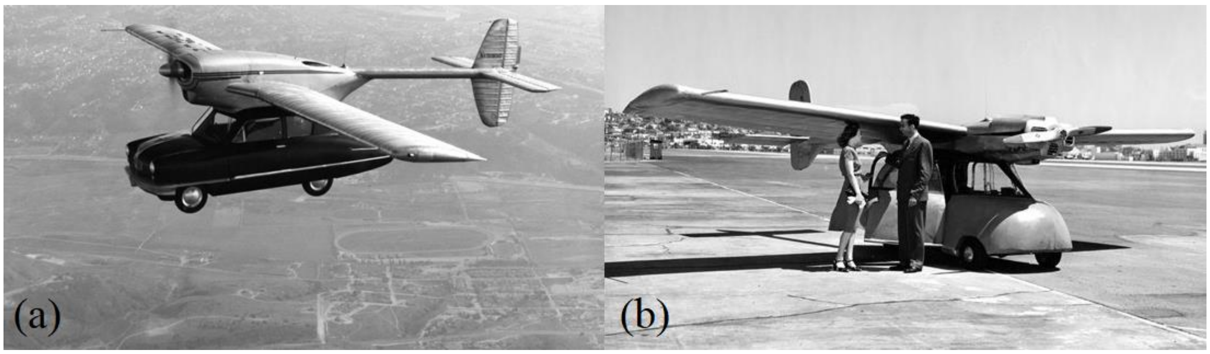

FIGURE 3. Some of the early roadable aircrafts (a) Convair 118, (b) Convair 116

Many concepts in this field are based on morphing or folding wing ideas. This type of wing is usually popular in flying cars. One of the first ideas of such a concept in flying cars dates back to the 1950s when Italian producers of Aerauto PL.5C and American Taylor Aerocar used a morphing wing concept to transform from car to plane mode[12]. In such a concept the wing usually folds in car mode to reduce the size of the vehicle. Fig4 illustrates some flying cars with morphing wing mechanisms.

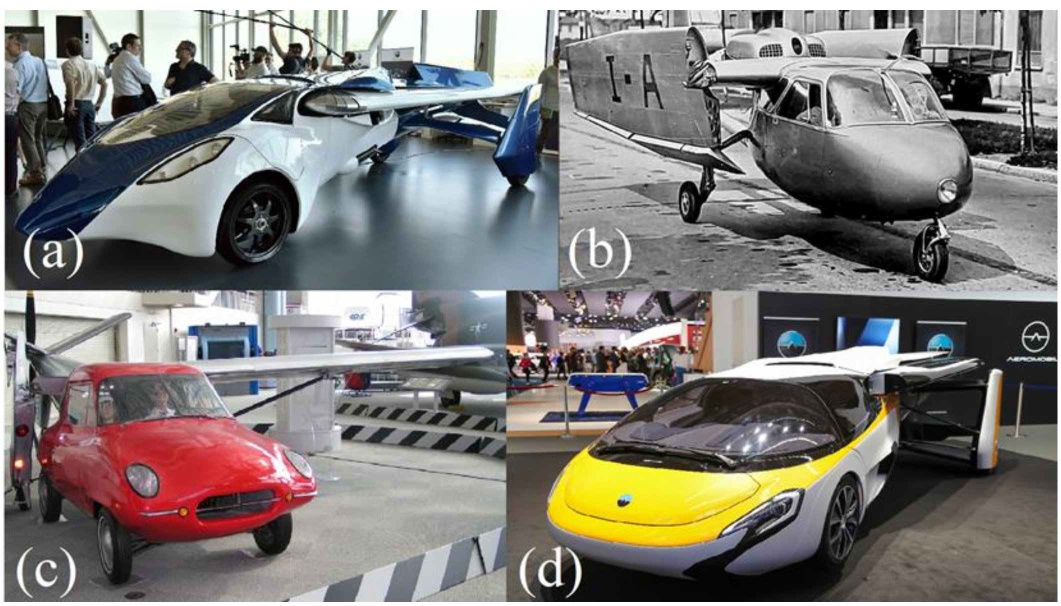

FIGURE 4. (a) AeroMobil 3.0, (b) Aerauto PL.5C, (c) Taylor Aerocar III, (d) AeroMobil 4.0

Terrafugia's Transition is an example of a morphing-wing AUV which uses a morphing-wing structure with a twin tail boom to carry two passengers. Its only engine is placed between cabin and tail which provides it with a speed of about 160km/h. The transition which is a flying car, after numerous prototypes and primary version, recently obtained an FAA Special Light-Sport Aircraft (LSA) airworthiness certificate. Its morphing wing design provides it with the capability to transform into a car to be used on road[13]. Fig5 illustrates different views of the Transition.

FIGURE 5. Different views of Transition (a) flying mode, (b) car mode [13]

2.1.3. Magnus Effect

There are a few concepts around Magnus-effect in air taxis, one example is the iCar concept, which is a car-plane concept for one-person use. iCar uses a Magnus wing to produce lift along with two rotors that can be embedded in the tires. It is powered by a gas turbine located in the rear wings. in driving mode, this engine feeds an electrical generator, through which the wheels are motorized. in flying mode, the engine continues to drive the electrical generator but also provides direct mechanical power to the wing's propellers, whose movement is also partially driven by electrical engines to make it more responsive to piloting and modulations in power. A rear principal set of telescoping Flettner rotors are hidden within oversized wheels when 'iCar' is used as a vehicle. When it is used as an aircraft, these wings telescope outward, and the hubcaps of the front wheels swivel forward to become propellers. The biggest advantage of using spinning cylinder wings is size efficiency [14]. Fig.6 illustrates a view of the iCar concept.

FIGURE 6 iCar Magnus-effect-based car-plane [14]

The significant advantages of a Magnus-effect mechanism are high-lift force or relatively high wing-loading and stall resistance in some specific types of Magnus wings. But using Magnus wings and rotors is more complex compared to a conventional wing and needs additional control mechanisms. The gyroscopic effects may help to increase stability but make major issues in control particularly in low airspeeds (in low Raynolds numbers and specific ranges of velocity ratios, a negative Magnus force may cause the lift to break down). Due to this, there is a need for other control mechanisms like control surfaces to control the roll.[6].

2.1.4. Gyroplane

Gyroplane is one of the oldest concepts in this field. One of the examples in this field comes back to the 1930s when Autogiro Company of America AC-35 was designed to provide a roadable plane solution for short travels. Although it was not a successful attempt, it opened the way for many other similar concepts. Gyroplanes look similar to helicopters but there are major differences between them. The main difference is that in a gyroplane the rotor is not powered and it is only used for lift production while in helicopters the rotor is powered and is responsible for providing thrust and propulsion. The main source of propulsion in a gyroplane is the propeller at the rear of the plane. The other difference is that gyroplanes are HTOL planes with short runways while helicopters are VTOL aircrafts. In contrast, gyroplanes have more simple structure compared to helicopters and are easier to fly. Considering expenses, gyroplanes are comparatively cheaper than helicopters.

After AC-35 many other examples were introduced in this field. Just to mention some examples we can mention Butterfly Super Sky Cycle which is a lightweight gyroplane for just one passenger. It can fly with 7.5 gallons of fuel with up to 10 gallons of reserved fuel which provides the passenger with up to 200km range and maximum speed of

136km/h[15]. Sar is another example from ParavarPars, which has seats for two passengers. It can fly for up to 4 hours with an average speed of 100km/h which provides the maximum range of 400km [16]. PAL-V Liberty is one of the latest gyroplanes which is designed for two passengers and is able to fly with the maximum speed of 160km/h for up to 4 hours which provides a range of 400-500km [17]. Fig7 illustrates some examples of gyroplanes.

FIGURE 7 Examples of gyroplanes (a) ParavarPars Sar, (b) PAL-V Liberty, (c) Butterfly Super Sky Cycle, (d) Autogyro Company of America AC-35

2.2. Vertical Take-off and Landing (VTOL)

Vertical take-off and landing vehicles can be considered as the most popular category of the UAM. They are able to hover flight, they do not need any runway and are suitable for personal use and few passengers. Due to the critical issues in the infrastructure section, and the fact that there are not enough airports for HTOL aircrafts specifically for urban applications, and short distances they seem to be the best solution. In the following section different VTOL configurations including helicopters, multirotors, and cyclocopters have been reviewed.

2.2.1. Helicopter

Helicopters consist of a rotor with one or more blades that are controlled by a swashplate mechanism and a fan-tail or stabilizing propeller. To overcome the reaction torque resulting from the rotation of the propeller, usually, a tail with a propeller or fan is applied to produce a resistant torque. Moreover, the speed of this fan determines the yaw motion. In helicopters, pitch and roll motions can be achieved by using a swashplate. Like other VTOLs, helicopters have remarkable capabilities to perform vertical take-off, landing, and hovering flight in complex and unknown environments at low altitudes and speeds. Because of these advantages, helicopters have a variety of military and civil applications. These drones have the most challenging control systems due to their complex swash-plate mechanism, gyroscopic effects, and stabilizing tail-rotor [6].

Helicopters are probably the most successful commercial vehicles in UAM, they are common in many countries and are being used for many applications including transportation, inspection, survey, agriculture, search and rescue and delivery [6]. Amongst many active companies in this field we can mention Air Methods Corporation, Alpine Helicopters Inc., Bristow Helicopters Limited, Carson Helicopters Inc., Erickson Incorporated, Gulf Helicopters Company, Heli Air Limited, PHI Inc., Paramount Business Jets, and Abu Dhabi Aviation. Recently Uber, the famous transportation company, has also started to offer helicopter transportation. So far, it is only available at New York city and can take passengers to the JFK airport in eight minutes [18].

2.2.2. Multirotor

Multirotors are typically limited in cruise speed, less efficient during cruise flight, and therefore have a shorter range compared to other configurations. However, they naturally have very good hover and VTOL characteristics [1]. In addition they have a simple structure and are easy to build and maintain. Furthermore, they have a good potential to be used with electrical motors. A significant portion of the eVTOL industry belongs to the multirotors or hybrid multirotors. As well as many VTOL aircrafts they benefit from vertical and hover flight which makes them very suitable for urban applications.

Due to their numerous advantages, many companies are working on developing urban solutions based on multirotor configuration. They can be found in many forms including bi-rotor, tri-rotor, quadrotor and so on. As some examples we can mention Johnson et al. concepts. They have provided some VTOL air taxi concepts for a wide range of applications including single passenger, six-passenger and fifteen-passenger [19,20]. Fig.8 illustrates their concepts.

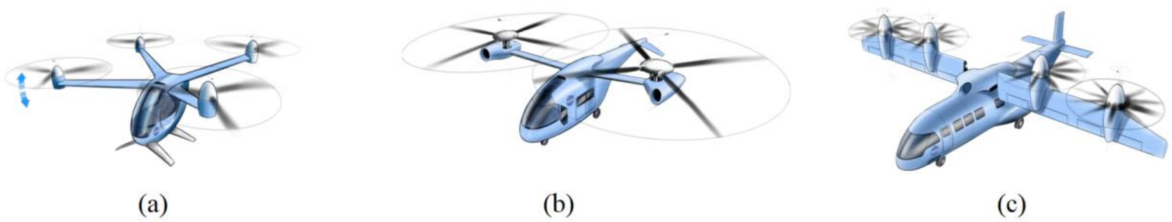

FIGURE 8 Different air taxi concepts by Johnson et al. (a) single-passenger quadrotor, (b) six-passenger bi-rotor, (c) fifteen-passenger hybrid aircraft [20]

Many big corporations have also started to work on multirotor urban air mobility solutions, amongst them we can mention CityAirbus and CityAirbus next gen. Fig9 illustrates some of the well-known multirotor aircrafts.

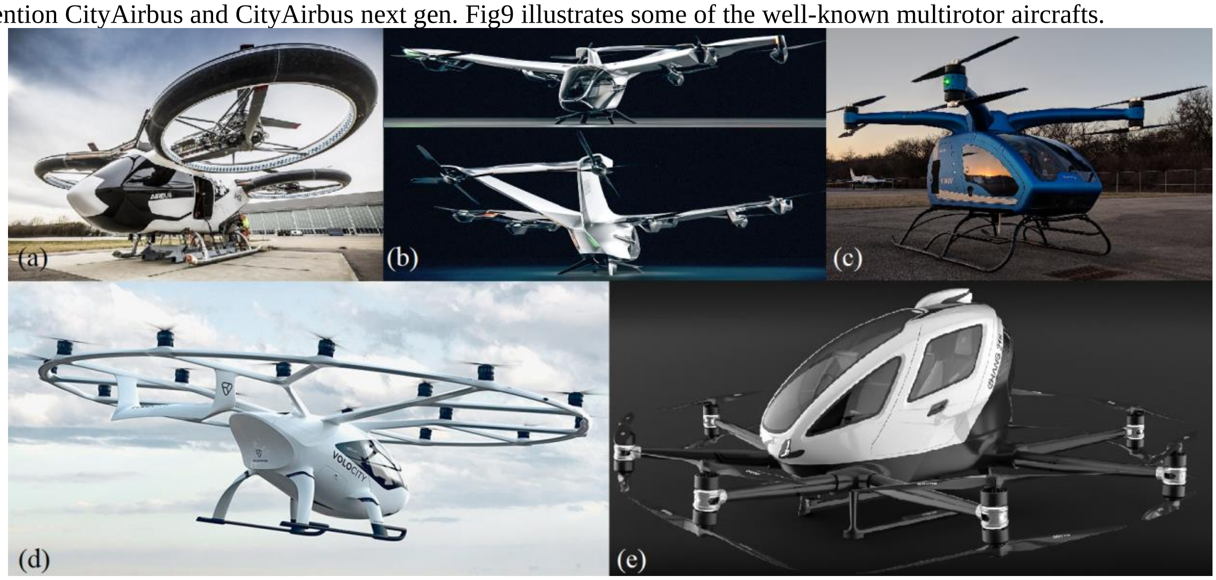

FIGURE 9 Examples of multirotor UAM solutions (a) CityAirbus, (b) CityAirbus Next Gen, (c) Moog Surefly, (d) Volocopter VoloCity, (e) Ehang 184

Airbus has designed a multirotor UAM aircraft with capacity for four passengers and 15 minutes endurance with the cruise speed of 120km/h. The next generation of the CityAirbus uses a novel design with a combination of a fixed-wing structure, but it does not have any control surfaces [21]. A similar vehicle is also designed by Boeing by the name of Boeing Passenger Air Vehicle [22]. Volocopter VoloCity is another example which by using eighteen electric rotors is able to carry two passengers. VoloCity has an endurance of about 0.5 hours which provides a range of 35km [23]. Another example which uses a quadrotor configuration with coaxial rotors is Moog SureFly. It has a range of about 110km and can carry up to two passengers using its electrical rotors. Ehang 184 is another commercial example in this category. It can carry up to two passengers for a range of 35km with its eight electric rotors [24]. Some other companies like Audi have also started to work in this field. Audi Pop Up Next is a conceptual design of an electric flying vehicle which was introduced by Audi at Geneva Motor Show 2018. This concept uses a quadrotor configuration which can be attached to a two-passenger automobile in order to provide flight capability.

2.2.3. Cyclocopter

A cyclocopter uses multiple wings in the shape of fins or blades, mounted on a rotating axis like a series of pedals to generate lift force. In cyclocopters, the rotors move like a watermill or bicycle pedals and this is the reason behind their name [6]. One of the cyclocopter UAMs belongs to the Cyclotech company. Cyclotech uses cyclo-rotors as the main propulsion system, with target ranges around 80-120km, enabling a more compact design of the aircraft, and therefore reducing the direct operating cost compared to existing concepts. Using such a concept provides them with 360-degree thrust control, maneuverability, and agile control. The 360-degree control of the cyclo-rotor is achieved by controlling the blades' angle of attack that enables vertical take-off and horizontal cruise flight. Fig10 illustrates the mechanism of thrust control in cyclo-rotors [25].

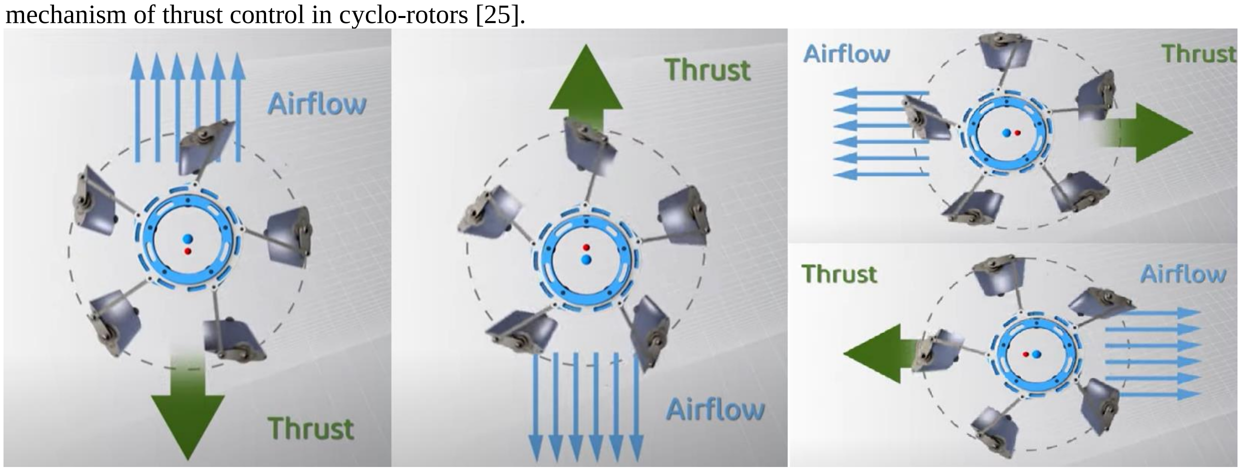

FIGURE 10 Thrust control mechanism in cyclo-rotors [25]

FIGURE 11 Thrust control mechanism in cyclo-rotors [25]

In addition, precise thrust vector control of the cyclo-rotor allows a smooth transition phase without any banking of the aircraft or the need to change the attitude of the aircraft. The performance of cyclo-rotors increases with rising speed. The energy consumption in cruise flight mode reduces in comparison to the hover mode. Thus, making the cyclo-rotor the ideal propulsion system for mid-range flight missions. In comparison to fixed-wing, tilt-wing, or tilt-rotor systems, aircraft with CycloRotors as the main propulsion system offer a reduction of the aircraft footprint of up to 75%[25]. A four cyclo-rotor-equipped aircraft (current version) has been claimed to be able to carry about 83kg payload, which makes it suitable for personal urban mobility. An upgraded version is under development to carry up to five passengers [25]. Fig11 illustrates the views of the CycloTech cyclocopter.

2.3. Hybrid

Hybrid systems are combinations of HTOL and VTOL configurations. They usually have the benefits of both groups at the same time, mostly vertical take-off from VTOLs and high cruise speed from HTOLs. The most popular hybrid configurations are dual systems and tilting aircrafts including tilt-body, tilt-wing, and tilt-rotors. The majority of hybrid aerial vehicles face challenges in the transition phase from VTOL to HTOL [6]. The following sections will review hybrid designs in AUVs.

2.3.1. Dual systems

A dual systems aircraft uses a separate power system during each take-off and cruise phase. In each phase one system is deactivated. Generally, these vehicles are composed of a combination of multirotor and fixed-wing configurations. Although they do not have a complex transition phase compared to tilt-wings or tilt-rotors, the unnecessary use of a deactivated system in each phase imposes an extra burden on the system and reduces the efficiency [6].

One of the examples is Ascendance Flight Technology's Atea. This aircraft uses electrical multirotor configuration embedded in a fixed-wing configuration with two extra propulsion systems for horizontal flight. Atea has a range of about 400km and is suitable also for regional flights. It is also designed to be green and quiet [26]. Wisk is also another similar air taxi. It uses a single-rotor fixed-wing configuration along with twelve electrical rotors to provide vertical take-off and landing. It has a speed of 160km/h and a range of 40km [27]. The automobile company Hyundai in cooperation with Uber, are also working on a similar dual-system electrical hybrid air taxi. This air taxi is designed to have a speed of 290km/h and a range of 100km [28]. Tetra aviation’s Mk-5 personal eVTOL is another example of dual system hybrid aircraft. It uses two wings equipped with 32 electrical motors for vertical take-off and another horizontal rotor to help in cruise mode. This single-seat fully electrical aircraft can travel up to 160km with a maximum speed of 160km/h [29]. Fig12 illustrates some examples of the dual-system hybrid UAM solutions.

FIGURE 12. Some examples of dual-system hybrid aircrafts (a) Hyundai-Uber air taxi (b) Wisk (c)Tetra Aviation MK-5

2.3.2. Tilt-Body

In tilt-body configuration, the whole body experiences a tilting or rotation. This configuration has some advantages like high cruise speed and high controllability, however, the major challenge in tilt-body drones, like other hybrid concepts, is their complex dynamics and control during the transition phase [6]. In addition, these aircraft cause serious problems for the passengers regarding a comfortable flight. Opener’s BlackFly is an example of a tilt-body AUV. It uses two wings with eight rotors for propulsion. Wings are equipped with control surfaces to provide the aircraft with better flight control. This all-electric personal aerial vehicle has vertical take-off and landing. During the take-off, landing, and hover flight, its body tilts to a semi-vertical situation to use the propulsion force of the rotors for the nutrition of weight. Such a flight mechanism provides BlackFly with a range of 65km and a maximum speed of 130km/h, although it might not be so comfortable for the passenger [30]. Fig13 illustrates the tilting mechanism of BlackFly.

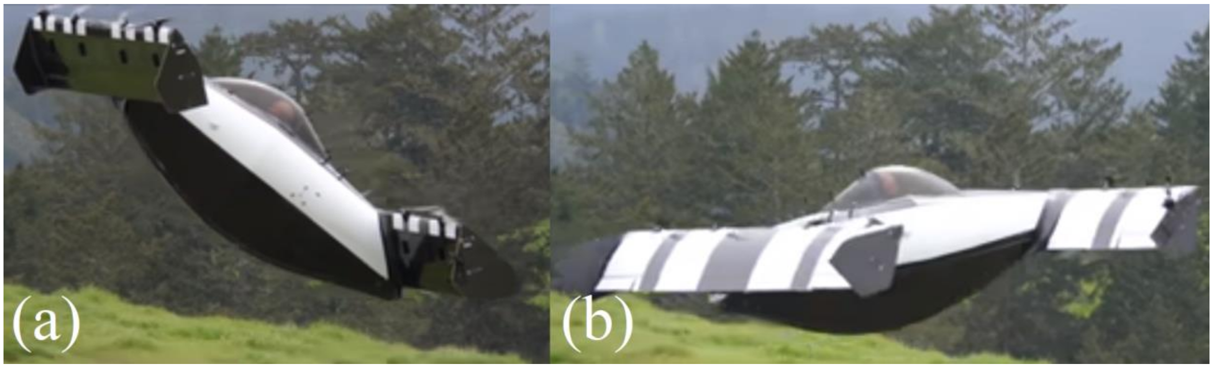

FIGURE 13. tilting mechanism of BlackFly (a)vertical take-off, landing, and hover (b)horizontal flight [30]

2.3.3. Tilt-wing

These aircrafts use a fixed-wing structure along with tilting capability for wings. In these vehicles during the transition phase from VTOL to HTOL the wings and their rotors or connected engines rotate about 90 degrees, but the rest of the body remains fixed during transition. The history of this type of aerial vehicle dates back to the 1960s and 1970s when Boeing developed its first tilt-wing manned aircraft. Compared with the tilt-rotors, tilt-wing configurations generally have a more sophisticated and complicated design. Furthermore, in low-speeds, like hover, takeoff, and landing phase, the wings need to be directed upward, which makes them more vulnerable to crosswind. Therefore, developing a tilt-wing AUV requires additional effort in designing control mechanisms to handle the attitude stabilization. These AUVs can perform vertical flight similar to multirotors and fly with high speed like fixed-wing aircrafts [6]. Of course, the necessary tilting mechanisms result in additional weight and increased system complexity 1].

One of the good examples in this category is the Airbus Vahana. This aircraft has two tilting wings with four electric motors on them. It is capable of flying with up to 220km/h which provides it with a range of 50km [31]. Vahana has passed its flight tests in 2019 and is being prepared for commercial use. Fig14 illustrates the schematic of the Airbus Vahana.

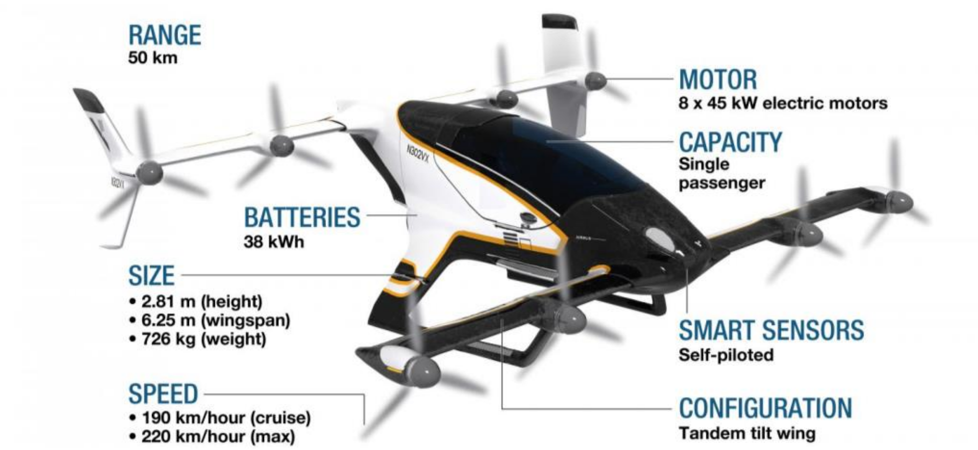

FIGURE 14 Airbus Vahana

2.3.4. Tilt-rotor

Tilt-rotor aircrafts are similar to multirotors in the takeoff phase, as reviewed in the previous sections, after the transition phase, they fly like fixed-wings in the cruise phase. In both main phases the rotors produce the required propulsion, and control surfaces are being used to control the UAS. The original idea of this type of aerial vehicle was first introduced by the Bell Helicopter Company in 1993. Nowadays, tilt-rotor UASs are popular among designers because of their flight efficiency, stability, and simple structure compared to other hybrid configurations. However, tilt-rotors still have complexities and challenges in their design. There are few rotors and engines which are suitable for both vertical and horizontal flight which causes some limitations for tilt-rotor aircrafts. These aircraft can be easily equipped with ducted rotors or coaxial rotors. It is also easy to combine different multirotor configurations with conventional fixed-wing or flying wings to easily benefit from each configuration's advantages [6].

One of the examples in this category is Kitty hawk HVSD eVTOL aircraft which is a tilt-rotor hybrid aircraft which is designed to be quiet enough for urban applications. It is a light-weight one-passenger aircraft with eight tilting rotors which has a range of about 90km [32]. Another example in this part is Lilium, an all-electric vertical take-off and landing jet. Four different generations of Lilium prototypes have been designed and tested to provide up to seven-seater air taxi solutions. Lilium is a tail-less tilt-rotor aircraft that employs a tilting set of ducted engines to provide the required propulsion. Along with fixed wings and canards, the engines are aerodynamically optimized to increase efficiency. Using up to 36 ducted fans, Lilium has a maximum range of 250km. Using ducted fans provides it with a high payload at a low footprint as well as a low noise level. This configuration makes the cruise flight highly efficient for Lilium. In order to increase the efficiency of the aircraft, a variable nozzle system is designed for this aircraft [33]. Fig15 illustrates the tilting mechanism of Lilium in take-off and cruise modes. Some other examples have been also developed by JobyAviation [34], KittyHawk [35], Aston Martin [36] and Archer [37].

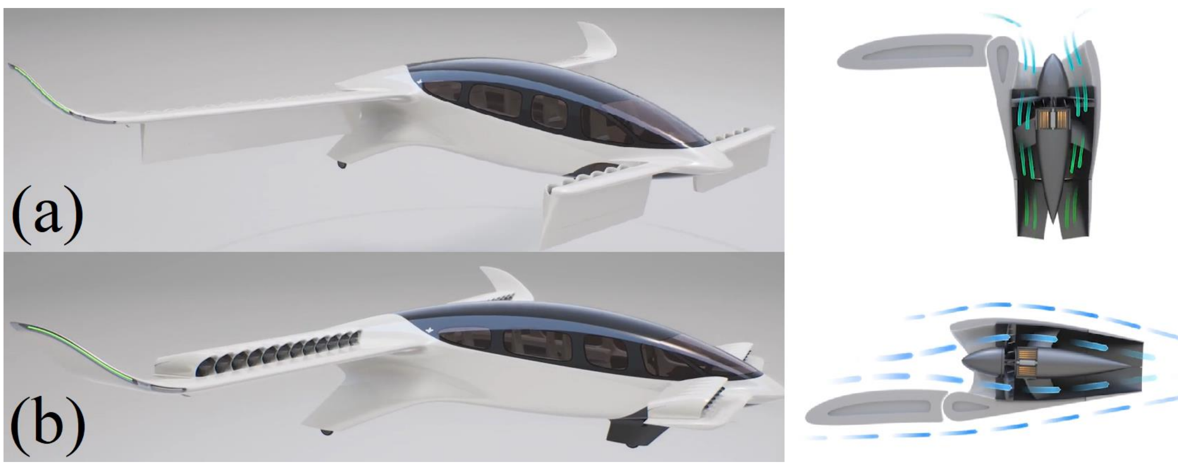

FIGURE 15 Tilting mechanism of Lilium (a)vertical take-off and landing (b)cruise mode [33]

3. INFRASTRUCTURES

The infrastructure is pointed out as one of the main challenges for UAM according to literature review in [38]. Dedicated infrastructure is required to provide [39]:

- Physical infrastructure – places where drones takeoff and land
- Digital infrastructure – communication, navigation, and surveillance (CNS)

The primary function of the physical infrastructure is to facilitate takeoff and landing. It includes airports, airfields, helipads, vertiports, vertistops, road segments, etc. In addition, it should ensure proper ground handling (embarking, disembarking,), servicing (charging/fuelling stations) and maintenance. Based on the number of landing pads, vertiports can be of different sizes, from vertipads (1-2) and vertibases to vertihubs (about 10 landing pads). The total number of landing pads for a medium city is expected to be about 20-45 and for a large city – 40-60 [38]. Detailed guidance on the design of vertiports is provided by EASA and will inform the development of future regulations to ensure safe vertiport operations [40].

A study of the potential of HTOL for UAM shows that runway lengths in the range 100-300 ft are feasible [41]. The trade-off between runway length and available space in the urban area is also modeled taking the Boston urban center as a representative example. It is shown that there is a significant number of potential locations for runways shorter than 300 ft and runways up to 600 ft are possible [41].

Communication, navigation, and surveillance should facilitate unmanned traffic management (UTM) systems. The scalability and constraints of the current air traffic control (ATC) system, ground infrastructure and community acceptance limitations are analyzed in [42]. The requirements for UAM communication and surveillance technologies are explored and specific recommendations are provided by Stouffer et.al [43]. These include command and control

(C2) communication, vehicle to vehicle communication (V2V). Concerns about urban blocking of communications and navigation signals provide area for further research.

Recent advances in communication systems with potential impact include [44]

- Satellite communications (like Inmars L-band low frequency service to enable an Aspire 400 terminal)
- Ground wireless connectivity (5G technology)
- Integration between ground and satellite communication

Current surveillance technologies are summarized in [45]. Cooperative surveillance is possible using current terrestrial and space-based ADS-B at 1090 MHz and Wide Area Multilateration. Alternative options are broadcasts in the 978 MHz band and the emerging concept of ADS-IP. Non-cooperative surveillance for UAM operations can be provided by high-resolution video cameras for daytime vehicle and other object detection and recognition; active and passive radar can be used at night and in adverse weather conditions (rain, fog). New developments in surveillance, such us holographic radar technology, aim to deliver [46]:

- Improved awareness for airspace and ground-based users, such as drones and airport authorities (e.g. reliable drone detection and identification for asset protection; assurance for positioning, navigation and timing);
- Resilience of autonomous systems to degradation in satellite-based (GNSS) navigation

While CNS infrastructure is considered quite mature, there are ongoing laboratory research, field tests, experimental testbeds and trials of UAV/UTM for studying the available technologies in the context of beyond visual line of sight (BVLOS) operations and autonomy [47,48]. DARTeC is developing, in conjunction with a consortium of partners (Blue Bear Systems Research, Thales and Vodafone) and with oversight from the Civil Aviation Authority (CAA), the National Beyond visual line of sight Experimentation Corridor (NBEC).

4. MAJOR CHALLENGES AND FUTURE OF UAM

In contrast to the UAM vehicles, that are developed mostly by individual companies, the problem of developing the general UAM system is far more complex. Beside the development of vehicles and infrastructures this process includes a variety of strongly inter-connected aspects of regulatory, legal, safety, security and public acceptance matter. That is why the development of the UAM transportation systems is addressed by large scale projects that are leaded by organizations like ICAO, FAA, NASA, EASA, Eurocontrol, DLR, etc.

A good effort to overview, describe and analyze the UAM system integration challenges was performed by NASA researchers [45]. The scope of the work is defined in terms of missions, aircraft, airspace, and hazards. As key factors for UAV system consistency the data exchange architecture and communication, navigation, and surveillance requirements are considered. The efforts of NASA, together with industry and academia stakeholders culminated in the development of In-Time System-Wide Safety Assurance Concept of Operations [49]. The aim was to integrate a wide range of safety systems and practices, some of which are already in place and many of which need to be developed. In Europe these types of UAM issues are addressed by the HorizonUAM project. A paper giving initial description of the activities of the project was published by DLR researchers [50]. Similar to the HorizonUAM project is the CORUS-XUAM project, coordinated by Eurocontrol [51].

A major factor for the future success of the UAM is considered to be the public acceptance of the new technology. This factor is the subject of a special investigation that was ordered by EASA [38]. The research shows a largely positive initial public response to UAM, but also concerns related with exposure to risks, in particular when related to safety, noise, security and environmental impact. Another distinguished issue is the limited trust in cybersecurity that probably will require g threat-prevention measures. To address these topics in the CORUS-XUAM project Çetin et.al. propose and investigate the implementation of special mitigations [51]. Especially focused on the cybersecurity is the work of Tang [52].

In addition to the above stated efforts there are also surveys aimed at understanding the challenges and the future perspectives of UAM through personal interviews and workshops with UAM stakeholders [53,54]. In [53] Cohen at.al. overview the history and perspectives of UAM. Once again it is concluded that most critical for the introduction of UAM are the development and verification of vital concepts of operations, as well as the good public acceptance.

CONCLUSION

Considering the reviewed configurations, we can conclude that in addition to common fixed-wing and VTOL configurations, many other categories of aircrafts are also being used in UAM. HTOLs, specifically fixed-wing aircrafts are so popular and classic configurations due to their old history and simple structure. They usually have high endurances, high ranges, and high speeds. The main problem on their way is the need for runway and infrastructures which makes them inappropriate solutions for urban mobility. In contrast they seem to be the best solutions for long transportations. Using a morphing-wing can also empower the fixed-wing aircrafts with higher adaptability level and efficiency, although it may make them more complex. In the category of HTOLs, Magnus-effect planes are also some considerable concepts, they have small size and acceptable efficiency by providing high lifts. In contrast to some aerodynamic issues due to the use of Magnus effect they can provide high stability and resistance. Gyroplanes are also popular for their simple structure and low price. In contrast with other HTOLs they need a shorter runway.

VTOLs are in the core of attention due the lack of enough infrastructures for HTOL configurations. Amongst them, helicopters are being used for many years in different sections including survey, search and rescue, agriculture, and transportation of course. Helicopters are able to hover flight in low altitudes which makes them suitable options in urban environments. But they use a complex system and are not too maneuverable. Their sound pollution is also a major concern. In contrast to helicopters, multirotors have a very simple structure, they are easy to build and maintain. By considering their VTOL capabilities they are one of the best solutions in UAM. in spite of all these benefits, they are less efficient and have low endurance and speed which makes them suitable only for short travels. Cyclocopters are another group of VTOL aircrafts, they use rotors which are capable of producing 360 degree thrust which makes them maneuverable. They also have good range and endurance which makes them suitable for mid-range flights.

Another popular group of aircrafts are hybrids. They benefit from VTOL capabilities along with the high range and endurance of HTOL aircrafts. They do not need a runway which makes them suitable for urban environments, but they may have complex structures and control as tilting aircrafts are. Among tilting solutions tilt-rotors have a more simple structure. Dual systems are also a group of hybrids which are under the attention of companies and researchers. They do not have the complexity of the tilting hybrids specially regarding the transition phase from VTOL to HTOL. But using two separate systems makes them less efficient. Table 1 summarizes the pros and cons of the different UAM aircraft configurations.

TABLE 1. Comparison of the different configurations in UAM

Configuration		Advantages	Disadvantages
HTOL	Fixed-wing	●Simple structure ●High endurance ●High speed ●Cargo capacity	●Need for runway and infrastructure
	Morphing-wing	●More efficiency ●Adaptive flight and robustness ●High endurance ●High speed ●Cargo capacity	●Complex structure ●Complex control ●Need for runway and infrastructure
	Magnus-effect	●Small size ●Efficiency ●High lift ●Stability and stall resistance	●Complex control system ●Negative aerodynamic forces in some specific conditions ●Need for runway and infrastructure
	Gyroplane	●Simple Structure ●Low price ●Short runway	●Need for runway and infrastructure
VTOL	Helicopter	●No need for runway ●Scalability	●Complex structure ●Low maneuverability ●Noise emission
	Multirotor	●No need for runway ●Simple ●Low price	●Low endurance ●Low speed ●Low efficiency in cruise flight

	Cyclocopter	●360-degree thrust control ●Maneuverability ●Smaller size ●Smooth transient phase ●Suitable for mid-range flights	●Small size
Hybrid	Dual system	●No need for runway ●Simple structure ●Simple control ●Longer endurance compared to VTOLs	●Low efficiency ●Extra payload in each phase
	Tilt Body	●No need for runway ●Efficiency ●Longer endurance compared to VTOLs	●Complex transition phase ●Uncomfortable flight
	Tilt-wing	●No need for runway ●Efficiency ●Longer endurance compared to VTOLs	●Complex transition phase ●Complex structure compared to tilt-rotor
	Tilt-rotor	●No need for runway ●Efficiency ●Simple structure ●Longer endurance compared to VTOLs	●Complex transition phase

In addition to the UAM aircraft technology itself, a very important role in the introduction of UAM plays the development of the related infrastructures. The infrastructures can be generally divided into physical infrastructure and digital infrastructure (communication, navigation, and surveillance).

Decisive role for the success of UAM will play the development of sustainable UAM ecosystems, harmonizing the interests of all stakeholders. The development of sound UAM concepts of operations and building of positive public acceptance are key factors to achieve this goal.

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