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A Review of Current Technology and Research in Urban On-Demand Air Mobility Applications

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ABSTRACT

The purpose of this report is to summarize the current technology and challenges facing the market for eVTOL aircraft for urban on-demand air mobility applications. This report has two parts. The first part reviews existing electric drones for on-demand air mobility services for human transportation and package delivery drones. In this section, eVTOL projects are classified and compared by design parameters, specifications, and performance. While electric aircraft are the primary focus, some hybrid-electric and gas-powered aircraft will be used for comparison purposes. The second component reviews research publications discussing optimization and urban strategies for these aircraft. Challenges currently facing the industry are also discussed. These challenges include battery technology, efficiency, and safety. In this section, applications of eVTOL technology and future development are also reviewed.

INTRODUCTION [1]

With a rising population and more cars on the road, travelling across metropolitan areas is slow and wastes energy, fuel, and productivity. Holden and Nikhol (Ref. 1) anticipate people and products moving more quickly and efficiently over medium-range distances with electric-powered aircraft. Through design characteristics and specifications, the performance details of each aircraft vary drastically. In this report we review these characteristics and performance specifications.

This report consists of two main parts. The first discusses forty-four eVTOL projects currently implemented or being tested and designed. Their parameters are discussed in four subsections; design and configuration; motor and battery specifications; takeoff weight and payload capacity; and performance. Relevant data are presented at the beginning of each section. Designs are compared, and the trends shown in the data are reviewed. The second part reviews existing research with three subsections; eVTOL design, battery technology, and on-demand mobility with eVTOL aircraft. These publications discuss current and future trends and challenges for urban on-demand air mobility.

PART I — CURRENT TECHNOLOGY

Aircraft Design and Configuration

Table 1. Aircraft Design and Configuration Specifications

Project Title	Payload Type[1]	Number of Rotors	Tilt-Wing, Ducted[2]	Electric, Hybrid, Other[3]
Advanced Tactics Panther	C	6	-	E
AeroMobil 5.0	P	2	-	H
Airbus Helicopters CityAirbus	P	8	D	E
Airbus Skyways	C	8	-	E
Airbus Vahana A^3	P	8	T	E
AirSpaceX MOBi	P	6	T	E
Astro Aerospace Elroy (Passenger Drone)	P	16	T	E
Aurora eVTOL	P	9	-	E
Aurora LightningStrike	O	24	T D	H
Bartini Flying Car	P	8	D	E
Boeing Cargo Drone	C	8	-	E

Table 1. (Continued)

Project Title	Payload Type[1]	Number of Rotors	Tilt-Wing, Ducted[2]	Electric, Hybrid, Other[3]
Carter Air Taxi	P	2	-	E
Davinci ZeroG	P	8	-	E
Digi Droxi	C	6	-	E
eHang 184	P	8	-	E
Joby S2	P	16	-	E
Joby S4	P	6	-	E
KARI PAV	P	8	-	E
Kármán XK-1	P	8	D	E
Kitty Hawk Cora	P	13	-	E
Kitty Hawk Flyer	P	10	-	E
La Poste Drone	C	6	-	E
Lilium Jet	P	36	D	E
MMIST Snowgoose	C	2	-	O
Moeller Skycar	P	4	D	O
NASA Puffin	P	2	-	E
Opener BlackFly	P	8	T	E
Pop.Up Next	P	8	-	E
Rolls-Royce eVTOL	P	6	T	H
Sikorsky Firefly	P	2	-	E
Solution F	P	1	-	E
Swiss Postal Matternet M2	C	4	-	E
Terrafugia TF-2 Lift+Push	P	5	-	E
Terrafugia TF-2 Tiltrotor	P	2	-	E
Terrafugia TF-X	P	2	-	H
Trek FlyKart 2	P	1	D	E
Urban Aeronautics CityHawk	P	2	D	O
Vimana	P	8	T	H
Volocopter 2X	P	18	-	E
Volocopter VC200	P	18	-	E
Volta Aquinea	O	2	-	E
Workhorse Horsefly	C	8	-	E
Workhorse Surefly	P	8	-	O
XTI Trifan	P	3	D	H

[1] Passenger (P), Cargo (C), Other (O)

[2] Tilt-Wing (T), Ducted (D)

[3] Electric (E), Hybrid-Electric (H), Other (O)

The designs for the aircraft listed in Table 1 can vary dramatically depending on the project. Designs can be divided into two main categories. The first group uses open-mounted, fixed motors as the primary source of lift. The second group vectors thrust to different configurations while in takeoff and landing and during cruise.

In the first category, the most common configuration uses only horizontally-mounted fans to generate lift, like a common drone. This type of design is simple but can limit the range and cruising speed of the aircraft, to be discussed in further detail in a later section. This group can be further simplified into three subgroups. In this report, these three subgroups will be labelled as multicopters, helicopters, and winged multicopters. This report reviews twenty-seven fixed motor designs as shown in Table 1.

Out of the twenty-seven fixed motor designs reviewed, sixteen projects fit the multicopter architecture. For the purposes of this report, this is defined as an aircraft that has only horizontally mounted props for vertical thrust. These props can be configured in several ways. For example, as noted by the World eVTOL Aircraft Directory, Ullman et al, and eHang (Ref. 2, 3, 4), the eHang 184 use a quadcopter-style design with eight motors mounted X-style on four corner supports. Similarly, according to the World eVTOL Aircraft Directory, Matternet Inc., and SureFly, (Ref. 2, 5, 6), three other designs use an X architecture; the Workhorse Surefly, Swiss Postal Matternet M2, and the Pop.Up Next. According to the World eVTOL Aircraft Directory, Advanced Tactics Inc., MediaRoom, and Passenger Drone, (Ref. 2, 7, 8, 9), the Advanced Tactics Panther, Boeing Cargo Drone, Astro Aerospace Elroy Passenger Drone, and Kitty Hawk Flyer fix their props on two rails mounted above the main fuselage. According to the World eVTOL Aircraft Directory and Ullman et al (Ref. 2, 3), two Volocopter aircraft, the 2X and VC200, mount their props above the fuselage using a branching architecture surrounded by an outer circular framework. According to Airbus, Workhorse, Davinci, and DPDgroup (Ref. 10, 11, 12, 13), the Airbus Skyways and Workhorse Horsefly delivery drones have traditional octocopter layouts, while the Davinci ZeroG and La Poste DPD Group Drone use traditional hexacopter designs; each having twelve and six open-mounted props, respectively. Uniquely, the Kármán XK-1 uses a ducted hexacopter architecture for lift and uses two additional vertically-mounted ducted fans for forward thrust as shown on the World eVTOL Aircraft Directory (Ref. 2).

There are five helicopter designs discussed in this report; the Carter Aviation SR/C Air Taxi; MMIST Snowgoose CQ-10B; Sikorsky Firefly; Solution F; and the Volta aircraft (Table 1). According to Carter (Ref. 14), the SR/C Air Taxi is a winged helicopter, using one central helicopter rotor for lift during takeoff, landing, and hover, while the high aspect ratio wing provides the lift during cruise conditions. This is made possible with the use of a rotating, vertically mounted motor in the rear providing forward thrust during cruise and preventing fuselage rotation during takeoff, hover, and landing. According to MMIST (Ref. 15), the Snowgoose CQ-

10B does not use wings for lift, however the design uses a fixed vertically-mounted motor in the empennage for forward thrust. According to the World eVTOL Aircraft Directory (Ref. 2), the Sikorsky Firefly and Volta aircraft follow a traditional helicopter design with single lift rotor and tail rotor systems, while the Solution F uses two counter-rotating rotors for lift and a rudder at the tail for yaw control.

Per the World eVTOL Aircraft Directory (Ref. 2), six aircraft follow a winged multicopter design; the AeroMobil 5.0, Aurora eVTOL, Kitty Hawk Cora, NASA Puffin, Terrafugia TF-2 Lift + Push, and the Opener BlackFly. The AeroMobil is a winged flying car design with two horizontally-fixed motors at the wingtips. The Aurora eVTOL, Kitty Hawk Cora, and Terrafugia TF-2 Lift + Push use horizontally-mounted motors for vertical takeoff and landing. During cruise, the aircraft use wings and a vertically-mounted thrust motor in the rear for added efficiency. The NASA Puffin and Opener BlackFly have fixed motors on fixed wings and rotate the chassis to generate thrust either vertically for takeoff and landing or near horizontally for cruising flight.

The second group of aircraft studied uses thrust-vectoring in the form of rotating wings, ducted fans, or both (Table 1). Of the aircraft mentioned in this report, sixteen aircraft fit this description. Different designs use one or both of these characteristics, which generally offer a longer range and faster cruise speed relative to the fixed-motor configurations. As Olcott discusses in Reference 16, ducted fans increase thrust for a motor with the same output and reduce noise. However, as noted by Finger et al in Reference 17, these ducts can add weight and drag to the design. As Duffy et al discuss in Reference 18, the advantage of tilt-wing designs is that they allow for reduced drag during cruise compared to fixed-rotor designs. The mechanisms used to vector the thrust increase the weight of the propulsors. A disadvantage however is the increased complexity and therefore lower reliability.

As referenced by the World eVTOL Aircraft Directory, Bartini, Lilium, Moorman, XTI Aircraft Company, and Yoeli (Ref. 2, 19, 20, 21, 22, 23), and shown in Table 1, six of the studied designs incorporate ducted fans; the Bartini Flying Car, Lilium Jet, Aurora Lightning Strike, Urban Aeronautics CityHawk, XTI Aircraft Trifan 600, and the Moller Skycar M400. Five of these aircraft have ducts that rotate to different configurations for takeoff, hover, and landing, and cruise conditions. These aircraft are the Bartini Flying Car, Lilium Jet, Lightning Strike, Trifan 600, and Skycar M400. The proof of concept CityHawk has fixed ducted fans for lift and uses vanes in the ducts to direct the thrust.

14 aircraft use wings for lift according to the World eVTOL Aircraft Directory, Lilium, XTI Aircraft Company, AirSpaceX, Stoll et al, Lovering, and Vimana Global (Ref. 2, 20, 22, 24, 25, 26, 27). These aircraft are the MOBi AirSpaceX, Airbus Vahana A^3, Joby S2, Joby S4, Lilium Jet, Digi Robotics Droxi, KARI PAV, Terrafugia TF-2 Tiltrotor, Terrafugia TF-X, Vimana Global AAV, Aurora Lightning Strike, Rolls-Royce eVTOL, Moller Skycar M400 and XTI Trifan 600 (Table 1). The AirSpaceX, Vahana A^3, Rolls-Royce, and AAV have open-mounted motors on rotating wings. These wings are rotated vertically during takeoff, landing, and hover, and are rotated horizontally during cruise. The Joby S2, S4, Digi Robotics Droxi, Moller Skycar, Lilium Jet, Trifan 600, Terrafugia TF-2 Tiltrotor and TF-X have fixed wings and use mechanisms to rotate the motors. The XTI Trifan 600, Moller Skycar M400, and the Lilium Jet use both ducted fans and rotating motors over fixed wings. The Aurora Lightning Strike uses ducted fans mounted below rotating wings for thrust-vectoring during vertical takeoff and landing.

Aircraft Motor and Battery

Table 2. Aircraft Motor and Battery Specifications

Project Title	Motor Output^1 (kW)	Total Output^2	Battery Density^3	Battery Capacity^4
Advanced Tactics Panther	-	-	-	-
AeroMobil 5.0	-	75	-	-
Airbus Helicopters CityAirbus	100	800	-	110
Airbus Skyways	-	-	-	-
Airbus Vahana A^3	45	360	200	-
AirSpaceX MOBi	-	-	-	-
Astro Aerospace Elroy (Passenger Drone)	-	-	-	-
Aurora eVTOL	-	-	-	-
Aurora LightningStrike	125 (18x), 90 (6x)	2790	-	-
Bartini Flying Car	40	320	200	64
Boeing Cargo Drone	-	-	-	-
Carter Air Taxi	-	-	300	-
Davinci ZeroG	-	-	-	52.8
Digi Droxi	0.8	4.8	-	-
eHang 184	19	152	140	17
Joby S2	-	-	-	-
Joby S4	-	-	-	-
KARI PAV	-	-	-	-
Kármán XK-1	30	240	-	-
Kitty Hawk Cora	-	-	-	-
Kitty Hawk Flyer	-	-	-	-
La Poste Drone	-	-	-	-
Lilium Jet	-	-	-	320

Table 2. (Continued)

Project Title	Motor Output[1] (kW)	Total Output[2]	Battery Density[3]	Battery Capacity[4]
MMIST Snowgoose	-	-	-	-
Moeller Skycar	-	535	-	-
NASA Puffin	44	88	-	-
Opener BlackFly	-	-	-	12
Pop.Up Next	20	160	-	70
Rolls-Royce eVTOL	-	500	-	-
Sikorsky Firefly	-	1416	-	-
Solution F	20	40	-	-
Swiss Postal Matternet M2	-	-	-	-
Terrafugia TF-2 Lift+Push	-	-	-	-
Terrafugia TF-2 Tiltrotor	-	-	-	-
Terrafugia TF-X	-	-	-	-
Trek FlyKart 2	-	-	-	9.6
Urban Aeronautics CityHawk	-	-	-	-
Vimana	60	480	-	-
Volocopter 2X	2	32	-	-
Volocopter VC200	3.9	70.2	-	-
Volta Aquinea	-	90	-	22
Workhorse Horsefly	-	-	-	-
Workhorse Surefly	-	150	-	15
XTI Trifan	-	750	-	-

[1] Per Motor, kW

[2] Overall Power, kW

[3] Battery Energy Density, Wh/kg

[4] Battery capacity, kWh

Battery technology poses a challenge for eVTOL aircraft. As Luo et al discusses in Reference 28, the theoretical limit for the lithium ion batteries currently used in these aircraft is 250 Wh/kg. As the data in the above table show, all but one aircraft has an energy density below this value (according to Carter in Reference 14, the Carter SR/C Air Taxi has only been prototype tested and has not yet been commercially developed).

Different design configurations have differing requirements for power output of their motors. As mentioned by the World eVTOL Aircraft Directory, Ullman et al, Bartini, Vimana Global, Pradeep and Wei, and Volocopter (Ref. 2, 3, 19, 27, 29, 30) and shown in Table 2, the eHang 184, Kármán XK-1, Pop.Up Next, Volocopter 2X, and VC200, with their horizontally mounted open props, require far less power than their thrust-vectoring counterparts. This can be seen in Table 2; while passenger-carrying multicopters have an average total output of 113 kW, the thrust-vectoring aircraft use an average of 490.8 kW of total output. However, of the aircraft studied in this report, passenger-carrying thrust-vectoring aircraft have a higher passenger capacity than passenger-carrying multicopters. When taking passenger capacity into account, multicopter aircraft have an average of 79.7 kW output per passenger, while thrust-vectoring aircraft have an average output of 123.1 kW per passenger. Helicopters, similarly to multicopters, have an average total output of 90.5 kW and 66.9 kW per passenger. An important parameter to keep in mind is how the motor thrust is being applied in each aircraft. With non-winged multicopter designs, nearly all available thrust is being forced in the downward direction to keep the aircraft flying. Therefore, a higher percentage of the energy capacity is dedicated to vertical lift and not horizontal thrust as there are no wings to relieve the motors of this required vertical force generation. As mentioned earlier and shown in Table 1, there are sixteen such multicopter designs discussed in this report. For example, in the case of the Vimana Global AAV the wings generate lift, however, the motor output is higher to account for the necessary thrust to keep the aircraft from stalling. This report discusses nineteen multicopter and thrust-vectoring aircraft that incorporate wings, shown in Table 1. Although most thrust-vectoring aircraft incorporate wings, this is not always the case. For example, the Bartini Flying Car has no wings; only eight rotating ducted fans. In this case, the thrust vectors increase to account for the lift and thrust simultaneously, which can be done with less power output using a ducted fan rather than open motors. Bartini in Reference 19 claims a lift-to-drag ratio of 0.8, allowing more of the thrust force to be dedicated to horizontal flight during cruise.

For different gross weights of aircraft, different amounts of power are required to get the aircraft off the ground and flying, which in turn depends on the design of the aircraft. With many projects still in development, data on battery capacity and energy density are limited. These capacities currently range from 140 to 300 Wh/kg (Table 2). According to Ullman et al (Ref. 3), it can be generally inferred eVTOL aircraft with maximum gross takeoff weights of 1500 kg will require 120 horsepower (89 kW) of output for a range of 90 miles (145 kilometers). As aircraft approach a max gross takeoff weight of 1800 kg, the required battery mass increases more significantly.

The battery capacity of the aircraft is dependent on the mass, volume, and type of battery used on the aircraft. The data shown in Table 2 gives the total capacity for the respective aircraft. The requirement for battery capacity is mainly determined by the engine power, and subsequently, the maximum takeoff weight.

Takeoff Weight and Payload Capacity

Table 3. Takeoff and Payload Specifications

Project Title	Passenger Capacity	Payload Capacity (kg)	Max Gross Weight (kg)
Advanced Tactics Panther	-	3.2-10	-
AeroMobil 5.0	4	-	-
Airbus Helicopters CityAirbus	4	-	-
Airbus Skyways	-	4	-
Airbus Vahana A^{3}	2	200	815
AirSpaceX MOBi	4	499	-
Astro Aerospace Elroy (Passenger Drone)	2	120	260
Aurora eVTOL	2	225	800
Aurora LightningStrike	-	737	5900
Bartini Flying Car	4	400	1100
Boeing Cargo Drone	-	225	-
Carter Air Taxi	4	499	2494.8
Davinci ZeroG	1	150	240
Digi Droxi	-	5	14
eHang 184	1	100	260
Joby S2	2	177	907
Joby S4	4	-	-
KARI PAV	1	-	500
Kármán XK-1	2-8	200	-
Kitty Hawk Cora	2	181	-
Kitty Hawk Flyer	1	-	-
La Poste Drone	-	4	-
Lilium Jet	5	-	2000
MMIST Snowgoose	-	260.8	-
Moeller Skycar	4	-	-
NASA Puffin	1	91	-
Opener BlackFly	1	113	-
Pop.Up Next	2	-	-
Rolls-Royce eVTOL	5	-	-
Sikorsky Firefly	2	-	929.9
Solution F	1	75	245
Swiss Postal Matternet M2	-	2	11.5
Terrafugia TF-2 Lift+Push	4	500	4080
Terrafugia TF-2 Tiltrotor	4	500	3630
Terrafugia TF-X	4	-	-
Trek FlyKart 2	-	-	-
Urban Aeronautics CityHawk	2	-	1930
Vimana	4	400	1050
Volocopter 2X	2	160	450
Volocopter VC200	2	150	450
Volta Aquinea	1	10	520
Workhorse Horsefly	-	4.5	-
Workhorse Surefly	2	181	680
XTI Trifan	6	816	2404

The main parameters that affect the payload of eVTOL aircraft are battery weight and capacity, the motor output, and the configuration of the design. The higher the energy density of the batteries, the lower the mass for an equal amount of energy, and therefore a higher mass can be dedicated to the payload of the aircraft. The higher the motor output, the more thrust can be generated. The configuration determines how much motor output (and therefore energy stored in the batteries) is required to fly the aircraft, which can be increased or decreased based on aerodynamic optimization for each type of design.

Table 3 shows the XTI Trifan 600 and Vimana Global AAV hybrid aircraft have some of the highest payloads out of the sample of aircraft. This is due to their higher thrust power output due to their hybrid designs. In terms of fully electric aircraft, the winged, ducted fan, and thrust-vectoring aircraft have much higher payload capacities than their horizontal-mounted motor counterparts. For example, the ducted fan Bartini Flying Car has a 400 kg capacity versus the eHang 184's 100 kg capacity. Note, from Ullman et al and Bartini (Ref. 3, 19) and shown in Table 2, both aircraft have 64 kWh and 17 kWh battery capacities, respectively. This shows a clear trend; higher battery capacities lead to higher payload capacities. This result is quite trivial. Since the Bartini Flying Car has a four-passenger capacity compared to the single passenger eHang, the larger size requires a larger battery to carry the necessary payload.

The strongest fully electric design comes from the Lilium Jet. The design combines all three of the aforementioned parameters giving the aircraft an estimated 5 passenger payload, the highest of the sampled projects. This further supports the trend of these parameters leading to a higher payload. As additionally noted in Reference 3, its 320 kWh battery capacity (Table 2) is high enough to facilitate such a heavy payload.

Aircraft Performance

Table 4. Aircraft Performance Specification

Project Title	Cruise Speed (kph)	Flight Time (min)	Range (km)
Advanced Tactics Panther	113[1]	5-29[1]	-
AeroMobil 5.0	-	-	700
Airbus Helicopters CityAirbus	120	15	30
Airbus Skyways	-	-	-
Airbus Vahana A^3	230	26	100
AirSpaceX MOBi	241	25	104
Astro Aerospace Elroy (Passenger Drone)	70[1]	25	29
Aurora eVTOL	180	-	-
Aurora LightningStrike	555	-	-
Bartini Flying Car	300	30	150
Boeing Cargo Drone	-	-	-
Carter Air Taxi	282	-	256
Davinci ZeroG	70[1]	25[1]	-
Digi Droxi	100 (150[1])	90	-
eHang 184	60	25	38
Joby S2	322	60	322
Joby S4	225	-	246
KARI PAV	200	15	50
Kármán XK-1	450[1]	-	-
Kitty Hawk Cora	180	19	100
Kitty Hawk Flyer	-	12-20	-
La Poste Drone	30[1]	-	25
Lilium Jet	300	60	300
MMIST Snowgoose	-	-	-
Moeller Skycar	533[1]	350	1300
NASA Puffin	241[1]	19	80[1]
Opener BlackFly	128[1]	30	64
Pop.Up Next	150[1]	-	50
Rolls-Royce eVTOL	402.3	-	804.7
Sikorsky Firefly	159.3[1]	15	-
Solution F	-	10	-
Swiss Postal Matternet M2	36	-	20
Terrafugia TF-2 Lift+Push	240[1]	-	400
Terrafugia TF-2 Tiltrotor	333[1]	-	555
Terrafugia TF-X	320	-	800
Trek FlyKart 2	83 (102[1])	30	-
Urban Aeronautics CityHawk	270	60	150-360
Vimana	244	-	900
Volocopter 2X	100	27[1]	27[1]
Volocopter VC200	100	-	-
Volta Aquinea	-	40	-
Workhorse Horsefly	80[1]	30	-
Workhorse Surefly	113[1]	60	113
XTI Trifan	555[1]	-	2222

[1] Indicates maximum value

The data presented in Table 4 show most aircraft have similar flight times (18 of which have 25-30-plus minute flight times), but significantly different ranges and cruise speeds. For example, the Volocopter 2X travels at a top speed of 70 kph with 32 kW of power output, a whole 10 kph faster than the eHang 184, despite the 184 outputting nearly five times the power (Tables 2 and 4), both with multicopter architectures. Similarly, the Bartini flying car outperforms the Vimana AAV with a top speed of 300 kph with a 320 kW output, which is 56 kph faster than the 480 kW AAV, despite its design incorporating hybrid technology and a higher engine power output.

The maximum flight time, despite the marginal differences, is mostly dependent on the battery capacity and motor output of the aircraft. For example, the Lilium Jet has a battery capacity of 320 kWh and a flight time of 60 minutes (calculated using given data from range and cruising speed), while the Bartini Flying Car has a 64 kWh battery capacity for half the flight time (Tables 2 and 4). However, this is a general trend and not always a definite quantifiable difference, as seen when comparing the eHang 184 and the Davinci ZeroG. Both aircraft have the same maximum flight time despite the ZeroG having a 52.8 kWh battery and the 184 having 17 kWh, each with a similar 240 and 260 kg maximum takeoff weight, respectively.

The longest-range aircraft are those with higher cruising speeds. Some also use longer flight times; the hybrid AeroMobil, Trifan 600, Terrafugia TF-X, Rolls-Royce, and AAV use their high energy capacities to increase their flight time and therefore their range (Tables 2 and 4). Both the Joby S2 and S4 combine high velocities and long flight times resulting in impressive potentials. The Lilium Jet follows closely behind while boasting a five-passenger payload to the S2's two passenger cockpit. On the other end of the spectrum, the eHang 184 and Volocopter 2X are limited in their ranges by their low flight time and maximum cruise speed due to their designs. For the aircraft with low flight times (25 minutes or less), their ranges are limited by their cruise speeds.

PART II — EXISTING RESEARCH

Aircraft Design

Moore and Goodrich at NASA in Reference 31 have put out goals for increased investment in on-demand aviation, so-called “thin-haul” applications. The primary challenges for this emerging market are in costs of operation, reliability, safety, and emissions, which can be negated by integrating electric propulsion and autonomy to designs. For increased efficiency, NASA sees significant contributions to hybrid-electric propulsion systems, eventually integrating technologies such as high aspect ratio wings and fully electric propulsion systems, as a long-term goal (Ref. 31). Safety through autonomy can be increased by simplifying piloting skills for currently piloted aircraft in order to decrease pilot mistakes, which can make self-preserving autopilot systems less complex and more reliable and eventually making full autonomy simpler.

For urban on-demand air mobility, electric power sources are more advantageous than gas-powered propulsion. According to Moore and Fredericks in Reference 32, electric motors have a higher thrust-to-weight ratio than gas-powered jet engines due to having fewer heavy components. Electric engines are also much easier to scale up or down due to their relative simplicity. This opens a number of possibilities to overcome aerodynamic and structural challenges posed by traditional aircraft. For example, motors can be placed on the chassis where they make the most significant change to the attitude of the aircraft rather than being limited to where they can be structurally supported. Ullman notes in Reference 3 that for winged aircraft, incorporating the propulsor with the upper boundary layer is simpler with more compact and less sophisticated propulsors. This increases lift as pressure on the upper boundary of the wing is lowered.

Hybrid aircraft are also common for urban applications, as discussed in Part I. As Patterson, M. D. et al discuss in Reference 33 the use of fuel in hybrid aircraft gives the aircraft a higher range compared to fully electric aircraft, as fuel has a higher energy storage than current batteries. Since batteries have this limitation, the higher battery mass can decrease efficiency at a point as range increases. This maximum value can be increased by increasing the specific energy density of the batteries, which comes as a result of increased development in battery technology. Additionally, according to Moore (Ref. 34), the current industry for flying taxi services puts costs for travel under $1.50 per passenger mile. This number is expected to decrease as the aircraft become more common, and the technology is further developed.

Currently, according to Duffy et al in Reference 18, eVTOL design takes into account three factors; cost, safety, and noise pollution. In Reference 35, Fredericks et al note low cost comes from an increase in efficiency, and electric motors offer a solution with higher thrust to weight ratios than their gas-powered counterparts. However, the battery weight is not burned in flight like gas. Because of this, eVTOL aircraft require a significant amount of power during takeoff and hover. This power requirement can be mitigated if the aircraft incorporates wings into the design, making this high required power limited in time, and therefore allowing for a smaller battery with less power exertion required during cruise. Additionally, according to McDonald in Reference 36, the use of ducted electric motors as opposed to open motors increases efficiency during high altitude cruise, which, for urban applications, is not a likely scenario. The performance of these motors is reduced at lower altitudes which are more common in these applications. Otherwise, noted by Xu (Ref. 37), the use of wings can increase the value of the L/D by nearly a factor of 2; increasing the value from a reasonable 3 in horizontally-fixed rotor aircraft to up to 5.5 as seen in winged helicopters. Ultimately, optimization for electric aircraft needs to mitigate high battery weights by incorporating high lift over drag ratios. According to Pornet and Isikveren (Ref. 38), These higher ratios can be obtained via larger propellers, more efficient weight distribution among the structure, and increasing the flow over control surfaces to increase responsiveness to controller inputs. As Riboldi and Gualdoni discuss in Reference 39, previous design iterations can be scaled to improve designs. During the sizing optimization process, the use of data from previous projects is beneficial as battery and engine weights, power outputs, and their relations can be interpolated from these trends. As battery technology progresses to higher energy densities per unit mass or volume, previous designs can be iterated until a new optimal efficiency is obtained for a given mission. More specifically, from Reference 40, the process follows a trend of preliminary sizing, incorporating the battery weights and engine parameters, and the process is iterated until said optimum value is obtained. Generally, this is accurate for scaling within 10% accuracy of the parameters of the aircraft.

Reference 25 notes safety is increased in eVTOL aircraft in part by using distributed electric propulsion in order to add redundancy. Despite the definition of distributed propulsion being broad, as noted by Gohardani in Reference 41, an increased safety factor implies redundancy in the propulsion system, therefore making the aircraft less susceptible to an emergency scenario in the event of one engine failure. For example, according to Reference 17, in octocopter designs like the aforementioned eHang 184, having two motors on each branch of the X configuration adds redundancy to the lift propulsion system and therefore increases the aircraft’s factor of safety. The X configuration also has higher lateral stability compared to a + design in turbulent conditions, according to Bershadsky in Reference 42. Challenges in implementing redundancy in electric propulsion come from the limitations of modern electric generators. As mentioned in Reference 43, generators that have a higher power output are volumetrically larger and heavier, making them difficult to implement in aircraft. This is a more significant challenge for commercial flight, but with a flying taxi application, less power is required to fly the aircraft and therefore smaller generators can be used. Additionally, as noted in Reference 44, the Auxiliary Power Units (APUs) used in these aircraft are likely required to be specialized for these designs individually. The maximum thrust value required for the aircraft is especially important to know early in the design process, as a higher required output will require a different APU entirely, possibly with different dimensions and mass than another unit of a different size. Therefore, it is important to note the maximum required output of the motors and cap the system at said value to avoid APU or engine failure, overheating, or structural damage.

Additionally, the noise produced by the aircraft can limit its applications geographically based on codes in the urban area of application. This is discussed in Reference 45. For example, if the aircraft is too loud to fly over an urban area, its flight plan may be required to fly over a local body of water or take a non-direct flight plan in order to comply with said ordinances, which can lead to longer flight times and less efficient use of energy. This is most effectively combated with a complete redesign of the aircraft if noise pollution is too significant. Replacing the motors with units focused on limiting noise reduces pollution by about 1 dBA. Increasing the aspect ratio of the fan blade can be effective, however the structural integrity and rotational speed of the fan must be taken into account, so the safety is not compromised and the increased rotational speed does not increase noise pollution if the diameter of the rotor is increased.

Batteries

As mentioned in Part I, current battery technology is a limiting factor in electric aviation. Batteries with higher energy densities are still being developed. With current battery capacities around 200 Wh/kg, the applications are limited to small one or two passenger aircraft. This will likely increase with the increase in capacities per unit mass and will likely become more useful in aircraft propulsion in the next 20-40 years, according to Reference 46. In the future, eVTOL aircraft will incorporate batteries that are currently in development that have a higher potential energy density, such as the 2500 Wh/kg potential lithium-sulfur batteries or 3000 Wh/kg potential hydrogen fuel cells. Currently, according to Reference 28, the battery mass accounts for about 45% of the total mass of these eVTOL aircraft. In Reference 31, NASA challenged the industry to build “structural batteries” in order to more effectively and efficiently use this weight while keeping the safety standards set by the companies’ respective governing bodies.

On-Demand Mobility

Fleet management in urban on-demand air mobility differs significantly from fleet management currently used in industrial aircraft. As noted in Reference 47, a significant challenge for these aircraft is full autonomy as pilots add cost, increase the likelihood of an accident, and cut the already low payload of these aircraft significantly. This however puts the responsibility on the manufacturer to design a safe system where the human error is now in the hands of a designer rather than a pilot. This also adds costs for maintenance and may require certification with currently unwritten regulations. Reference 48 adds the autonomous system must also be able to stick to a flight plan consistently and precisely in order to avoid collisions with surrounding hazards, maintain enough battery power to complete the flight, and for the overall management of the fleet. As discussed in Reference 49, fleets need to be managed via a remote operations center, or ROC, that can gather data about weather, fleet designated airports (so-called veriports), and the aircraft within the fleet. This would act similarly to a current airport but with fewer personnel that could provide all-around support to ensure the proper distribution of personnel for all different roles required for the ports to operate. Research into the most efficient personnel support structure has yet to be performed. However, according to Reference 50, the airspace capacity of a geographical area will be highly constrained with limited ATC personnel, therefore limiting scalability at lower altitudes, in which these aircraft would operate. Reference 51 suggests as these aircraft fleets are incorporated into the urban landscape, the ATC system will become less realistic as a management system as there will be too many aircraft to be managed in such a small airspace. Therefore, the system design and safety will be the responsibility of the aircraft manufacturers. Regulations will need to change, for managing an entire fleet of on-demand aircraft will be no simple task for flight planners and air traffic management personnel. With this lack of human communication between ATC and pilots, there must be a communication system between ROCs and the autonomous aircraft for warnings about weather, terrain, airspace, nearby aircraft, and the urban landscape, according to Reference 52. These systems account for and project the demand of the fleet’s services and make sure the service is operated smoothly.

As discussed in Reference 29, using an efficient flight trajectory can lower flight times and decrease energy consumption, adding efficiency to the fleet. Current eVTOL aircraft have a higher energy consumption, limiting their efficiency. Not only this, but the power required for the aircraft to climb to higher altitudes would drastically reduce battery charge, making a higher altitude cruise less viable. Additionally, a descent with a smaller angle and maintaining constant cruise altitude for less time results increased efficiency. Kleinbekman et al in Reference 53 perform a computational model for the optimization of aircraft arrivals over the span of one hour. Assuming the use of the eHang 184 aircraft and forty incoming aircraft per hour, an aircraft can arrive optimally approximately every eighty seconds. This allows the aircraft to use an energy efficient descent angle to limit battery consumption. Wei and Pradeep (Ref. 54) use an algorithm to optimize the arrival sequencing of winged and wingless eVTOL aircraft. According to their models, winged and wingless eVTOL aircraft should use separate airways for final approach. This is because winged aircraft have higher cruising speeds which allow them to overtake the wingless aircraft, making the landing process more efficient.

According to Kohlman in Reference 55, the most economically efficient fuel system for VTOL aircraft is using natural gas for VTOL applications. This is due to low energy costs and rapid turn-around time compared to all-electric designs. However, this cost advantage comes with added complexity and negative traits such as increased noise and increased emissions. Similarly, hybrid-electric systems are favorable in turn-around times, range, and costs, but come with higher complexity, noise pollution, and emissions.

German et al in Reference 56 produced a case study of delivery aircraft in the San Francisco Bay area. A significant issue discussed was the necessary density for veriports and their distribution throughout the area. Based on the population around those veriports, the estimated demand must also be taken into account. If the demand in one area is particularly high due to population density, the traffic can be mitigated through higher veriport density or larger veriports in these areas. The report also discusses basic aircraft parameters for the sake of speed of delivery and range, which have been discussed in earlier sections of this report. Ultimately, the project compares two designs for UAVs for package delivery and sees which one can deliver more mass and volume of packaging per 12 hour "shift", acting as a well-organized initial model for such technology in a potential market. The effectiveness of the system comes down to two main factors; the effectiveness of the infrastructure and the organization of the fleet.

CONCLUSIONS

The future of on-demand transportation lies in eVTOL UAVs. Current projections from the American Institute of Aeronautics and Astronauts (AIAA) in Reference 57 projects more than 660 million people will use UAVs each year by 2035. These projections also anticipate the cost per passenger mile to drop to $0.20 in that same time frame. This will account for a significant portion of mid-range transportation. Through a sample of case studies, Uber in Reference 1 estimates the average commuting time to be reduced by about 88%, and for prices to drop close to current ride sharing fares in the long term. The talking points of this report have focused on current designs and research into the future of urban on-demand air mobility services. With further development in aircraft performance and fleet management, urban on-demand air mobility will likely become more prevalent in modern society.

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