A Review of Recent Personal Air Vehicle Concepts

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ABSTRACT

Recent activities on the field of urban air mobility have brought up a broad range of personal air vehicle configurations. This review paper provides an overview of these configurations with emphasis on operational capabilities, design focus and system complexity. Initially, a classification scheme is proposed, to identify clusters containing concepts with comparable performance characteristics. Further, a comprehensive overview of the current vehicle programs is given. Technical aspects and design characteristics are discussed regarding urban air transportation. Performance data available from the public domain is presented and compared. Finally, two metrics for system complexity analysis of personal air vehicles are described. The obtained complexity of representative configurations is evaluated and compared to a common reference.

KEYWORDS: *personal air vehicle, VTOL, urban air mobility, performance, system complexity*

NOMENCLATURE

Symbols:

c	No. of identical components [-]
α	Component complexity weighing factor [-]
β	Crosslinking complexity factor [-]
$\phi_{sys,c}$	Coupled system complexity index [-]
$\phi_{sys,uc}$	Uncoupled system complexity index [-]

Subscripts:

dev	development
ref	reference
sys	system

Abbreviations:

A/C	Aircraft
AAV	Autonomous Air Vehicle
BAT	Battery
CTOL	Conventionally Take-off and Landing
ESTOL	Extreme Short Take-off and Landing
LSA	Light Sport Aircraft
L/D	Lift-to-drag Ratio
PAV	Personal Air Vehicle
PMAD	Power Management and Distribution System
PROP	Propulsor
STOL	Short Take-off and Landing
UAM	Urban Air Mobility
VTOL	Vertical Take-off and Landing

1 INTRODUCTION

As a potential answer to the growing inner-city transport demand due to the worldwide urbanization [1], urban air mobility (UAM) is a research field of rising activity and interest. UAM implicates, in addition to ground-based private transport and public transport services, a significant share of person transportation within and/or across city boundaries to be performed airborne. Small aircraft configurations designed for a small number of passengers, personal air vehicles (PAV), are intended to fly inner city and/or inter-city transport missions while fulfilling the accompanying, stringent design requirements.
The requirements for such vehicle configurations are diverse and, in part, novel in aircraft design. While predictions for operation modes and therefore, classic performance requirements such as range, payload and speed are widely divergent, low noise levels, CO_2 and NO_x emissions as well as high reliability/safety standards are commonly identified as key prerequisites [2] [3] [4]. Further, costs play a key role in PAV design. While costs of production and thereby, acquisition price is a fundamental introduction barrier, also operating costs are of central relevance. Since there is potential for mass production, small cost advantages per vehicle may have substantial impact on purchase decisions.
In the last few years, for several reasons numerous projects have been launched aiming at the development of PAVs. On the one hand, technological progress in electric components, motors, power electronics and batteries, acted as an enabler for this kind of aircraft. Electric power transmission may enable a broad range of configurations with distributed propulsion systems, offering attractive characteristics addressing the requirements of UAM. Moreover, a broad range of organisations and companies identifies serious socio-economic potential of UAM in general and on-demand urban air transportation in special. While NASA ran several research programs and projects on PAV and intra-urban on-demand mobility since the 2000s already, several framing activities for UAM and PAV development launched with both scientific and widespread commercial background in the current decade. Especially, the *Elevate* initiative [2] of on-demand car transportation service company Uber attracted attention lately. In the associated white paper [2] the path to market for a network of small, electrically powered aircraft with vertical take-off and landing (VTOL) capabilities is outlined. At the first *Elevate* summit, numerous start-ups as well as established companies presented their PAV concepts, prototypes and demonstrators. Recently, the Roads and Transport Authority of Dubai announced a test program for taxi services based on Autonomous Aerial Vehicles (AAV) [5]. Several PAV manufacturers were selected to participate with their vehicles.
The purpose of this paper is to give a structured, comprehensive overview of current, but also anterior vehicle concepts pursuing promising technical solutions for UAM. A classification scheme is introduced to identify vehicle clusters with similar characteristics regarding performance and operation. Further, exemplary PAV concepts of all clusters are discussed. Design details and synergistic propulsion integration aspects as well as key aspects of the aircraft programmes are identified. Moreover, aspired performance targets are evaluated and compared. Finally, a complexity assessment of the vehicle concepts is conducted.

2 CLASSIFICATION OF PERSONAL AIR VEHICLE CONCEPTS

Considering the existing PAV configurations, a broad range of vehicle morphologies can be observed. Each morphology is connected to a unique set of characteristics providing a varying degree of suitability for UAM. Beside performance aspects, other criteria like noise emissions, complexity or production cost and operating cost depend on the vehicle configuration. Fig. 1 shows a classification scheme considering take-off and landing capabilities of the configuration in first step, and lift generation during cruise in a second step. The scheme is intended to subsume PAVs to classes with comparable performance characteristics and operational capabilities.
To determine and record the state of the art regarding PAVs, information from literature and publications was extracted and stored in a structured manner. Table 1 in the appendix contains a compact overview of recent projects, including concept studies, technology demonstrators and actual PAV development programs. Each vehicle entry is assigned to a vehicle class presented in Fig. 1. In the following chapters, all branches and leaves of the classification scheme are presented and representative assigned configurations are introduced.

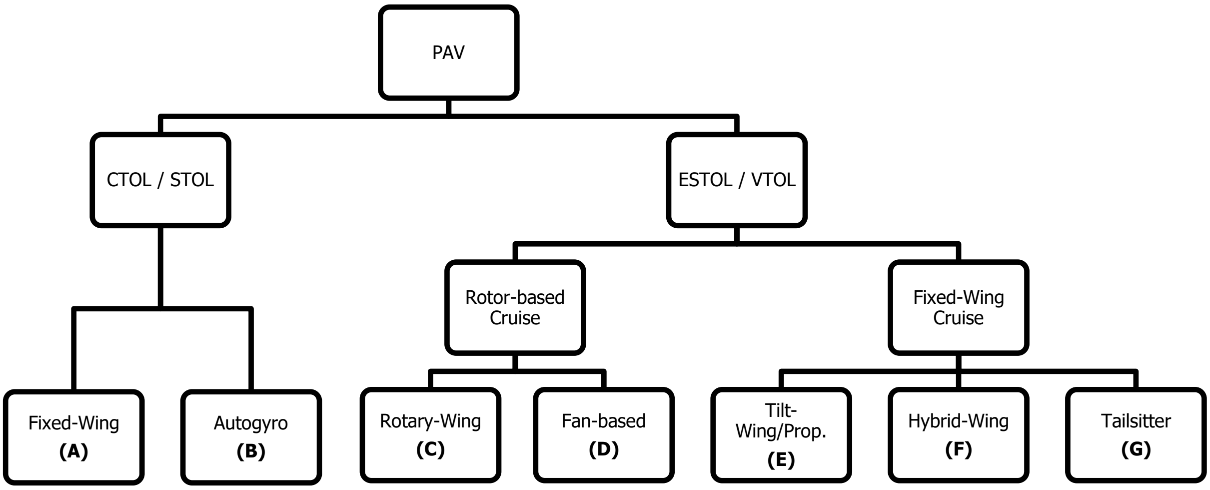

Figure 1: PAV classification scheme regarding take-off/landing capability and vehicle morphology

3 CTOL/STOL PAV CONFIGURATIONS

The left branch of the morphology tree in Fig. 1 contains conventional fixed-wing configurations (class A) with conventional (CTOL) and short (STOL) take-off and landing abilities. Since PAVs of this class need a dedicated runway for operation, they are presumably not the first choice for flexible inner-city transport missions. Nevertheless, this kind of aircraft could be part of an on-demand transportation system providing inter-city or city-to-airport connections as well as connections from cities to the urban surrounding and rural areas [6]. Optimized for the spatial dimensions of the PAV class, inner-city airports such as proposed in Ref. [7] could serve as multi-modal traffic junctions with significant transport capacity. This could be an essential step towards reaching the four hours door-to-door target formulated by the European Commission [8]. As operation is eventually taking place within urban areas, aircraft must fulfil the same stringent requirements applied to vehicles designed for inner-city transportation. Technology demonstrator programs like LEAPTech [9], SCEPTOR [10] (both NASA), Ampere [11] (ONERA), HYPSTAIR [12] (European Union), or the E-Fan [13] (Airbus & Siemens) could lead the way to community friendly PAVs in this category.
A subset of vehicles in this branch are flying cars. (As the classification scheme aims at flight characteristics only, no explicit subtype for roadable vehicles is provided.) Dual-mode configurations have a long history; Hall [14] presents an overview of dedicated programs of the last century. Younger projects are amongst others Terrafugia Transition [15] and Samson Switchblade [16] in the US, as well as PAL-V [17], Carplane [18] and AeroMobil [19] located in Europe. Three of them performed their first flight in the past. The Terrafugia Transition has a two times foldable main wing attaching to the passenger cabin in drive-mode, a u-tail and a single propeller in pusher configuration powered by a conventional piston engine. It performed its first flight in 2009 and can be operated as a light sport aircraft (LSA) with FAA approved exemptions for maximum take-off weight and stall speed. The exemptions are necessary to meet automobile standards for US highways [20]. The Transition team further published an early concept for a second roadable vehicle named TF-X, which is planned to be powered hybrid-electric and capable of VTOL [21]. The AeroMobil 4.0, developed since 2010 in Slovakia, swings its wings backward to gain a compact, street compatible size. A piston engine with turbo technology provides shaft-power for a single direct drive variable pitch propeller integrated in the tail of the vehicle. On the road, electric power transmission via a generator is used powering two electric motors on the front axle [19]. In 2014, the first flight was performed with the prototype AeroMobil 3.0. Two years earlier in 2012, a prototype of the PAL-V autogyro flew the first time. Powered by a conventional piston engine, the PAL-V can fold back its rotor blades and drive as a tricycle on roads. Thereby, the cabin actively tilts into curves to increase road holding [17]. The PAL-V is the only scouted representative classified as autogyro (class B).

Although flying cars are theoretically capable of personal door-to-door missions, a scenario including a significant traffic share covered by these concepts seems unlikely for several reasons. First, the technical compromises to fulfil both air and road requirements as well as the complex transformation mechanisms of present roadable PAVs prevail multi-modal flexibility so far. Furthermore, the manufacturers do not address UAM key requirements such as noise or emissions yet. Finally, no larger benefits regarding the ground-based urban traffic can be expected, as the transition from or to fly mode cannot take place in inner-city areas because of the need for dedicated runways.

4 PAV VTOL CONFIGURATIONS FOR URBAN AIR MOBILITY

The right branch of Fig. 1 contains aircraft capable of VTOL. As requiring a minimum ground area for take-off and landing, VTOL PAVs are predestined for inner-city operations and primary subject of most current initiatives.
For VTOL aircraft configurations, the V/STOL Wheel [22] provides a well-known classification. The Wheel differentiates on basis of the propulsion system architecture and includes detailed mechanisms for vertical thrust production. The proposed classification in this paper focuses on a clustering regarding similar performance characteristics. Therefore, the vehicle classes of both schemes are not identic but merely overlapping in some cases.
The VTOL branch of the proposed scheme divides further by means of lift production during cruise. The left branch contains PAVs using rotating wings for lift production in forward flight, dividing in open or ducted rotor concepts and fan-based concepts. The right arm comprises configurations capable of fixed-wing cruise. These concepts are sub-classified as tilt configurations, hybrid-wing configurations and tailsitters.

4.1 Rotary-wing concepts

Rotary-wing concepts (class C) use vertically mounted rotors for take-off and landing as well as cruise. This PAV category includes single-rotor and dual-rotor configurations as well as multicopter concepts with a highly distributed propulsion approach. Aircraft of this type have typically excellent hover and VTOL characteristics, but limited cruise velocity and a relatively low lift-to-drag ratio (L/D) compared to fixed-wing aircraft. Latter results in decreased cruise efficiency and therefore, reduced range [23].
The approach to distribute thrust production over many smaller rotors brings several essential advantages. First, it has a strong influence on rotor complexity. Configurations with a single or a few large rotors adjust the thrust vector by evoking cyclic and collective pitch. Therefore, complex rotor heads typically consisting of several hinges, rods and the swashplate are necessary. As multiple small rotors arranged in a two-dimensional plane are available, the overall thrust direction is adjustable by simply changing the absolute thrust produced by a single rotor. Since small rotors are more lightweight, absolute thrust can be regulated via modulating the revolution speed with fast response rates. This allows simple, fixed pitch rotor designs with comparably low production cost and maintenance effort.
Second, the higher frequency of smaller rotors leads to a higher frequency noise compared to the noise of a single, larger rotor producing the same amount of thrust. Higher frequency noise, on one hand can be more annoying for community if it is directly in the band of highest sensitivity of the human ear. This may require constructional noise prevention at take-off and landing areas, where the vehicle operates near populated places. On the other hand, the atmosphere attenuates higher frequency noise stronger and less noise reaches ground and people during flight. Third, depending on the rotor arrangement and overall power train design, advantages in stability and control as well as redundancy and safety are possible.
A very advanced representative of rotary-wing PAVs is the Volocopter 2X [24], depicted in Fig. 2. The full electric multicopter has 18 rotors, each one powered by electric motors arranged in two concentric circles. The underneath appended cabin houses two seats, power electronics and the battery system. Furthermore, a focal point of development is easy pilot control and autonomous flight. Therefore, the 2X implements automatic height and position control. In 2018, Volocopter aims for an approval in Germany as ultralight aircraft and a type certification as “Multicopter”, which shall be created newly [25]. Besides, the 2X is going to be part of the AAV test run in Dubai [26]. Based on the same rotor configuration, further concepts for one and four passengers as well as vehicles for unmanned operation exist.

The side-by-side arrangement of numerous rotors implicates relatively large vehicle designs. To get a more compact configuration, an alternative design option is to place rotors coaxially one upon another. However, this leads to a decrease of efficiency of the lower rotor. The fully electric CityAirbus concept has four times two, coaxially arranged ducted rotors mounted on top of a cabin accommodating up to four passengers, see Fig. 3. Emphasis of the project are cost efficiency, high-volume production and a low environmental footprint [27]. First test flights are scheduled for 2018 [28].

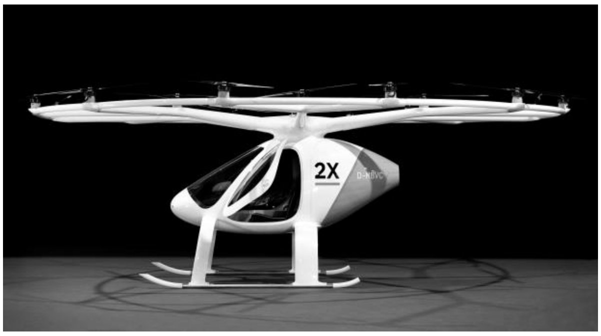

Figure 2: Volocopter's two-seated series model 2X lifted by 18 rotors [24].

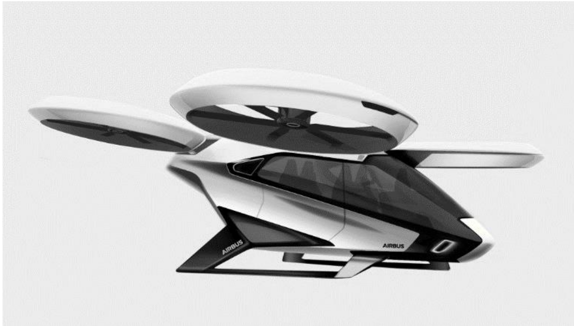

Figure 3: Illustration of the CityAirbus concept for up to four passengers [32].

A conjoint concept study of Airbus and Italdesign called Pop.Up suggests a modular passenger transport system consisting of a two-seated passenger cabin, which is combined with either a flying platform or a roadable module [29]. Considering the cabin attached to the flying platform, the configuration is similar to the CityAirbus concept. In both transportation modes, the vehicle moves fully autonomous.
The EHANG 184 [30], a transport drone designed for autonomous flight comes with four times two, coaxially arranged rotors mounted on four foldable arms. The centred passenger cabin towers above the rotor plane and accommodates a single person. A certification process is aspired in China. Furthermore, the manufacturer of a single person jetpack presented an early concept of an electric hexa-dual-rotor configuration [31].

4.2 PAVs cruising with fan-based lift

Considering PAV of this category (class D), instead of open or ducted rotors, vehicle-integrated fans produce lift for VTOL and cruise. Fans allow for high amounts of thrust at small cross-sections. This enables much more compact aircraft configurations with smaller footprints, which is potentially attractive considering UAM. The absence of open rotors increases safety and decreases weather influence [32].
The Urban Aeronautics CityHawk [33], a four-passenger, hydrogen powered PAV concept, is based on a combination of fan technologies previously developed and tested for military purposes [34]. Two large fans, one in the front and one in the rear produce thrust in vertical direction for VTOL, see Fig. 4. A patented vane control system changes the air flow at the inlets and outlets to enable movement along all six degrees of freedom independently. Further, the forward duct of the front fan and the aft duct of the rear fan open during cruise. This enables air to move through the ducts, reduces drag and allows for cruise speed of up to 220km/h. The fuselage is designed to generate a significant portion of lift during fast cruise [32]. The manufacturer proposes air taxi and medical emergency missions as potential applications for the CityHawk.
Another fan-based vehicle is developed by the British UAV producer Neva. The AirQuadOne [35], depicted in Fig. 5, is moved by four main fans arranged two-by-two in the front and in the rear, as well as eight smaller fans positioned on the left and the right side of the passenger cabin in the centre. Four tilt-able double fan packages attached in the front and the aft on each side produce both forward thrust and lift. The vehicle is designed for payloads up to 100kg, which can be a single person or cargo. Flight times up to 30 minutes, cruise speed of 80km/h and maximum altitudes of 3000ft are specified as expected vehicle performance. For longer flight times, a hybrid-electric version of the PAV is planned.

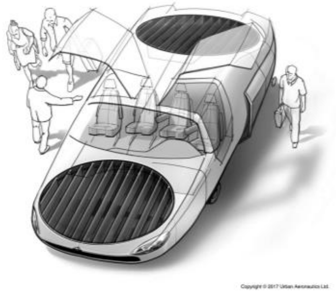

Figure 4: Illustration of the Urban Aeronautics CityHawk [33].

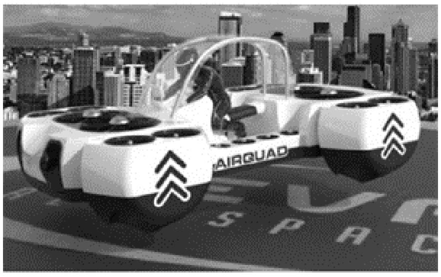

Figure 5: The single-seated AirQuadOne concept powered by numerous fans [35].

4.3 PAVs implementing tilt mechanisms

A way to enable fixed-wing cruise in combination with VTOL capability is to integrate tilt mechanisms. Depending on the position of the propulsors, they generate either lift for take-off/landing or thrust in cruise. Implemented mechanisms can tilt either the whole wing (including the mounted propulsors), each propulsor on its own, or multiple propulsors together. While tilt configurations (class E) enable higher cruise efficiencies and cruise speeds compared to rotary-wing configurations, usually a penalty in system complexity must be paid. Further, flight dynamics especially during transition are more complex than of other vehicle types.

Electric technology facilitates PAV concepts of this category as electric power distribution and electric actuators eliminate the need for heavy and complex mechanical constructions.

Distributing the thrust production leads to the same beneficial noise characteristics as described previously for rotary-wing concepts. Furthermore, synergistic blown wing/blown flaps configurations are possible. Due to front mounted propulsors, a wing faces a higher effective flow velocity and lift is increased. This enables smaller wing areas, which decreases friction drag during cruise [9]. Propulsors installed on top of a wing or flap increase lift by accelerating just the upper part of the flow. Considering the propellers/rotors of tilt configurations, a trade-off between hover and cruise design is necessary. Unlike in the case of rotary-wing concepts, the use of simple fixed pitch propellers might not be of advantage. To ensure reasonably efficient propulsion for hover as well as cruise, a variable pitch is necessary.

In 2013, AugustaWestland presented an electric tilt-rotor technology demonstrator called "Project Zero" [36]. Two fully electric powered ducted rotors integrated into the wing are rotating to a maximum angle of 90°. On the ground, both rotors can act as wind turbines for recharging the battery. For helicopter missions, the outer wing segments can be removed [37]. The aircraft can fly both manned and unmanned. Further, an alternative, hybrid-electric propulsion system extending operation time from 10 to 35-45 minutes as well as an active blade control system has been developed [38].

As a partner in the NASA SCEPTOR program [10], Joby Aviation has experience regarding distributed electric propulsion. After having presented a two-seat tilt-propeller PAV concept, the S2 [39], a configuration for up to four passengers is in development [40]. A comparative view of both concepts is presented in Fig. 6. The S4 is a rather conventional configuration consisting of a fuselage, a main wing

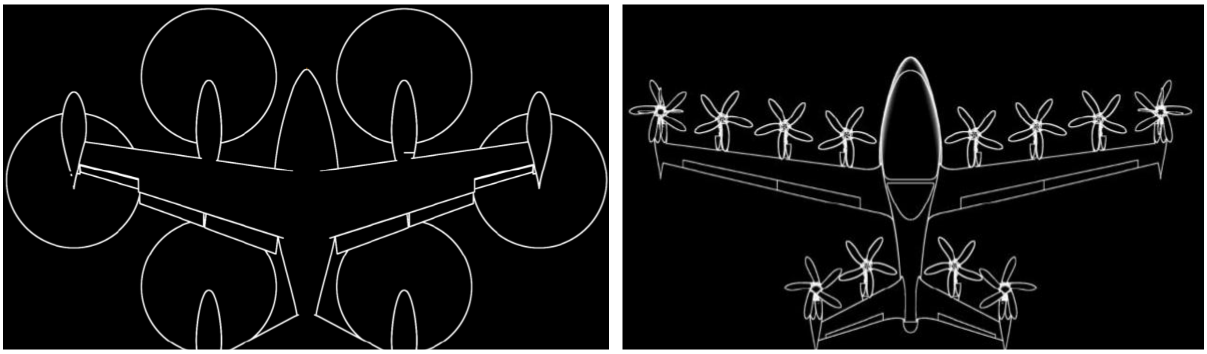

Figure 6: Top view of the Joby S4 (left) and the S2 (right) tilt-propulsor PAVs with foldable propellers [38].

and a V-tail but with six tilt-propellers. For VTOL, all propulsors are in upright position. The forward position of the propellers prevents from downwash blockage. During transition, all propellers tilt into forward direction, transforming the vehicle in a blown wing configuration. Then, most of the propellers are shut down and folded to decrease drag and enable highly efficient cruise flight. The forward swept wings provide increased flexibility regarding the location of the centre of gravity.
Project Vahana conceptualized by Airbus A^3 implements a tilt-wing PAV concept [41], see Fig. 7. Two wings, one in the front and one in the rear, provide lift for cruise flight. On each wing, two propellers are mounted in front producing lift during VTOL and thrust for cruise. The vertical offset of the rear wing minimizes aerodynamic interference. Designed for transport of a single person or cargo, the vehicle is planned to fly fully autonomous and integrates a collision avoidance system. In case of emergency, the Vahana deploys a ballistic parachute [42].
Heavily based on distributed electric propulsion, the Lilium Jet, see Fig. 8, implements numerous small electrically powered tilt-fans on a front and an aft wing [43]. The rear main wing has twelve fans on each side, three-by-three positioned on flaps acting as a powered high lift system at low speeds. The smaller canard wing in the front integrates six fans on each side using the same tilt mechanism. As both wings are nearly arranged in the same vertical level, aerodynamic interaction may result in a decrease of efficiency. For VTOL, all flaps are deflected to a maximum of 90°. While the final concept is designed for five passengers, a two-seated prototype performed an unmanned first flight in 2017.
The TriFan 600 [44], another tilt-fan concept, represents a rather conventional fuselage-wing configuration with a T-tail but integrates three ducted fans for VTOL. A fixed, vertically aligned fan is incorporated in the rear part of the fuselage. It provides lift for take-off and landing only and can be concealed during cruise. Two more tilt-able fans are integrated in the main wings near the fuselage. The human piloted PAV is designed for five passengers and powered by a hybrid-electric power train, including two turbo-shaft engines. An envisaged cruise speed of 550km/h as well as a maximum range of 2000km indicate suitability for inter-city transportation.
A patented concept with two tilt-fans, one in the front and one in the rear of the vehicle, is the DR-7 of DeLorean Aerospace [45]. As both fans are arranged in the centreline of the aircraft, a gimbal system has to provide roll and yaw control during hover [46]. In cruise mode, the fuselage blown by the fans creates lift, which increases stall resistance and facilitates smaller wing areas. A canard configuration ensures sufficient trim-ability regardless of whether one or two passengers are flying. The DR-7 is capable of conventional take-off and landing in case of emergency.

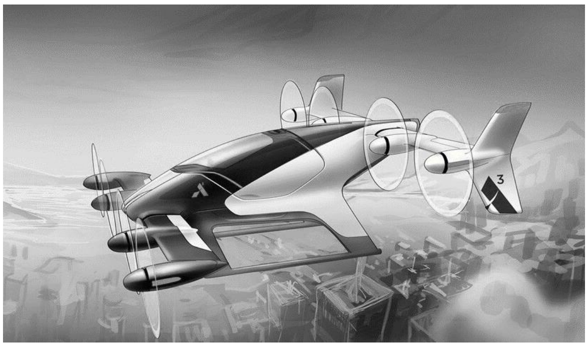

Figure 7: Artist's impression of the Vahana tilt-wing PAV [41].

Figure 8: Illustration of the Lilium Jet with tilt-able fans [43].

AirspaceX presents a modular roadable PAV concept called MOBi [47]. A four-seated passenger cabin can either be mounted on a ground module for street-based transportation, or be attached under a tilt-wing flying module. Four electrically powered propellers, positioned in the front of the wing blowing the wing itself and the control surfaces at the trailing edge.

4.4 Hybrid-wing PAV concepts

Achieving VTOL capabilities and fixed-wing cruise characteristics without tilt mechanisms requires vertically arranged rotors, a single or multiple fixed-wings and additional propulsors for cruise. During the recent PAV emergence, several concepts of this class (class F) have been developed. Again, the simple and lightweight electric power transmission is an enabler for most of those configurations.
Using distributed propulsion arrangements for the vertical rotors results in the same attractive hover and vertical flight characteristics as described for multicopters. The drag of the lifting surfaces decreases

climb efficiency after take-off. After reaching a desired flight level, cruise propulsion is activated and the vehicle is accelerated horizontally. As soon as the fixed lifting surfaces produce sufficient lift, the vertical rotors are throttled or shut down completely. If the rotors are not needed for lift production during cruise, folding mechanisms or other measures provide as clean aerodynamics as possible. While not achieving cruise efficiencies as good as of conventional fixed-wing or tilt-mechanism configurations, hybrid-wing concepts outperform rotary-wing vehicles. Further, system complexity can be reduced significantly compared to tilt aircraft.
The eVTOL PAV concept of Aurora combines eight fixed pitch rotors for take-off and landing and a single cruise propeller in pusher configuration [48]. The rotors are arranged four-by-four on top of skids mounted laterally on each side of the passenger cabin under the forward swept main wing, see Fig. 9. For short taxiing, the skids are placed on small wheels. A smaller canard wing in the front as well as a tailplane rudder fulfil both trim functionality and mechanical stabilization of the sleds. The cruise propeller sits at the back of the cabin in between two fins. Conceptualized for short-range hub-to-hub transportation of two passengers or cargo, the vehicle is powered fully electric and supports fully autonomous operation. First test flights including transition from vertical take-off to forward cruise of a subscale model have been performed in 2017. Considering a similar configuration, patented by Airbus [49], the cruise propeller is placed in front of a T-tail. The two-bladed VTOL rotors are incorporated in the skids. During cruise, the rotors are aligned in longitudinal direction and are therefore completely hidden from airflow.
The registered patent of Zee.Aero Inc. [50] describes a hybrid-wing configuration fitting in a standard car parking lot, see Fig. 10. Two wings in the front and in the aft, vertically staggered for low aerodynamic interference, are both foldable to decrease configuration width on the ground. On the top edges of the elongate fuselage, lift propellers, ducted or un-ducted, are arranged symmetrically over the full length. Again, this configuration ensures the ability of trim for various loadings. Two open propellers in the back produce thrust for forward cruise.

Figure 9: Aurora eVTOL hybrid-wing subscale prototype [51].

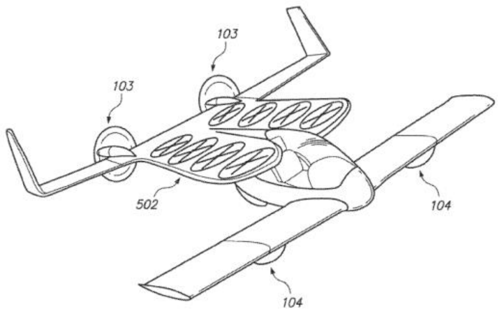

Figure 10: Zee.Aero patent figure of a hybrid-wing configuration, fitting in a standard car parking lot [50].

Another concept based on both, rotary-wing and fixed-wing lift during cruise is the Electric Air Taxi by Carter and Mooney [52]. The PAV has a single main rotor and a fixed, swept wing of the same span. At the end of a tail boom, a horizontally aligned, pivoting propeller is integrated. The vehicle can take off vertically using the main rotor for lift production and the tail propeller in slewed position for anti-torque control. In forward flight, the aircraft is pushed by the tail rotor and the main rotor switches to autogyro mode. As the lifting surface supports lift production, the main rotor can be slowed down. This mechanism allows for lower noise levels and better cruise efficiency.

4.5 Tailsitter

Tailsitter configurations (class G) enable VTOL in combination with efficient fixed-wing cruise by performing a ninety-degree transition of the full vehicle. At take-off, the aircraft stands in an upright position, the front aligned in the sky. After lift-off, the configuration more and more orientates to horizontal flight until cruise attitude is reached. While system complexity is potentially lower than of other VTOL configurations, the flight dynamics during transition is rather challenging. Further, passenger comfort is a critical aspect of tailsitter PAV. The complete tilt over requires reasonable solutions to ensure convenience and well-being. As with tilt configurations, propeller design is a

compromise between hover efficiency and cruise efficiency. Distributed and synergistic propulsion options of fixed-wing aircraft like a blown wing arrangement can be applied to tailsitters as well.
A concept study by NASA named "Puffin" considers a compact electric tailsitter configuration for single person transportation [53], see Fig. 11. Two tip-mounted propellers increase lift of the stubbed wings on one hand and on the other hand effectiveness of four control surfaces in X-arrangement at the back of the vehicle.

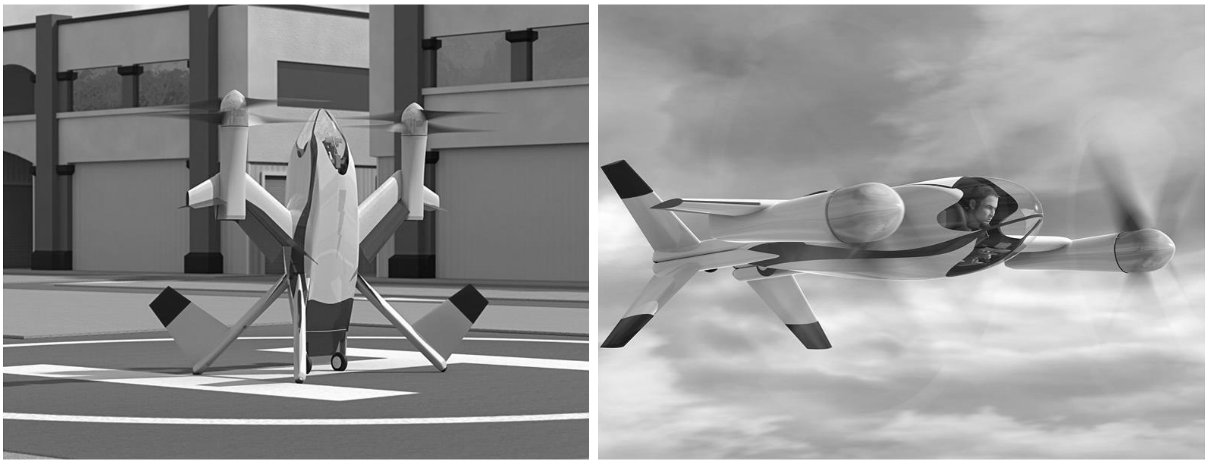

Figure 11: Illustrations of the NASA "Puffin" tailsitter configuration on ground in upright position (left) and during horizontal flight (right) [67].

The bi-planar rotors permit teetering flapping of the blades. This reduces blade loads as well as noise due to a high angle of attack during transition. A low tip-speed is reducing noise emissions in general. The X-tail contains small wheels and ensures stability while standing on the ground and during taxiing. The passenger is boarding in an upright position, and cruising in a prone position to allow a fuselage design providing minimal wetted area. Initial hover flight testing was performed with a 1/3 scale model. Although the "Puffin" has attractive performance characteristics and presents promising solutions for UAM vehicle requirements, currently no information on tailsitter PAVs being in development is publically available. A plausible reason for this may be the mentioned challenges regarding passenger comfort.

5 COMPILED PUBLISHED PERFORMANCE DATA

Fig. 12 presents published performance data of various PAV projects for UAM as well as some technology demonstrator programs. Considering the expected range of the configurations (x-axis), a clear separation between electric vehicles (circle marker) and hybrid-electric configurations (diamond marker) and conventionally fuelled (square marker) aircraft can be observed. While electric aircraft are expected to achieve ranges below 370km only, fuel-burning vehicles claim ranges up to 800km. Sole exception is the conventionally powered Workhorse Surefly (no. 39). However, the multicopter has a battery powered power train for emergency cases included. Obviously, the published ranges are based on diverging energy density assumptions for battery technology. Flown and validated concepts like the Airbus E-Fan (6) or the Volocopter 2X (28) can be considered as current technology reference. Published cruise speeds (y-axis) range from 70km/h of the Volocopter 2X to a maximum of about 320km/h, stated for the Joby configurations S2 and S4. The disadvantages regarding speed of rotary-wing based cruise (bold numbers) can be clearly identified. Highest cruise speed of a purely rotor based PAV achieves the PAL-V gyrocopter. The PAX targets (marker size) are heterogeneous, ranging from a single seated aircraft up to vehicles accommodating five persons.
The most attractive combination of speed and range is published by Terrafugia for the hybrid-electric flying car TF-X (35). Since the concept is in a very early stage of development and the way to a mature product may take several years, underlying technology assumptions are presumably radical.

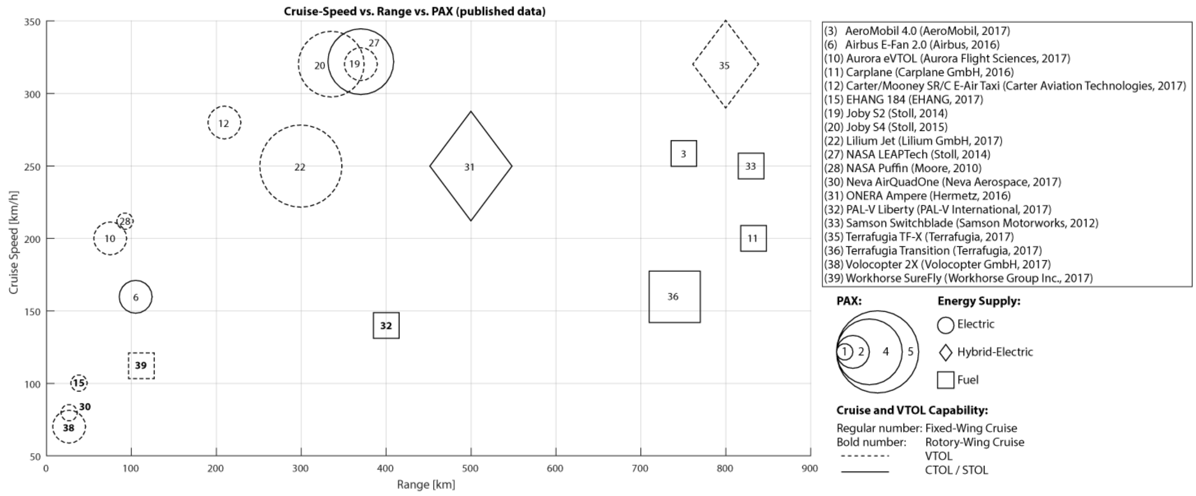

Figure 12: Published performance data of recent PAV projects.

6 COMPLEXITY ASSESSMENT

The previous section presented expected performance data of PAV concepts. Traditionally, these characteristics are of high relevance in aircraft design. However, the scenario of large-scale personal air transportation might shift development emphasis to other characteristics, or, at least bring up new criteria for successful vehicle concepts. Thereby, complexity of the configuration may be of immense importance due to several reasons. First, the number of produced units may be significantly higher than exhibited by all previous commercial A/C programs. Considering mass production as known from the automotive industry, the production cost of each vehicle has to be as low as possible. A small number of parts per vehicle as well as low complexity of components and systems have a high impact on the overall production costs. Second, costs for operation and maintenance potentially increase with rising extent and complexity of a system. Finally, system complexity may affect efforts regarding development and certification.
To obtain an impression of the complexity of the presented PAV concepts, a preliminary assessment is conducted. Therefore, a complexity assessment method for hybrid-electric power trains, [54], is adapted and applied to representative concepts of all vehicle classes. In addition to the power train, the flight control system of the PAV is considered. As public data on these aspects is rare, a consistent set of design assumptions for both systems is presented. Finally, based on these assumptions, abstract models for all PAVs are created and characteristic numbers for uncoupled system complexity and coupled system complexity are evaluated and compared to a reference configuration.

6.1 Metrics for Complexity Assessment

The uncoupled system complexity index defined in [54] is based on component classes, a related weighting factor, α, expressing the complexity of a class and the number of components. As most of the PAV concepts are full-electrically driven, the evaluation is not conducted on classes but on an abstract component level to differentiate more precisely between electric assembly parts. A system element, c_i, of a power train or a flight control system can be one of the types depicted in Fig. 13.

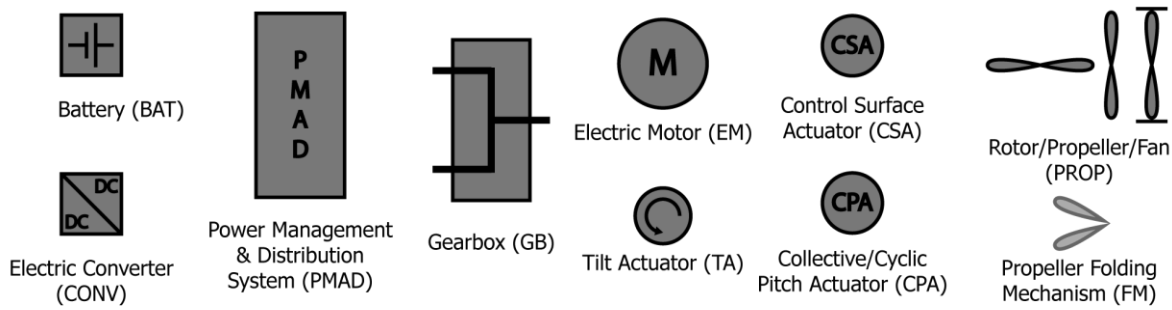

Figure 13: Abstract assembly parts of power trains and flight control systems

The adopted mathematical expression for the uncoupled system complexity index is

$$\phi_{sys,uc} = \sum_{i=1}^{N} \alpha_i c_i \qquad (1)$$

with N the number of components and c_i the individual complexity of a component. For an initial comparative study of system complexity, the weighting factor is set identically to $\alpha = 0.1$ for all assembly parts.

The previously presented uncoupled system complexity index neglects the interconnectedness of the individual components. However, if a component features a high degree of cross-linking, it indicates increased importance. This could implicate either a need for high redundancy, a need for increased quality assurance, or, more generally speaking, increased attention during the development process. To preliminarily measure this development complexity, the coupled system complexity index

$$\phi_{sys,c} = \sum_{i=1}^{N} \alpha_i \beta_i c_i \qquad (2)$$

is introduced. The additional complexity factor, β_i, of a component is defined as the number of directly connected components. A connection between components can be either electric or mechanic.

If available, system architectures are taken as published for complexity assessment. In case of no data accessible, power trains and control systems are designed using the following assumptions:

- Drive trains where failure leads to not trim-able flight states must be designed two times redundant.
- Considering distributed propulsion arrangements, two symmetrically aligned propulsors may be powered by a common battery. In case of a battery failure or PMAD failure, other propulsors provide increased thrust and the aircraft remains in a controlled state.
- PMAD units are supposed to include required redundancy and isolation mechanisms internally.
- Flight control systems are designed as fly-by-wire systems.
- Flight control systems including all electric actuators are designed as independent and isolated low-voltage systems with a double redundancy. Energy supply is covered by power train batteries if no loss of redundancy arises. Otherwise, separate batteries are included. Electric converters decrease system voltage for the control system.

As a reference configuration, a helicopter is selected as its transport mission comes closest to a presumable UAM mission. To ensure comparability, the conventional power train is replaced with a fully electric one. Based on the assumptions above, two independent drive trains deliver shaft power for the main rotor and the tail rotor, see Fig. 14. Further, a redundant low voltage control system is included.

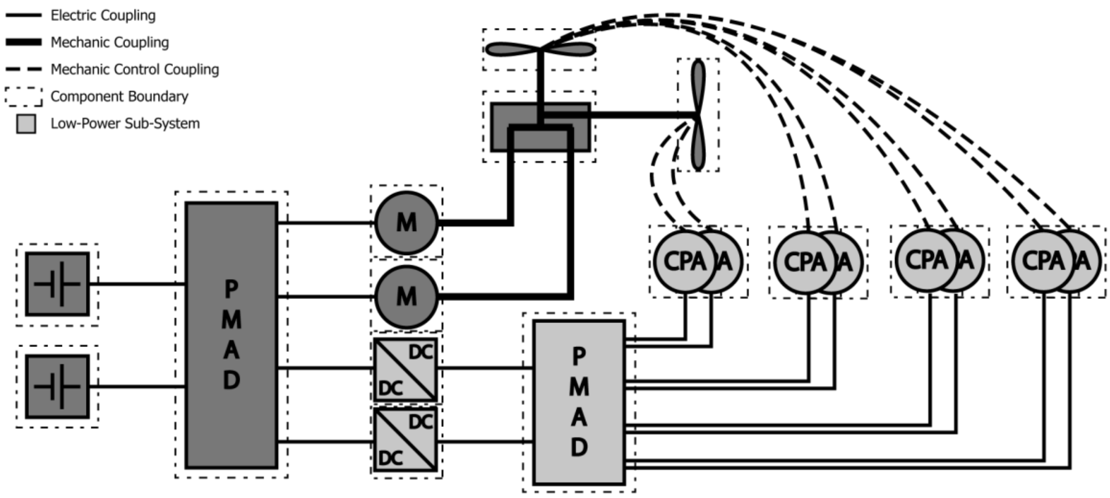

Figure 14: Reference power train and flight control system of a full-electric helicopter.

The complexity indices of all PAV configurations presented in the following are referred to the reference helicopter.

6.2 Uncoupled System Complexity and Number of Diverse Components

Fig. 15 depicts the normalized uncoupled system complexity, $\phi_{sys,uc}/\phi_{sys,uc,ref}$, (left bars) as well as the number of different components (right bars) of various fully-electric VTOL PAV concepts with a dedicated UAM background. As all components are weighted with equal component complexity, the presented complexity metric is strongly coupled with propulsion distribution. Therefore, the uncoupled system complexity index is roughly increasing with rising number of rotors, propellers or fans. Significantly more complex parts (e.g. a helicopter main gearbox) do not have a high impact in this initial study.

Considering the Carter/Mooney SR/C E-Air Taxi configuration relatively similar to the reference helicopter, the uncoupled system complexity index is slightly higher due to the tilt-able tail propulsor. Almost equally low indices are calculated for the multicopter configurations with eight rotors (EHANG 184, CityAirbus), as no dedicated pitch control systems and anti-torque measures have to be incorporated. The multicopter configuration Volocopter 2X, on the other hand, exhibits a nearly three times higher uncoupled system complexity index. This is due to the much higher thrust distribution on eighteen implemented rotors. The Lilium Jet features the highest amount of propulsors (36), which results in an even six times higher index compared to the reference. However, both configurations have one of the lowest number of diverse components since several identic assembly groups are installed. Considering maintenance effort, this could be an advantage since a defective assembly group may be replaced as a whole.

The hybrid-wing PAVs Aurora eVTOL and the Zee.Aero patent as well as the fan-based concept Neva AirQuadOne show the highest number of diverse components. Together with the tilt-configurations A^3 Vahana and the Joby S4 they are roughly on the same level with the reference helicopter.

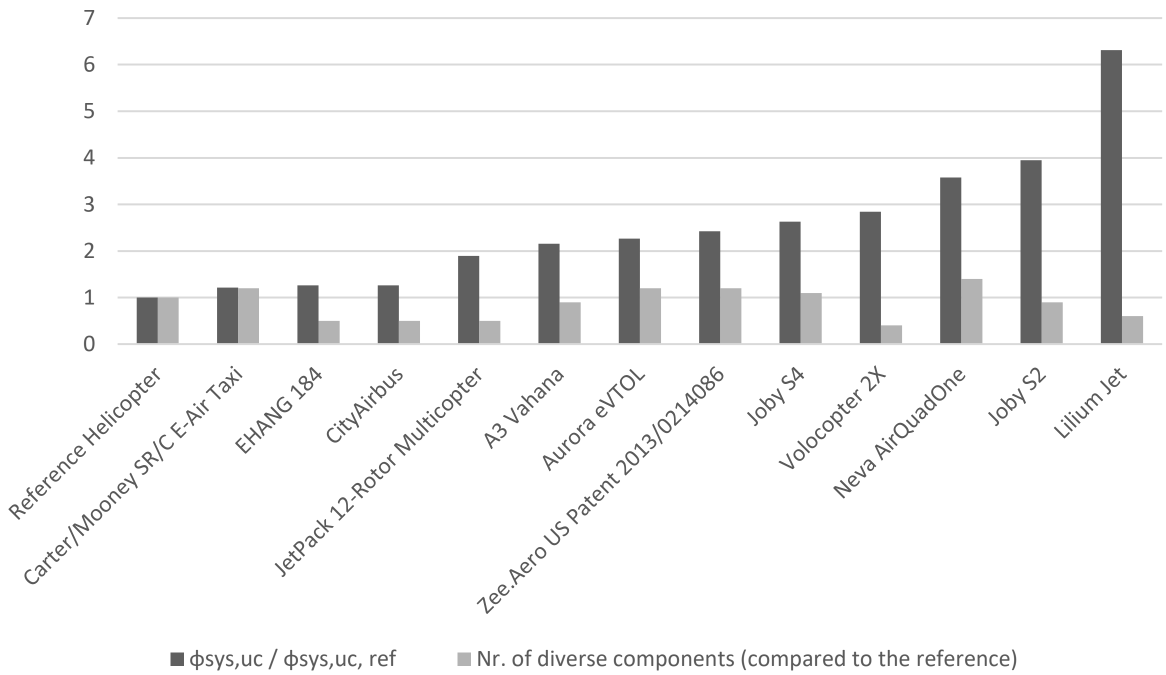

Figure 15: Normalized uncoupled system complexity and number of diverse components of fully-electric VTOL PAV configurations.

6.3 Coupled System Complexity

The calculated normalized coupled system complexity indices, $\phi_{sys,c}/\phi_{sys,c,ref}$, are presented in Fig. 16. The additionally considered degree of interconnectedness and influence of components leads to a grouping by vehicle class.

Multicopter concepts exhibit a low relative coupled system complexity index, most of them even lower than the reference configuration. This is because of the simple, uncoupled drive train architecture, fixed-pitch rotors and the elimination of physical flight control systems. The highest indices are determined for tilt-configurations due to tilt-mechanisms effecting multiple thrust vectors, or numerous complex tilt- and foldable propulsor arrangements. Hybrid-Wing PAVs like the Aurora eVTOL rank in the middle. Separating the propulsion systems for VTOL and cruise allows a simplification of each system and thus, to a lower coupled system complexity compared to tilt-concepts.

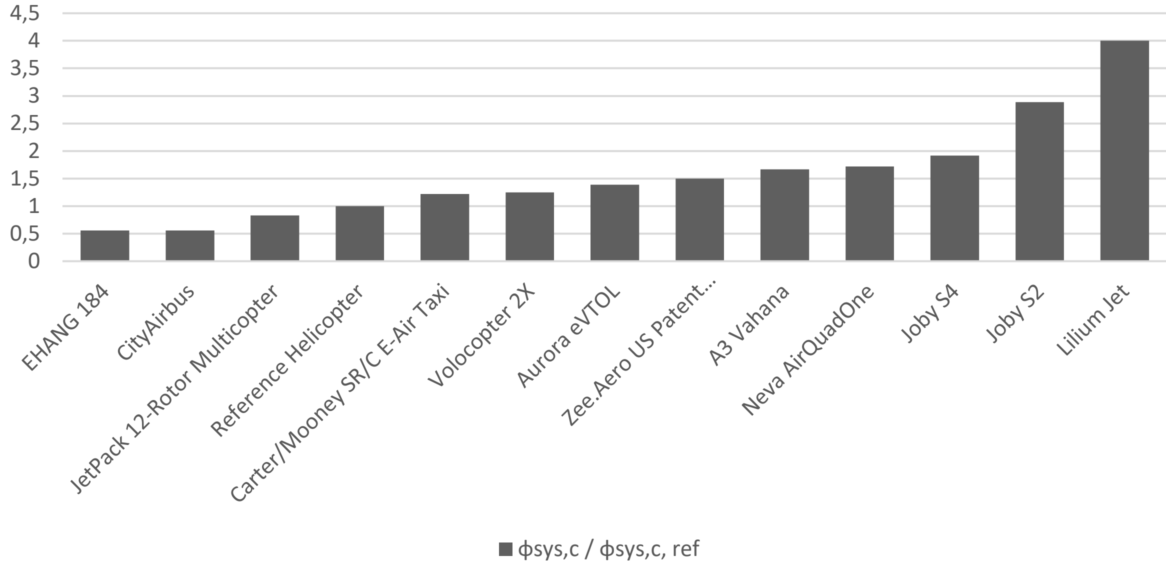

Figure 16: Normalized coupled system complexity of fully-electric VTOL PAV configurations.

7 CONCLUSIONS AND OUTLOOK

In this paper, a comprehensive overview of the emerging landscape of PAV configurations has been given. Various fundamentally different aircraft designs were classified by their take-off and landing abilities as well as lift production during cruise. Representative vehicles of each class including configurational characteristics were presented briefly. The class of PAVs cruising with rotary-wing lift only contains numerous multicopter configurations extensively based on distributed propulsion. Further, three PAV projects using fans for lift production were identified. Due to the attractive characteristics of electrical power distribution, an increased development activity of tilt-configurations was observed. Both tilt-wing mechanisms and tilt-rotors are incorporated by several manufacturers to enable VTOL for aircraft performing cruise with lift produced by fixed-wings. In the class of hybrid-wing configurations, six recent PAV projects were identified. The combination of a multicopter VTOL system and a fixed-wing arrangement for cruise seems to be a promising concept for reducing system complexity compared to tilt configurations. Considering tailsitters, no information on PAV concepts being in development is publically available.
As diverse as the presented vehicle morphologies is the spectrum of performance targets published by the manufacturers. High cruise efficiencies and high cruise speeds with VTOL capability are achieved, often at the expense of highly complex systems. To identify the most promising solutions, future studies on the potential of UAM regarding actual transport capacity as well as operational scenarios for PAVs must provide more detailed requirements.
The information on PAVs compiled in this paper was obtained from published data. To get a deeper insight on the actual vehicle performance, in a next step technical analysis based on consistent technology assumptions has to be conducted. Such analysis will have to include effects of synergistic propulsion-airframe integration and distributed electric propulsion. Further, assessment of PAVs has to be conducted in a more multidisciplinary way to quantify suitability for UAM. Therefore, other characteristics of the vehicles like noise emissions, production cost or operating cost have to be investigated.

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REFERENCES

[1] C. Sessa und R. Enei, „EU transport demand: Trends and drivers," European Union, 2009.

[2] J. Holden und N. Goel, „Fast-Forwarding to a Future of On-Demand Urban Air Transportation," 2016. [Online]. Available: https://www.uber.com/elevate.pdf. [Zugriff am 20 07 2017].

[3] M. Jump, P. Perfect G.D. Padfield, M. White, D. Floreano, P. Fua, J.-C. Zufferey, F. Schill, R. Siegwart, S. Bouabdallah, M. Decker, J. Schippl, M. Höfinger, F. Nieuwenhuizen und H. Bülthoff, „myCopter: Enabling Technologies for Personal Air Transport Systems," in *RAeS Rotorcraft Conference: The Future Rotorcraft – Enabling Capability Through the Application*, London, UK, 2011.

[4] M. D. Moore, „NASA Personal Air Transportation Technologies," in *SAE 2006 Transactions Journal of Aerospace*, SAE International, 2006.

[5] Roads and Transport Authority Dubai, „The Official Monthly Magazine of Dubai," 03 2017. [Online]. Available: https://www.rta.ae/links/magazine/masar/Al_Masar_105_Eng.pdf. [Zugriff am 20 07 2017].

[6] M. D. Moore, „Personal Air Vehicles: A Rural/Regional and Intra-Urban On-Demand Tranportation System," in *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years*, Dayton, Ohio, US, 2003.

[7] M. Urban, C. Jessberger, R. Rothfeld, M. Schmidt, V. Batteiger, M. Hornung und K. Plötner, „Multi-Modal Transport Hub Concept for Inner-City Airport Operation," in *Deutscher Luft- und Raumfahrtkongress*, Braunschweig, 2016.

[8] European Union, „Flightpath 2050: Europe's Vision for Aviation," European Union, Luxembourg, 2011.

[9] A. M. Stoll, J. Bevirt, M. D. Moore, W. J. Fredericks und N. K. Borer, „Drag Reduction Through Distributed Electric Propulsion," in *Aviation Technology, Integration, and Operations Conference*, Atlanta, Georgia, US, 2014.

[10] N. K. Borer, M. D. Patterson, J. K. Viken, M. D. Moore, S. Clarke, M. E. Redifer, R. J. Christie, A. M. Stoll, A. Dubois, J. Bevirt, A. R. Gibson, T. J. Foster und P. G. Osterkamp, „Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., US, 2016.

[11] J. Hermetz, M. Ridel und C. Döll, „Distributed Electric Propulsion for Small Business Aircraft: A Concept-Plane for Key-Technologies Investigations," in *30th Congress of the International Council of the Aeronautical Sciences 2016*, Daejeon, South Korea, 2016.

[12] Pipistrel d.o.o., „HYPSTAIR EU FP7 Project," [Online]. Available: http://www.hypstair.eu/. [Zugriff am 20 07 2017].

[13] L. Juvé, J. Fosse, E. Joubert und N. Fouquet, „Airbus Group Electrical Aircraft Program, The E-Fan Project," in *52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2016-4613)*, Salt Lake City, Utah, US, 2016.

[14] D. W. Hall, „Personal Air Vehicle & Flying Jeep Concepts," David Hall Consulting, Morro Bay, California, US, 2001.

[15] Terrafugia, „The Transition," Terrafugia, 2017. [Online]. Available: https://www.terrafugia.com/the-transition/. [Zugriff am 20 07 2017].

[16] Samson Motorworks, „Switchblade Flying Car," Samson Motorworks, 2012. [Online]. Available: http://www.samsonmotorworks.com/switchblade. [Zugriff am 20 07 2017].

[17] PAL-V International, „PAL-V," PAL-V International, 2017. [Online]. Available: https://www.pal-v.com/. [Zugriff am 20 07 2017].

[18] Carplane GmbH, „Road/Air Vehicle - Carplane GmbH," Carplane GmbH, [Online]. Available: https://www.carplane.de/. [Zugriff am 20 07 2017].

[19] AeroMobil, „AeroMobil: Flying Car," AeroMobil, 2017. [Online]. Available: https://www.aeromobil.com/flying-car/. [Zugriff am 20 07 2017].

[20] E. Kauh, „AVweb," Aviation Publishing Group, 23 06 2016. [Online]. Available: https://www.avweb.com/avwebflash/news/Terrafugia-Approved-For-Higher-Weight-Stall-Speed-226462-1.html. [Zugriff am 20 07 2017].

[21] Terrafugia, „TF-X," Terrafugia, 2017. [Online]. Available: https://www.terrafugia.com/tf-x/. [Zugriff am 20 07 2017].

[22] M. J. Hirschberg, „V/STOL Wheel, V/STOL Aircraft and Propulsion Concepts," [Online]. Available: https://vertipedia.vtol.org/vstol/wheel.htm.

[23] J. G. Leishman, Principles of Helicopter Aerodynamics, Cambrige University Press, 2006.

[24] Volocopter GmbH, „Volocopter," Volocopter GmbH, 2017. [Online]. Available: http://www.volocopter.com. [Zugriff am 20 07 2017].

[25] e-volo GmbH, „World Premiere of the Volocopter series model 2X," 04 2017. [Online]. Available: http://press.volocopter.com/index.php/press-releases-main/english-kategorie/109-world-premiere-of-the-volocopter-series-model-2x-the-flying-taxi-is-just-about-to-be-launched-onto-the-market. [Zugriff am 20 07 2017].

[26] Government of Dubai, Road and Transport Authority, „An agreement with German VOLOCOPTER to operate the Autonomous Aerial Taxi," 19 06 2017. [Online]. Available: https://www.rta.ae/wps/portal/rta/ae/about-rta/news-and-media/all-news/NewsDetails/an+agreement+with+german+volocopter+to+operate+the+autonomous+aerial+taxi. [Zugriff am 20 07 2017].

[27] Airbus S.A.S, „Rethinking Urban Air Mobility," Airbus S.A.S, 17 06 2017. [Online]. Available: http://www.airbus.com/newsroom/topics-in-focus/urban-air-mobility.html. [Zugriff am 20 07 2017].

[28] D. Perry, „FlightGlobal: City Airbus demonstrator to start flight tests in 2018," FlightGlobal, 21 06 2017. [Online]. Available: https://www.flightglobal.com/news/articles/paris-city-airbus-demonstrator-to-start-flight-test-438676/. [Zugriff am 20 07 2017].

[29] Airbus S.A.S, „Italdesign and Airbus unveil Pop.Up," 06 03 2017. [Online]. Available: http://www.airbus.com/newsroom/press-releases/de/2017/03/ITALDESIGN-AND-AIRBUS-UNVEIL-POPUP.html. [Zugriff am 20 07 2017].

[30] EHANG Inc., „EHANG 184," EHANG Inc., 2017. [Online]. Available: http://www.ehang.com/ehang184/. [Zugriff am 20 07 2017].

[31] L. Blain, „Jetpack pioneer David Mayman's new electric VTOL flying car project," New Atlas, 01 02 2017. [Online]. Available: http://newatlas.com/david-mayman-vtol-flying-car-jpa-interview/47700/. [Zugriff am 20 07 2017].

[32] Urban Aeronautics, „Technology," [Online]. Available: http://www.urbanaero.com/category/technology-1. [Zugriff am 20 07 2017].

[33] Urban Aeronautics, „Press Release April 207," 17 04 2017. [Online]. Available: http://www.urbanaero.com/category/2017. [Zugriff am 17 04 2017].

[34] Tactical Robots Ltd., „Products - Comorant," [Online]. Available: http://www.tactical-robotics.com/category/cormorant. [Zugriff am 20 07 2017].

[35] Neva Aerospace, „AirQuadOne," [Online]. Available: https://www.neva-aero.com/index.php/airquadone. [Zugriff am 20 07 2017].

[36] Leondardo, „Leonardo - Project Zero," 19 06 2013. [Online]. Available: http://www.leonardocompany.com/en/-/project-zero. [Zugriff am 20 07 2017].

[37] AeroKurier, „AeroKurier," 05 03 2013. [Online]. Available: http://www.aerokurier.de/general-aviation/hubschrauber/heli-expo-agustawestland-enthuellt-kipprotor-testtraeger-project-zero/488264. [Zugriff am 20 07 2017].

[38] D. Perry, „FlightGlobal," 16 02 2016. [Online]. Available: https://www.flightglobal.com/news/articles/singapore-project-zero-tiltrotor-to-gain-diesel-eng-421964/. [Zugriff am 20 07 2017].

[39] A. M. Stoll, J. Bevirt, P. P. Pei und E. V. Stilson, „Conceptual Design of the Joby S2 Electric VTOL PAV," in *Aviation Technology, Integration and Operations Conference*, Atlanta, Georgia, US, 2014.

[40] AHS International, „The Electric VTOL News," [Online]. Available: http://evtol.news/aircraft/joby-aviation/. [Zugriff am 20 07 2017].

[41] A³ by Airbus, „Vahana," 2017. [Online]. Available: https://vahana.aero/. [Zugriff am 20 07 2017].

[42] D. Muoio, „Business Insider," 19 05 2017. [Online]. Available: http://www.businessinsider.de/airbus-vahana-aircraft-cost-same-taxi-zach-lovering-2017-5?r=US&IR=T. [Zugriff am 20 07 2017].

[43] Lilium GmbH, „Lilium Technology," 2017. [Online]. Available: https://lilium.com/technology/. [Zugriff am 20 07 2017].

[44] XTI Aircraft, „TriFan 600," [Online]. Available: http://www.xtiaircraft.com/trifan-600/. [Zugriff am 20 07 2017].

[45] P. J. DeLorean, „Vertical takeoff and landing aircraft". US Patent US9085355 B2, 07 12 2012.

[46] AHS International, „DeLorean unveils DR-7 VTOL," 11 06 2017. [Online]. Available: http://evtol.news/2017/06/11/delorean-unveils-dr-7-evtol/. [Zugriff am 20 07 2017].

[47] AirspaceX, „AirspaceX - On demand air travel has landed," 2017. [Online]. Available: http://www.airspacex.com/. [Zugriff am 20 07 2017].

[48] Aurora Flight Sciences, „eVTOL AIRCRAFT," 05 2017. [Online]. Available: http://www.aurora.aero/wp-content/uploads/2017/05/evtol_Brochure_X.pdf. [Zugriff am 20 07 2017].

[49] H. Niedzballa, „Aircraft capable of vertical takeoff". US Patent US 2016/0236774 A1, 09 02 2016.

[50] I. Kroo, „Personal Aircraft". US Patent US 2013/0214086 A1, 11 02 2013.

[51] Aurora Flight Sciences, „eVTOL," 2017. [Online]. Available: http://www.aurora.aero/evtol/. [Zugriff am 20 07 2017].

[52] Carter Aviation Technologies, „Uber Elevate Summit Presentation," 2017. [Online]. Available: http://www.cartercopters.com/system/sdocs/28/original/Carter%20Presentation.2017-04-25.Uber%20Elevate%20Summit%202.pdf?1493651657. [Zugriff am 20 07 2017].

[53] M. D. Moore, „NASA Puffin Electric Tailsitter VTOL Concept," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, Texas, US, 2010.

[54] J. Bijewitz, A. Seitz und M. Hornung, „A Review of Recent Aicraft Concepts Employing Synergistic Propulsion-Airframe Integration," in *30th Congress of the International Council of the Aeronautical Sciences*, Daejeon, South Korea, 2016.

[55] ACG Aviation, „Xplorair," 2016. [Online]. Available: http://www.acg-aviation.com/en/concept-en/xplorair/. [Zugriff am 20 07 2017].

[56] Cartivator, „Cartivator Skydrive," 2017. [Online]. Available: http://cartivator.com/skydrive. [Zugriff am 20 07 2017].

[57] Faradair Aerospace Limited, „Faradair BEHA," 2017. [Online]. Available: http://faradair.com/fwp/introducing-beha/. [Zugriff am 20 07 2017].

[58] FLUTR, „Flutr Air Vehicles," 2017. [Online]. Available: http://www.flutrmotors.com/. [Zugriff am 20 07 2017].

[59] A. Stoll, „Analysis and Full Scale Testing of the Joby S4 Propulsion System," 2015.

[60] Kitty Hawk Corporation, „Kitty Hawk Flyer," 2017. [Online]. Available: https://kittyhawk.aero/. [Zugriff am 20 07 2017].

[61] Moller International, „SkyCar200," 2016. [Online]. Available: http://www.moller.com/moller_skycar200.html. [Zugriff am 20 07 2017].

[62] Moller International, „SkyCar400," 2016. [Online]. Available: http://www.moller.com/moller_skycar400.html. [Zugriff am 20 07 2017].

[63] Moller International, „Neuera 200," 2016. [Online]. Available: http://www.moller.com/moller_neuera.html. [Zugriff am 20 07 2017].

[64] The Engineer, Centaur Communications Ltd., „Silent flight: Sikorsky's electric helicopter," interconnect/it, 15 11 2010. [Online]. Available: https://www.theengineer.co.uk/issues/15-november-2010/silent-flight-sikorskys-electric-helicopter/. [Zugriff am 20 07 2017].

[65] Workhorse Group Inc., „SureFly,“ 2017. [Online]. Available: http://workhorse.com/index.php/surefly. [Zugriff am 20 07 2017].

[66] Uber, „Uber Elevate,“ Uber Technologies Inc., 2016. [Online]. Available: https://www.uber.com/info/elevate/. [Zugriff am 20 07 2017].

[67] K. Barnstorff, „The Puffin: A Passion for Personal Flight,“ 02 08 2010. [Online]. Available: https://www.nasa.gov/topics/technology/features/puffin.html. [Zugriff am 28 09 2017].

APPENDIX

Table 1: Synopsis of current PAV concepts and technical demonstrators.

No.	Concept Designation	Class[1]	Cruise Speed [km/h]	Range[2] [km]	Seats [-]	Energy Source	Refs.
1	A^3 Vahana	E	175	-	1	Electric	[41]
2	ACG Aviation PX200	-	200	800	1	Fuel	[55]
3	AeroMobil 4.0	A-TR[3]	259	750	2	Fuel	[19]
4	Airbus CityAirbus	C	-	-	4	Electric	[27]
5	Airbus US Patent 2016/0236774	F	-	-	2	?	[49]
6	Airbus E-Fan 2.0	A	160	105	2	Electric	[13]
7	Airbus Pop.Up	C-MR[4]	100[5]	-	2	Electric	[29]
8	AirspaceX MOBi	F-MR[4]	113[5]	< 185	4	Electric	[47]
9	AugustaWestland Project Zero	E	-	-	1	Electric	[36]
10	Aurora eVTOL	F	200	75	2	Electric	[48]
11	Carplane	A-TR[3]	200	833	2	Fuel	[18]
12	Carter/Mooney SR/C E-Air Taxi	F	280	210	2	Electric	[52]
13	Cartivator Skydrive	C-TR[3]	100	-	1	?	[56]
14	DeLorean DR-7	E	240	-	2	Electric	[45]
15	EHANG 184	C	100	38	1	Electric	[30]
16	Faradair Beha	A	-	-	6	Hybrid-Electric	[57]
17	FLUTR	C	250[5]	-	2	H2/Fuel	[58]
18	JetPack 12-Rotor Multicopter	C	-	-	1	Electric	[31]
19	Joby S2	E	322	370	2	Electric	[39]
20	Joby S4	E	320	335	4	Electric	[59]
21	Kitty Hawk Flyer	C	-	-	1	Fuel	[60]
22	Lilium Jet	E	250	300	5	Electric	[43]
23	Lilium Jet "Eagle"-Prototype	E	-	-	2	Electric	[43]
24	Moller Skycar 200	F-TR[4]	330	800	2	Hybrid-Electric	[61]
25	Moller Skycar 400	E-TR[3]	457	1200	4	Fuel	[62]
26	Moller Neuera 200	D	120	-	2	Fuel	[63]
27	NASA LEAPTech	A	322	370	4	Electric	[9]
28	NASA Puffin	G	212	92	1	Electric	[53]
29	NASA SCEPTOR	A	278	-	4	Electric	[10]
30	Neva AirQuadOne	D	80	27	1	Electric	[35]
31	ONERA Ampere	A	250	500	4-6	H2/Electric	[11]
32	PAL-V Liberty	B-TR[3]	140	400	2	Fuel	[17]
33	Samson Switchblade	A-TR[3]	250	830	2	Fuel	[16]
34	Sikorsky Firefly	C	145[5]	36	1	Electric	[64]
35	Terrafugia TF-X	F-TR[3]	320	800	4	Hybrid-Electric	[21]
36	Terrafugia Transition	A-TR[3]	160	740	4	Fuel	[15]
37	UrbanAeronautics City-Hawk	D	-	-	4	H2	[33]
38	Volocopter 2X	C	70	27	2	Electric	[24]
39	Volocopter VC 100	C	-	-	1	Electric	[24]
40	Volocopter VC 400	C	-	-	4	Electric	[24]
41	Workhorse SureFly	C	112	112	2	Fuel	[65]
42	XTI Trifan 600	E	630	2030	6	Hybrid-Electric	[44]
43	Zee.Aero US Patent 2013/0214086	F	-	-	1	Electric	[50]

[1] See Fig. 1 for nomenclature
[2] Maximum range at most efficient cruise speed
[3] Roadable, with transformation mechanisms (TR)
[4] Roadable, modular concept (MR)
[5] Maximum Cruise Speed