Development of eVTOL Aircraft For Urban Air Mobility At Joby Aviation

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ABSTRACT
Typical existing VTOL aircraft—notably, helicopters—are limited in their suitability to civil transportation due to high operating costs, high noise levels, and safety levels below other forms of commercial aviation. Modern electric propulsion technology offers potential solutions to these drawbacks and potentially allows for practical VTOL aircraft configurations less compromised than traditional solutions. Through a multiyear study of various configurations, Joby selected the tilt-propeller as the optimal approach to safely achieve relatively high speed, long range, and low noise in urban air mobility operations. Full-scale flight testing began with a demonstrator phase, demonstrating successful transition between thrustborne and wingborne flight in 2017, and proceeded to a pre-production prototype phase, demonstrating high performance, including a 249 km (134 nm) VTOL flight and a true airspeed of over 322 km/h (174 kt), as well as low noise, measuring 45 dB(A) at 500 m (1,640 ft) equivalent in flyover and under 65 dB(A) at 100 m (328 ft) equivalent in hover.

INTRODUCTION
While existing VTOL aircraft theoretically provide an ability to take off and land almost anywhere and circumvent road traffic, as well as geographical barriers such as mountains or waterways, to transport passengers to, from, and around cities relatively quickly, they have been unable to become a practical everyday transportation solution for most people due to a range of limitations. In the notable case of helicopters, the most successful VTOL aircraft to date for civil transportation:

• Helicopter trips are prohibitively expensive for the vast majority of the traveling public.
• The high noise level of helicopters often restricts their ability to take off and land near where many people live and work, meaning would-be helicopter passengers often need to travel across the city (or outside of the city) to and from landing pads, limiting the net time savings these helicopter trips are able to provide.
• Travel via helicopter is not as safe as other forms of commercial aviation.

Electric propulsion provides the opportunity to address all the above issues:

• By running off batteries and charging from sustainable energy sources, electric aircraft can be operated with virtually zero carbon footprint.
• Electric propulsion systems require drastically less maintenance than traditional combustion powerplants, lowering operating costs by reducing maintenance expenditure. (While electric aircraft are too new to validate quantified maintenance cost predictions against past performance, results from ground vehicles are illuminating, where the USDOE found in 2021 that light-duty battery-electric vehicles required about 40% lower scheduled maintenance costs than equivalent internal combustion-powered vehicles (Ref. 1); similar savings are expected to be realized in aircraft.)
• Electric propulsion frees the aircraft designer from many constraints inherent to the use of traditional combustion
propulsion systems—particularly, the need to use a small number of large, heavy combustion engines—and instead allows for a large number of small and lightweight electric motors which can be placed in more favorable locations. Without these design constraints, electric VTOL aircraft can realize configurations that are more efficient in cruise, reducing energy requirements and allowing for higher cruise speeds. Combined with the high efficiency of electric propulsion systems and the relatively low price of electricity compared to fossil fuels, the energy costs of a flight can be significantly lower than they would with a helicopter.

- Electric motors are many times quieter than combustion engines of similar power. In addition, the high specific torque of electric motors and the flexibility provided by the ability to employ many small electric motors around the aircraft open the door for quieter propulsion—for example, the high tip speeds generally required of helicopter rotors can be avoided, as can noisy tail rotors.

- The ability to use a large number of smaller motors imparts yet another benefit: no longer must the occupants accept the safety compromises of the large number of single points of failure of a helicopter, since a redundant distributed propulsion architecture can be employed in which even an entire motor or propeller can fail without any significant loss of control.

These points have been expanded upon in NASA (Ref. 2) and Uber Elevate (Ref. 3) publications.

Joby Aviation was founded in 2009 when it became apparent that various elements of technology, such as electric propulsion, batteries, fly-by-wire controls and the associated modern inexpensive and miniaturized electronics, and modern composite structures, had advanced to the point that they showed great promise for applications for VTOL aircraft for personal transportation. This paper describes the company history that led to its development of a 5-seat electric tilt-propeller aircraft, shown in Figure 1, and details of the design of this aircraft.

COMPANY AND DEVELOPMENT HISTORY

The first VTOL aircraft design seriously considered by Joby Aviation was the Monarch, announced in 2010 and illustrated in Figure 2. This was a tilt-wing adaption of the high-performance Windward Performance SparrowHawk sailplane, and was designed to deliver VTOL capability to a single occupant with the ability to fly 161 km (87 nm) at 161 km/h (87 kt) on a radically low amount of energy. As Joby developed its motor design capability, the first full-scale (albeit CTOL) occupied aircraft designs began to take off under Joby power: first Dale Kramer’s Electric Lazair in 2011, powered by two 13 kW (17 hp) motors, followed by the Earthstar eGull in 2012, powered initially by a single 20 kW (27 hp) Joby motor, and later, a 30 kW (40 hp) model. Not long into the development of the Monarch, it became apparent that adapting a pre-existing aircraft into an electric VTOL design would not impart as much of a cost and schedule benefit as hoped, and therefore designing a from-scratch aircraft (which could be a less compromised design) would be a better use of resources. Work on the Monarch stopped in favor of returning to the drawing board for a clean-sheet design.

Over the next few years, as Joby explored a wide range of electric VTOL concepts for urban air mobility, they also began a partnership with NASA on research and development of electric VTOL UAV and electric CTOL concepts. This began with cooperation on the Greased Lightning tilt-wing electric VTOL UAV (which was similar in general concept to the Joby Monarch design), before Joby shifted to the NASA-funded Lotus long-endurance electric VTOL UAV project. Based on NASA’s Dos Samara design concept (Ref. 4), this unusual aircraft featured wingtip-mounted two-bladed rotors used in VTOL and transition; once the aircraft had taken off and accelerated past stall speed, the rotors stopped and the blade pairs scissored together to form an extended wingtip. This innovative concept allows the lifting surfaces used as rotors in VTOL to be repurposed as additional wing area in cruise, enhancing the aircraft’s loiter performance. A tilting tail propeller provided pitch authority in thrustborne flight and propulsion in cruise. The Lotus design is illustrated in Figure 3 and described in greater detail in publications by Stoll et al. (Refs. 5–7).

Joby and NASA, along with the electric aircraft R&D/integration company ESAero, began collaboration on another inventive electric aircraft idea in 2013: the Leading Edge
Asynchronous Propeller Technology, or “LEAPTech,” program. This project addressed the competing desires of general aviation CTOL airplanes for low stall speeds (which improve safety) and efficient cruise performance (which is vital for battery-powered aircraft) by pairing high wing loading with 18 small propellers mounted on the wing leading edge, each driven by its own electric motor. On takeoff and landing, these propellers were powered up to increase the dynamic pressure over the wing, allowing the wing to lift the aircraft at much lower takeoff and landing speeds than its small size would otherwise allow. This design was tested at full scale at a low cost and on a tight schedule by outfitting a Peterbilt semi-truck with a suspended test platform, mounting the 9-meter (31 ft) span wing with the 18 motors and propellers, and driving at takeoff and landing speeds (up to about 40 m/s or 75 kt) across the dry lakebed at NASA Armstrong Flight Research Center. This test methodology allowed the project team to collect full-scale experimental data without the large cost and time requirements of traditional wind tunnel testing. The LEAPTech program is described more thoroughly by Stoll (Ref. 8). The success of this program led to the full-scale flyable demonstrator of this technology, the X-57 Maxwell; Joby was heavily involved in the design of the X-57 (Ref. 9). In a tangential NASA research project, Joby also studied the effect of the application of distributed electric propulsion to CTOL aircraft designs for low-density short-range airline operations—so-called “thin haul” routes (Refs. 10, 11).

During this time period, but separately from the collaboration with NASA, Joby was independently deep in concept development for its electric VTOL personal transportation aircraft, a process involving internal CFD simulations, scale model construction, CAD layout studies, and performance and economics model development. Joby adopted the following priorities for its aircraft design:

1. Safety: While the accident rates of small general aviation aircraft have improved over the years, current levels leave significant room for improvement. Therefore, Joby prioritized safety in the aircraft design, taking full advantage of the reliability of electric propulsion and the redundant configurations it facilities, as well as the safety aids possible with modern sensors and fly-by-wire control systems (Ref. 3).

2. Acoustics: In order to be a practical transportation solution as envisioned, the aircraft must be able to operate from residential and business areas. Largely due to their noise, helicopters have been driven out of most parts of many cities, so this is a problem that must be seriously addressed for the aircraft to be practical in its intended use case. Because of the noise characteristics of electric propulsion mentioned previously, there is great potential for the intrepid inventor to vastly improve on the acoustics of traditional VTOL aircraft.

3. Affordability: Joby’s goal of creating time savings for a great number of people is not achieved by developing a transportation method usable only by the wealthy. Tackling affordability requires striking a balance between minimal energy usage (which generally precludes heavier designs, even though a heavier aircraft can achieve the desired payload-range performance with a cruder design), maintenance requirements, and flight times.

4. Performance: To provide significant utility over existing transportation options, operation in most cities will require appreciable range and block speeds. High block speeds are particularly important when the passengers must travel some distance to and/or from the vertipads, due to the additional time required for these travel segments.

5. Comfort: To be viable as a desirable transportation option for the masses, human factors considerations are of high importance. Ingress and egress must be comfortable and easy, ride quality cannot be too bumpy or involve uncomfortable gradients or shifts in accelerations or attitude, the seats must be comfortable and the cabin should not feel cramped, and passenger visibility must be good.

A range requirement has a different impact on the design of a battery-powered aircraft than a traditional fuel-powered design, because the specific energy of contemporary batteries is at best an order of magnitude lower than that of conventional fuels (even given the significant improvements in battery capacity over the past decade). Therefore, the fundamental bounds on various design aspects required to achieve the desired range must be carefully considered. The cruise range \( R \) of an electric aircraft can be expressed as

\[
R = \frac{E}{W_b} \frac{L}{D_e} \frac{W}{W_b} \tag{1}
\]

where \( E/W_b \) is the weight-specific energy of the battery pack, \( L/D_e \) is the effective lift-to-drag ratio (accounting for aerodynamic, propulsive, and powertrain efficiency) in cruise, and \( W_b/W \) is the battery mass fraction. Noting that weight-specific energy can be expressed in units of distance (with a conversion factor of approximately 1.00 Wh/kg = 367 meters), this equation provides a very simple assessment for bounding the design requirements of an electric aircraft. (The physical significance of expressing specific energy in units of distance is that this value is the altitude at which the energy content of the battery will be equal to its gravitational potential energy.) For example, with a specific energy of 80 km (218 Wh/kg), a cruise \( L/D_e \) of 12, and a battery mass fraction of \( \frac{1}{3} \), the cruise range will be simply \( R = (80 \text{ km})(12)/(\frac{1}{3}) = 320 \text{ km} \). (As this equation as described relates only the cruise range, additional battery mass must be bookkept for the energy requirements of the takeoff and landing segments.)

In working towards meeting the above goals, Joby considered a large number of configurations, including:
**Tilt-wing** A tilt-wing imparts some advantage in takeoff and conversion to wingborne flight, where download is minimal and the propwash actually improves flow attachment and the lifting performance of the wing. However, in order to achieve this, relatively high disk loading is typically required to adequately energize the airflow over the wing, which drives up power requirements, reducing or negating the benefit of lower download. Additionally, the same factors that lead to these advantages result in a limited deceleration/descent envelope on reconversion, when the requirements for low or negative forward thrust coupled with enough lift and upwards thrust to support the aircraft’s weight are difficult to meet simultaneously. This is because low thrust results in lower-velocity propwash, and resultantly, the flow over the wing will not remain attached as readily as the wing tilts up to rotate the thrust vector. As an example, NASA found that the low-speed descent rate limits of the full-scale Canadair CL-84 tilt-wing aircraft did not “appear to provide enough margin for operational use” (Ref. 12). This problem was repeatedly encountered in tilt-wing flight test programs (Ref. 13), and contributed to the abandonment of the tilt-wing concept in the 1970s, after many full-scale demonstrators had flown. While the performance of these tilt-wing designs was evaluated in the context of military operational requirements, a generous descent and deceleration envelope during approach and landing is also desirable in a high-cadence urban air taxi.

Even if the reconversion performance limits were able to be accommodated acceptably, another concern presented itself: in the aim of eliminating any significant single points of failure to maximize safety, tilt wings possess an additional complication of considering the failure of a wing tilt mechanism. While two tilting wings or tails, such as on the Acubed Vahana or NASA Greased Lightning, can provide a favorable layout for achieving adequate pitch control authority in thrustborne flight, the scenario of a failure of either one of the two tilting mechanisms independently must be able to be accommodated.

**Tilt-duct** The tilt-duct configuration, in which ducted fans are tilted through a range of around 90° between takeoff/landing and wingborne flight, presented challenges in meeting the aircraft design goals. If the disk loading is low, the ducts will be large enough that their weight, and, particularly, parasitic drag contributions can become substantial; this was encountered in the Bell X-22 tilt-duct aircraft, which was flight tested in the 1960s (Ref. 14). However, if disk loading is increased (by using smaller ducted fans) such that these compromises are significantly reduced, then, even with the hover efficiency gains of ducting, the takeoff and landing power can become extremely large. This complicates thermal management propulsion system and drives up the weight of the associated power electronics, and reduces the usable energy from batteries, which must then be able to output at a high discharge rate at the end of the flight. Additionally, high disk loading is associated with high noise generation (Ref. 15), and ducting can ameliorate this only to an extent.

**Lift plus cruise with stopping lift propellers** This configuration, adopted by electric VTOL aircraft such as the Beta ALIA and Wisk Cora, promises an attractive high degree of mechanical simplicity, since fewer or no tilt actuators are needed, and reasonably-high cruise speeds may be practically attainable without requiring variable pitch mechanisms on the cruise propellers. However, the additional drag of the stopped propellers in cruise is significant (limiting $L/D_c$ in Equation 1), and Joby was not able to arrive at a design employing this configuration with satisfactory efficiency at the cruise speeds of interest.

**Tilt-propeller** In the tilt-propeller configuration, multiple tilting propellers provide vertical force in thrustborne flight and tilt to provide propulsion in wingborne flight. Instead of resorting to the complicated cyclic pitch mechanisms required by helicopters and tilt-rotors, tilt-propeller configurations achieve control in thrustborne flight by independently varying the thrust of multiple propulsion elements spaced around the aircraft. Additionally, the use of a larger number of smaller rigid propellers, instead of two large articulated or flexible proprotors, greatly ameliorates whirl flutter issues which impose significant constraints on the design of tilt-rotors. This configuration was pioneered by Curtiss-Wright in the late 1950s and early 1960s. However, there is not a practical solution for powering multiple propellers spaced around the aircraft in a robust and failure-tolerant manner with traditional propulsion technology, where power transmission must be accomplished with driveshafts and gearboxes rather than electrical cables, as illustrated in Figure 4. Traditional propulsion technology, coupled with download considerations, also limits where propellers can be placed; because of this, Curtiss-Wright was driven to adopt a less efficient tandem wing configuration, although they would have preferred a more conventional configuration with four wing-mounted propellers, had it been practical to accomplish (Ref. 16). Thus it was that this promising concept remained effectively unrealized for about 50 years, until the advent of electrical propulsion provided strategies to address these issues.

Although a tilt-propeller deftly circumvents the aforementioned reconversion issues of the tilt-wing, and generally is able to navigate a much more generous transition corridor by
decoupling the angle of attack of the wing from the thrust vector angle (Ref. 17), it pays a price in download in thrustborne flight. While electric propulsion provided a straightforward path to address the problems of drivetrain complexity and layout limitations that had hampered the tilt-propeller configuration to date, Joby faced an additional challenge in laying out the propeller locations to provide adequate control and maneuverability even in the event of the failure of any motor, while avoiding significant download over the wing and/or tail. The key to solving this challenge was found in actuating wing-mounted propellers along with the motors that power them using a linkage design that pushes the propellers forward when tilting up, allowing their downwash to clear the wing in hover and reducing download to tolerable levels. This is apparent in Figure 5, which overlays the propeller locations in both wingborne (0º tilt) and thrustborne (90º tilt) orientations: the propellers on the wingtips and tail translate aft as they tilt up, while the propellers mounted mid-span on the wing are actuated with linkages and translate forwards as they tilt up. (Download on the wingtips and tail is not as consequential due to the presence of control surfaces that are able to deflect down at low speeds.)

**Design maturation**

By early 2014, Joby had finally arrived at a general configuration for its electric VTOL personal transportation aircraft that met all of the team’s demanding desires. The design was initially named the “S2,” and was a two-seater with 322 km (174 nm) of range and a cruise speed of 322 km/h (174 kt). Tilting propellers covered the leading edges of the wing and V-tail (Ref. 18). An early rendering of the S2 concept is presented in Figure 6.

As development of this concept progressed and design choices were analyzed in further detail, the number of motors on the S2 was reduced from 12 to 6, in a complex tradeoff involving, among other considerations, disk loading, wingspan, wing area, and excess thrust requirements for motor-out performance. As an example of one of these considerations, the wing aspect ratio \( AR \), the total number of propellers \( N \), the fraction of propellers mounted on the wing \( f_w \), the wing loading \( W/S \), and the disk loading \( W/A \) are constrained in the following relation (which is simplified for illustrative purposes to ignore the fuselage width):

\[
AR \geq \frac{4}{\pi} \frac{(N f_w - 1)^2}{N} \frac{W/S}{W/A}
\]  

(2)

A low disk loading is desired because it reduces power requirements during vertical takeoffs and landings, which allows for smaller, lighter power electronics (such as inverters) and cooling systems. (Since electric motors are chiefly sized by torque, rather than power, disk loading does not strongly influence motor weight at a fixed propeller tip speed.) Additionally, lower disk loading is associated with less noise generation at the same thrust and tip speed (Ref. 15). A larger number of propellers will decrease the required relative thrust increment to trim in a motor-out scenario, which scales approximately with \( N/(N - 2) \), but when combined with low disk loading, the above equation indicates a high wing aspect ratio and/or a low wing loading will be required. A high aspect ratio may unacceptably drive up wing structural weight, and a low wing loading may lead to excessive wing wetted area and the associated parasite drag, and may negatively affect ride quality. For these reasons and many others, the successful design of such a configuration is a careful balance of a large number of factors.

Although reducing the number of propellers disproportionately increases the motor performance requirements due to motor-out considerations, this effect was tempered by attaining a more efficient geometric arrangement of the propellers when reducing the number to six. Although the motor-out relative thrust requirement is given by \( N/(N - 2) \) in an ideal case, asymmetric layouts will result in a higher factor. This is illustrated by the examples in Figure 7, which show the ideal (minimax) thrust redistribution to maintain roll and pitch trim given a loss of the right wingtip propeller for three different six-propeller geometries. In the first case, the motors must be able to produce 16% more thrust than in the third (ideal) case (174% nominal compared to 150% nominal). By thoughtfully designing the tilt mechanisms, Joby was able to attain close to
the optimum propeller layout at 90º tilt, without unduly con-
straining the locations of the propellers at 0º tilt.

In early 2015, as focus began to solidify on the air taxi operat-
ing model as the most effective way to employ the aircraft, the
design was enlarged from two seats to four seats (which can
split the cost of the pilot amongst up to three passengers rather
than only one), which necessitated a name change from “S2”
to “S4.” To allow room for rear passengers and a luggage com-
partment, and to increase safety on the ground by positioning
the propellers higher, the mid-mounted wing was raised to a
high wing. A polyhedral wing shape was adopted: dihedral
in the inner span raises the inboard propeller nacelles, easing
ingress and egress and improving visibility to the sides, and
anhedral on the outer span lowers the wingtip propellers so
that their thrust line is close to the center of gravity in wing-
borne flight.

Development progressed rapidly, with the first of a couple of
quarter-scale remotely-piloted aircraft taking to the air in 2015
(one of which is shown in flight in Figure 8), and the first full-
scale technology demonstrator completing its first full trans-
ition between thrustborne and wingborne flight in summer
2017 (also remotely-piloted). To the authors’ knowledge, this
was the first successful transition flight of a full-scale tilt-
propeller aircraft using only propellers and control surfaces
for control, finally realizing the vision and potential of the
idea pioneered by Curtiss-Wright over 50 years prior. A full-
scale demonstrator in wingborne flight is shown in Figure 9.
Full-scale flight testing validated Joby’s design concept for
the aircraft, demonstrating straightforward and robust transition performance and the desired low noise levels. Flight test
results of shaft tilt angle vs. normalized airspeed for trimmed
flight weight are shown in Figure 10.

This first demonstrator also first brought Joby’s vision of en-
hanced safety through redundancy to a full-scale flying air-
craft. Most obviously, this is realized through a multitude of
independent motors and propellers (such that flight can con-
tinue given the complete failure of any one), but there are fur-
ther levels of redundancy: each motor is dual-wound and pow-
ered by two inverters, each of which is independently powered
by a different battery pack. This allows the aircraft to con-
tinue flight even in the event of the failure of an entire battery
pack (even in power-hungry conditions such as a hover out
of ground effect); in addition, if an inverter were to fail, the
motor can continue operating on its remaining inverter. The
redundant distributed architecture is illustrated in Figure 11.
In an additional boost to safety, the aircraft can readily perform conventional landings in the event of a failure in any of the vertical lift components, without requiring the sacrifice of propellers or any other components (in contrast to a traditional tilt-rotor, which would destroy its two large proprotors in a conventional landing). The aircraft can also readily perform rolling takeoffs, should the need arise. The control surface arrangement also follows the philosophy of mechanical redundancy, with four independent ailerons and six independent ruddervators. Each control surface is controlled by an independent electric actuator mounted on the inboard edge. Additionally, the fly-by-wire system is triplex-redundant.

In 2017, Joby decided to again enlarge the design, this time from four to five seats (now seating one pilot and four passengers). This further improves operating economics by sharing the cost of the pilot among up to four passengers instead of three, and allows for more efficient vertiport utilization by transporting more customers per aircraft. This enlargement also moved the pilot to a separate row, providing for better physical separation of the pilot from the passengers.

This final, five-seat iteration of the design (the name of which has not been announced at the time of writing, “S4” referring to the earlier four-seat design) first took to the air in 2019 in the form of an optionally-occupied pre-production prototype. This design is shown in flight in Figure 12, and on the ground with an S4 demonstrator and a subscale S4 in Figure 13. Multiple pre-production prototypes were built to validate the performance and reliability of the aircraft and its redundant systems. As part of this validation, these aircraft have, to date, demonstrated a VTOL flight of 249 km (134 nm) range (Ref. 19), an endurance of 67 minutes on a VTOL flight, a true airspeed of over 322 km/h (174 kt), and flight at an altitude of 3,400 km (11,000 ft); these abilities significantly surpass the demonstrated performance of any other eVTOL aircraft that has been publicly announced. These pre-production prototypes have performed hundreds of test flights to date, including some with a pilot onboard. (While these prototypes can be flown remotely, a pilot will be onboard in operational service to enable integration with the existing national airspace system.)

Throughout the design process of the aircraft, many computational and full-scale experimental studies (using analysis tools such as the OVERFLOW CFD code and the PSU-WOPWOP acoustics code) were performed to optimize the propeller design for acoustics without unduly sacrificing efficiency (Ref. 20). Figure 14 shows a sampling of experimental blade designs tested in these design studies. In acoustics flight testing of a pre-production prototype performed by NASA in 2021, free-field peak flyover noise was measured at 45 dB(A) at 500 m (1,640 ft) from the aircraft, and noise during hover (both in and out of ground effect) was below the design goal of 65 dB(A) at 100 m (328 ft), when adjusted for observer distance using spherical spreading relations. Spectral analysis of flyover noise shows significantly lower tonal content than similarly-sized conventional airplanes and helicopters flying at the same speed, which allows the Joby aircraft to blend into the ambient acoustic environment in a way that is not possible for comparable conventional aircraft (Ref. 21).

**OVERVIEW OF AIRCRAFT SYSTEMS**

The design of the aircraft incorporates innovative features not just in its architecture, but internally as well. Inspired by groundbreaking work on the experimental VAAC Harrier VTOL research platform (Ref. 22) and later the F-35, the Joby aircraft employs a control strategy referred to as “unified flight control.” VTOL aircraft are traditionally difficult and relatively dangerous to pilot due to changing effects of control inputs between thrustborne and wingborne flight—for example, in a Harrier, increasing the throttle in hover increases the climb rate, while increasing throttle in wingborne flight increases the airspeed, and in transition it accomplishes a bit of both effects. This discrepancy makes the aircraft less intuitive to pilot and impedes the development of quick piloting reflexes. In contrast, the unified flight control strategy takes advantage of a fly-by-wire system’s ability to abstract pilot inputs (such as pulling back on the stick) from control outputs (such as increasing propeller RPM, or deflecting a control surface) to provide the same type of aircraft behavior for given
In addition to unified flight control, piloting the aircraft is also made safer and easier by envelope protection functions of the flight control system, which limit maximum airspeed, angle of attack, and normal load factor.

The aircraft is controlled by a right sidestick (see Figure 15) and a throttle-like inceptor on the left; pedals are not needed. The sidestick controls the vertical axis, bank angle, and roll rate, and the left-hand inceptor controls longitudinal acceleration. For flight in and close to hover, a translational rate command mode is automatically engaged; this mode allows the pilot to easily make positioning changes, and returns the aircraft to a stationary hover if the controls are released, even in a crosswind. Translational rate command has been shown to be the optimum control strategy for precise control and low pilot workload in hover (Ref. 23).

Four independent liquid-cooled lithium-ion battery packs, with a total capacity of approximately 150 kWh, are located inside the inboard wing sections and inboard propeller nacelles, as illustrated in Figure 16. This placement improves safety by locating the batteries away from passengers. The battery packs are flush with the lower surface of the wing and nacelle surfaces to provide easy access for removal and maintenance. A vent associated with each battery pack vents hot gas overboard in the unlikely event of a thermal runaway. The battery cells utilize robust and proven automotive cell construction and chemistry; an 811 nickel-manganese-cobalt cathode and graphite anode were chosen, following internal testing, to deliver the optimal compromise between the specific energy required to fly 241 km (130 nm), the specific power required to takeoff and land vertically, and the cycle life required to deliver an affordable service (Ref. 19).

The six propulsion motors drive the propellers directly, without gearboxes, and are liquid-cooled; a fan pulls air past each motor and through an exhaust vent at the base of each nacelle. The torque density of the motor and inverter combination is approximately 60 Nm/kg (20 ft-lb/lb). To put that figure in perspective, a Tesla Model 3 motor alone (without inverter) delivers only about 10 Nm/kg (3.3 ft-lb/lb) (Refs. 24, 25). An installed propulsion motor is shown in Figure 17.

Carbon fiber materials are used throughout the vehicle structure, propulsion systems, and interior components, in addition to multiple structural additive titanium components, manufactured using laser powder bed fusion technology.

Specifications of the production aircraft are given in Table 1.

**INDUSTRY JOINT ACTION**

As Joby and other companies progress toward certifying eVTOL aircraft and launching air taxi services, there are numerous areas where collaboration between actors will benefit all involved.

Development of reliable predictive aerodynamic performance and controls tools at medium fidelity levels would reduce barriers to entry and ensure safety across the industry. A greater
Figure 15: The control stick in the cockpit of one of Joby’s pre-production prototypes.

Figure 16: The locations of the battery packs (green) and propulsion motors (purple).

Figure 17: A detail view of a propulsion motor (silver cylinder) installed on a pre-production aircraft.

With a focus on acoustics research, particularly into the fundamentals of interactional phenomena and aeroacoustic behavior at low tip Mach numbers, would benefit industry in the long term and improve the ability to operate at higher tempos, and/or with larger aircraft, in noise-sensitive areas.

While early air taxi operations will begin within the structure of today’s existing air traffic management systems, the ultimate goal of providing unlimited scale for all segments of aviation requires eventual maturity beyond that paradigm. To support the evolution of more complex air traffic management solutions, industry must continue to agree on and invest in the maturation of shared solutions. It is important for the industry as a whole to contribute to standards development efforts on physical and cyber security, and digital infrastructure, de-confliction, and conflict resolution methodologies. Additionally, data sharing platforms are being developed in order to exchange flight information and intentions, such as position, velocity vector, measured wind vector, and maneuverability on a standard forward-looking segment of the trajectory, of every vehicle between all operators.

CONCLUSIONS

1. Through a thorough study of various VTOL aircraft design configurations, including tilt-wing, tilt-duct, tilt-propeller, and lift plus cruise with stopping lift propellers, Joby has concluded that the tilt-propeller design best combines with distributed electric propulsion for a
Table 1: Joby Production Aircraft Characteristics.

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<tr>
<th>Characteristic</th>
<th>English</th>
<th>Metric</th>
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<tr>
<td>Powerplant</td>
<td>6 × Joby electric motors</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>4 passengers + 1 pilot</td>
<td></td>
</tr>
<tr>
<td>Wingspan</td>
<td>38 ft</td>
<td>12 m</td>
</tr>
<tr>
<td>Length</td>
<td>21 ft</td>
<td>6 m</td>
</tr>
<tr>
<td>Max Takeoff Weight</td>
<td>4800 lb</td>
<td>2177 kg</td>
</tr>
<tr>
<td>Max Range</td>
<td>130 nm</td>
<td>241 km</td>
</tr>
<tr>
<td>Ceiling</td>
<td>15,000 ft</td>
<td>4,572 m</td>
</tr>
<tr>
<td>Max Cruise Speed</td>
<td>174 kt</td>
<td>322 km/h</td>
</tr>
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safe urban air mobility aircraft with relatively long range, high cruise speed, and low noise.

2. In full-scale demonstrator and pre-production prototype flight testing, the performance and acoustics of this design has been validated, including demonstrating a VTOL flight of 249 km (134 nm) and a true airspeed of over 322 km/h (174 kt), as well as flyover noise of 45 dB(A) at 500 m (1,640 ft) and hover noise below 65 dB(A) at 100 m (328 ft).

3. Collaboration between actors in the development and deployment of eVTOL aircraft in numerous areas will benefit all involved. Such areas include development of aerodynamic and aeroacoustic prediction tools, and, to support future large-scale urban air mobility operations, agreement on and investment in shared solutions for more complex air traffic management.

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