The Future of Flight On-Demand

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By

Alfredo Basile

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Student

____Date: 11/8/2021

Advisor

____Date: 12/03/2021

Richard D. Jacques, Ph.D., Department of Engineering and Society

Introduction

The Jetsons is a TV show that showed what many people's dreams of the future could look like and one of the most iconic images is of the use of their flying car. The car hums quietly, produces no fumes, can hover and when George is not paying attention, it can fly itself. This is a dream that is right around the corner and the first companies to deliver services that resemble a Jetsons like future are air taxis and drone delivery which fall under the umbrella of on-demand air mobility or ODAM. A literature review on ODAM and its operational considerations lists a few of the companies that are right around the corner in delivering these services like Uber who plan to launch in 2023 starting in Dallas, Texas, and Los Angeles, California, and other startups like Lilium and Kitty Hawk, who plan to launch air taxi services in 2025 and 2023, respectively (Sun et al, 2021). The three advances in aviation that make ODAM possible are: the electrification of aircraft, vertical take-off / landing (VTOL), and pilot automation. Each is researched for its own merit; each has already existed for some time but the combination of all three is what makes the future applications of on-demand air mobility possible. Understand the effects of these services requires that we understand the technology that enables them as well as the how the service directly affects users, the people around them and the environment. My goal is to show that there are independent drivers of the individual technologies that make air taxis and drone delivery possible and all but guarantees their appearance in our skies in the coming years. Knowing this, it is important to understand the consequences of this progression as well as what work being done to mitigate the problems associated with a more complex urban airspace. Additionally, throughout the paper I will be using the Lilium Electric Jet as a case study for how the integration of all three technologies in an aircraft can be practically achieved and what engineering design choices, they went with to mitigate the possible problems associated with their use.

Part I: Electrification

Hydrocarbon

Aviation relies on hydrocarbon fuels for flying that produces added heat to the atmosphere, carbon dioxide and other byproducts of combustion. A paper, by D.S. Lee and many others, showing the contribution of aviation to global warming reported that aviation accounts for 2.5% of CO2 emissions and 3.5% to global warming as of 2018 (Lee et al, 2021). OurWorldinData.org used the data from the Lee paper to produce a graph of the growth of CO2 emissions from 1940 to 2018, shown in Figure 1. Going to electric aircraft is one solution to reducing aviation's contribution to global warming, but it comes with its own benefits, engineering challenges and environmental challenges.

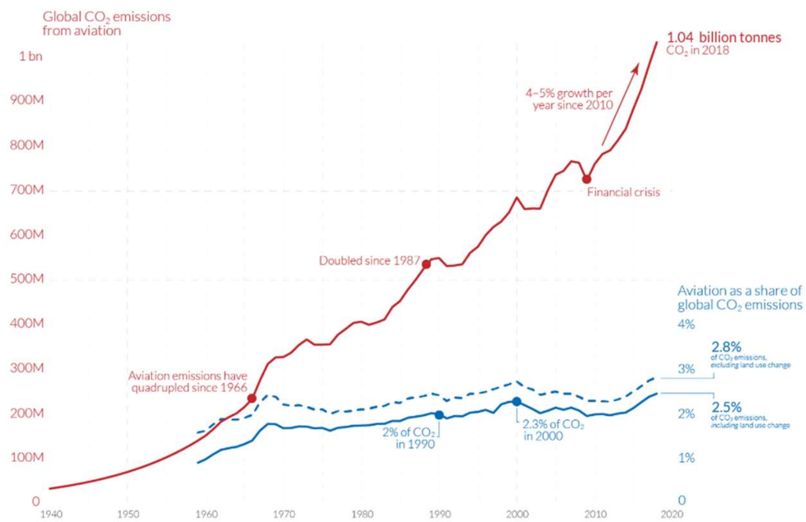

Figure 1: Global carbon dioxide emissions from aviation, ourworldindata.org

Energy Density

To understand the main engineering challenge of electric aircraft we need to discuss energy density. This is a measure of how much energy is contained per unit of mass of a fuel source. The amount of weight of an aircraft is the most important factor in flying so the energy density of a fuel is one of the criteria for determining fuel performance. According to the U.S. Department of Energy, Jet fuel has an energy density equal to 43 MJ/kg, while lithium-ion batteries in today's electric vehicles have an energy density equal to 0.72 MJ/kg (200 Wh/kg).

Figure 2: The Lilium Electric Jet seven-seater eVTOL aircraft, [*https://interestingengineering.com/flying-taxi-lilium-unveils-aircraft-design*](https://interestingengineering.com/flying-taxi-lilium-unveils-aircraft-design)

The amount of weight severely limits battery use in large passenger aircraft" (Holladay, 2020). That is almost a sixty-fold gain in energy density of jet fuel compared to Lithium. The Department of Energy also makes the point that electrification will not work for large passenger aircraft, however, this level of energy density is enough for short inter-city travel and until battery technology broke through to these levels, urban air mobility was impossible. Another drawback of batteries is the weight of the battery remains pretty much the same as it discharges unlike jet fuel which expends the fuel out the exhaust.

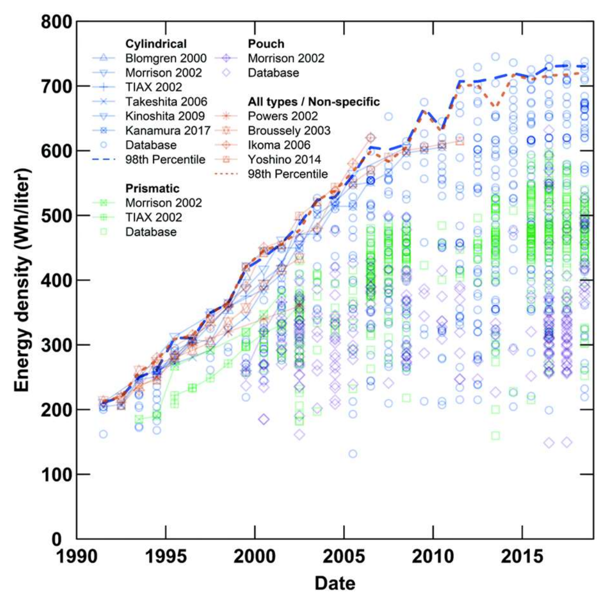

Figure 3: Increase in energy density of lithium-ion batteries (Zeigler, Trancik, 2012).

These challenges require that manufacturers of electric aircraft make them as efficient as possible. Companies like Lilium, have overcome these challenges enabling them to produce a five-seater electric aircraft that has a range of 300 km (~186 mi) on one charge at a speed of 100 km/h and a new seven-seater version, Figure 2, which has a 240 km range according to the company's blog post. A company spokesman notes that the improvements in batteries was a key enabling technology, he says, in a video that details the technology and features of the electric jet, "20 years ago there were no batteries that could have made our aircraft lift off, however, due to the continuous improvements to power and energy densities, we are now at an inflection point that allows us to make manned vertical takeoff and landing aircraft." This progression in energy density is shown in Figure 3, taken from Zeigler and Trancik who examined the improvements of lithium-ion batteries since their appearance in the early 90s.

The Material Cost

While electric vehicles have less of an environmental impact then combustion engines it is important to consider the environmental impact of the materials in batteries as well. Lithium and cobalt are the two ingredients in batteries that have the greatest social and environmental cost. According to a news feature in *Nature* that investigated the supply versus increasing demand problem of lithium-ion batteries, Lithium mining requires large amounts of energy for the process of extraction and cobalt has social costs related to the conditions of those who mine it, the majority of which occurs in the Democratic Republic of Congo (Castelvecchi, 2021). Solutions to these problems include cobalt free batteries and mining that can extract lithium from geothermal water and uses geothermal energy to drive the extraction process. Also, the current rate of advancement in battery life gives projections that soon many battery packs will

Figure 4: ducted electric engine of the Lilium Jet (Lilium Blog, 2019).

outlive their vehicles and can be reused in less demanding applications (Castelvecchi, 2021). Improving recycling of batteries is also key to reducing the amount of mining needed for more lithium. Areas that researchers are exploring is being able to extract the crystal structures used in the cathodes of batteries which, if salvageable, would recover a large amount of the energy needed to make the battery since those crystals have a high energy cost to produce (Castelvecchi, 2021). So, while there are still negatives to battery production, there is progress towards lessening those effects associated with the increased demand for lithium-ion batteries.

Benefits of Electrification

There are also many benefits to electric aircraft that allow for unique designs like the Lilium Electric Jet, which uses thirty-six ducted fan electric engines, see Figure 4. According to Lilium's blog post on the engineering design choice they write, "Having 36 engines makes the Lilium Jet more efficient, safer and more maneuverable. The increase in efficiency stems from integrating the engines into the wings." (Lilium Blog, 2019). Adding more combustion engines in the same manor is impossible due to the added complexity, but electric motors only have one moving part, and they are not nearly as difficult to manufacture. The engines rotate back ninety degrees for vertical flight and in horizontal flight use the aircrafts wings to produce the lift requiring that the engines only need to produce 10% of the total thrust to maintain cruise at high speed (Lilium Blog, 2019). Another benefit of electric over combustion, is near instantaneous thrust delivery in response to control input. The smaller engines can 'spin up' from the minimum thrust to the maximum thrust in less than one second (Lilium Blog, 2019). Their control system is also capable of detecting an engine failure and automatically correct for the difference in thrust. This means that every additional engine they have that is greater than the amount needed to safely land, is a redundant added safety factor. Single engine aircraft on the other hand have a single point of failure for thrust. These benefits to performance and safety are why electrification of aircraft for use in urban environments is a starting requirement and it is the linchpin for electric VTOL capability.

Part II: Getting Off the Ground

VTOL

VTOL is vertical take-off and landing and is a capability that has existed since the first practical helicopter flew in 1939, but electric VTOL (eVTOL) is specifically the advancement for aircraft that has made urban air mobility possible. Traffic in urban areas is increasing as urbanization continues to grow. In a report by the United Nations , "Globally, more people live in urban areas than in rural areas, with 55 percent of the world's population residing in urban areas in 2018. In 1950, 30 percent of the world's population was urban, and by 2050, 68 percent of the world's population is projected to be urban" (UN, 2019). This will result in more traffic in cities where there are limits to expanding roadways to accommodate the increased population. Utilizing the third dimension to fly over traffic is one means to aid in providing urban mobility.

Operational Considerations

The infrastructure needed for VTOL aircraft is significantly less than that for a traditional airport which is why it is a necessary capability for urban air transportation. Table 1 shows the possible infrastructure support capability of several U.S. cities. New York, for example requires VTOL or eVTOL for use and an ability to support 10 – 85 VTOL skyports and 10 eVTOL skyports (Sun et al, 2021). For New York, the paper also notes that to get a 10% market share there needs to be at least 9 ports to get market penetration.

Table I: An Overview of the ODAM Location and Port Problem, (Sun et al, 2021)

Region	Vehicle types	Problem size	Data type	Data avail.	Short summary
Miami, U. S.	STOL	15,666 potential park locations	FAA Obstacle Data Team's database	No	The Miami metropolitan area showed that an average airpark geodensity of 1.66 airparks per square mile can be achieved with a 300-foot long runway.
South Florida, U. S.	STOL	Up to 10,310 parcels	U. S. Light Detection and Ranging data and NOAA	Partially	Doublet runways are needed to find suitable parcels in South Florida due to poor weather conditions; and the climb/descent gradient has to be greater than six degrees.
New York, U. S.	VTOL	10–85 sites	Taxi records	No	Certain locations including large facilities and smaller stops for New York City are suggested. The percentage of time savings and willingness to fly did not impact the location decision significantly, while the on-road travel limit does.
U. S.	VTOL	156 vertiports	Simulation data	No	The ratio of gates to touchdown and liftoff pads at a vertiport is a key design factor; vehicle staging stands are recommended; vertiports with multiple touchdown and liftoff pads which allow fully independent operations or simultaneous arrivals and departures would be beneficial as well.
Seoul, South Korea	VTOL	10–36 vertiports, 3 routes	Commuting data in Seoul, Incheon, and Gyunggi	Yes	The number of vertiports was based on the K-means clustering algorithm, based on the commuting data for three major routes in the case study of Seoul.
New York, U. S.	eVTOL	10 skyports	Taxi and Limousine Commission records for Jan. 2018	Yes	When the number of skyports $p > 6$, there is not much variation in the incoming demand; an even higher value ($p > 9$) is required to achieve at least 10% market penetration.
San Francisco, U. S.	eVTOL	1–8 vertiports	Census tract data and population and income data	No	The objective function is to maximize the package demand served, with limits on the number of vertiports. Increasing the time threshold for the allowable driving time from the vertiport to the customer would result in a wider geographical distribution of vertiports.
San Francisco and Los Angeles, U. S.	eVTOL	10, 20, and 40 vertiports	Census data (LODES and ACS)	No	The objective function is to maximize the cumulative time saved in commuting throughout the network. Most appealing trips are relatively short-range trips in San Francisco; the strongest growth is in the central area for Los Angeles.

Power and Efficiency Considerations

Some engineering challenges with VTOL is the power requirement for vertical flight. Since the engines must provide the force to lift the aircraft and move forward, the flight speed and efficiency are negatively affected in most VTOL aircraft. The Lilium Jet overcomes this design challenge by having a tilt rotor that vectors the thrust down in hover and horizontally for cruise. The Lilium Jet also has ducted fans integrated along the wing. Figure 5 shows a cross-section of this design transitioning from horizontal flight to hover flight. Since the engines are in

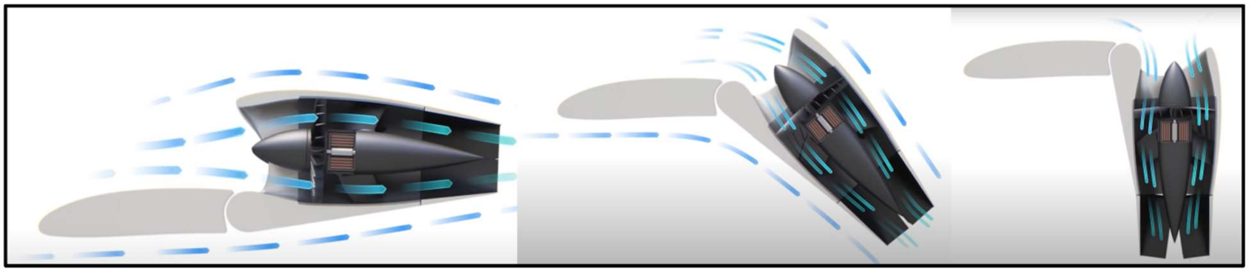

Figure 5: Lilium Jet engine and wing cross-section, Images from Lilium YouTube channel and promotion video. https://www.youtube.com/watch?v=s0VNWIghgp0

the rear of the wing, they suck air in and over the wing so that when the aircraft has even a little forward speed, it is more efficient than other VTOL aircraft. Since the electric motor configuration of the Lilium Jet allows the placement of 36 engines across the surface of the wings, this total effect is magnified across the surface of the wing.

Part III: Automation

Automation is a key part of urban air mobility and is not just being sought after for aviation but is aggressively researched for cars. Uber, for example, is planning on having both autonomous air and ground taxis, meaning that regardless of the future for air mobility, autonomous operation of vehicles will be coming soon. Previously mentioned company Lilium will initially have pilots for their air taxis but will transition to full autonomy later. In general, it has been a natural progression for us to use technology to automate tasks that would otherwise be done by humans. Removing the need for a pilot will give an economic advantage to businesses that implement autonomous piloting and passing some of the cost savings to consumers will encourage their adoption and use. In the future, as urban airspaces increase in traffic, it may be necessary for the aircraft to be equipped with automated piloting and to have to use it during high traffic times and areas with foot traffic below the flight path. During these peak times it may be that fully autonomous aircraft working on a shared network to communicate position and planned flight path, may be the only way of safely implementing ODAM.

First, a quick overview of the levels of automation as defined by the Society of Automotive Engineers:

i. Level 0 (No Automation). All driving tasks are accomplished by the human operator.
ii. Level 1 (Driver Assistance). The human operator controls the vehicle, but driving is assisted with the automation system.
iii. Level 2 (Partial Driving Automation). Combined automated functions are applied in the vehicle, but the human operator still monitors the environment and controls the driving process.
iv. Level 3 (Conditional Driving Automation). The human operator must be prepared to operate the vehicle anytime when necessary.
v. Level 4 (High Driving Automation). The automation system is capable of driving automatically under given conditions, and the human driver may be able to operate the vehicle.
vi. Level 5 (Full Driving Automation). The automation system is capable of driving automatically under all conditions, and the human driver may be able to control the vehicle. (Sun et al, 2019).

It’s important to note that there are several different automation level systems, which highlights the difficulties researchers face since there is no standard across different research fields. All eVTOL are at least automation level 2 or 3 since controlling the rotors independently on any multi-rotor aircraft is impossible. Quadcopters that hobbyists own all the way to the Lilium Jet, require a stability and control system that converts the pilot inputs into throttle adjustments to the individual motors. The goal for ODAM would be level 5, full driving automation and in air taxis, the ability to control the aircraft may only be in emergencies, like in the event of a sensor failure.

Part IV: The Applications

The applications that should be appearing the soonest in urban air mobility are air taxis and drone delivery. Certain engineering challenges associated with increased air traffic in densely populated areas need to be addressed so that the impact on traffic and pedestrians in terms of noise and safety need to be understood and measured so that cities can best choose which aircraft will deliver the best services. There still needs to be legislation plans for determining liability when two autonomous vehicles collide. For instance, if an autonomous package delivery drone hits an air taxi, then loses control and hits a pedestrian, does the city pay for the pedestrian's medical bills or the drone company? Engineers cannot answer legal questions, however, knowing what they might be helps indicate which potential problems need to be addressed to prevent incidents from occurring in the first place. For instance, real-time tracking of all arial vehicles in populated areas and machine learning applied to managing the traffic flow, route planning and collision avoidance.

Other design choices engineers consider for making ODAM as convenient as possible while avoiding the common negatives associated with air travel is noise reduction. Electric vehicles are already quieter than combustion engines, but additional thought to design for limiting noise is important. The Lilium for example minimizes its noise through its design of the ducted electric motors which isolate the sound produced from each motor from each other and the surroundings and the add an acoustic dampening material withing the out casing of each motor. According to the manufacturer, the Lilium Jet is 6 to 8 times quieter than a helicopter while in hover and is no louder than a normal conversation (Lilium Blog, 2019).

An important consideration for these applications is will people use them, especially with air taxis. Preliminary research shows that the benefits need to be rather high for mass adoption, in terms of safety, travel time, and cost (Fu et al, 2019). Some of the travel time cuts needed to be as high as 40% for travelers to want to use an air taxi over a regular taxi (wang et al, 2020). Other factors include weather, which showed people would be less trustworthy of air taxis in poor weather, which would influence ground traffic when there is an influx of travelers that would have been flying if the weather was better.

Conclusion

The future of flight is on-demand and while there are significant challenges, many companies have come up with incredible solutions and there does not seem to be a possibility of not having automated aircraft flying through our cities. Growing city populations means that all avenues of transportation need to be advanced in a multi-pronged approach that includes air mobility but is not limited by it. Air mobility will only account for a small percentage of traffic relief but its use in conjunction with other travel solutions will have a big effect on how we move around in the future. The main benefits will come in the form of a reduction in emissions and noise and the added convenience of being able to get to places faster. The advancements in battery technology have been the major milestone to breakthrough before eVTOL would be able to get off the ground, coupled automation the future of flight is going to be smarter, more efficient, cheaper and a lot more exciting.

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