Franklin Li Duan

When AIAA Meets IEEE

Intelligent Aero-Engine & Electric Aircraft

This book is about the cooperation of AIAA and IEEE, two major engineering organizations from two distinct focus points of technologies: intelligent aero-engine and electrified aviation. AIAA and IEEE both have their intrinsic needs for each other and their co-working is a must-have in the rest of 21st century. AIAA needs IEEE to become smarter and greener and IEEE needs a much broader scope to enlarge its marketplace and playground. The topics related to AIAA's and IEEE's co-project are highly multi- and inter-disciplinary related and highly goal-oriented. The target audience of this book is IEEE, AIAA members and other related professionals from universities, industries and institutes in the fields of AI-driven smart systems and electric airplanes with the associated new electric aero-engines and mobile aviation electric powers.

The key contents

When AIAA is Meeting IEEE
- AIAA vs. IEEE
- How to interact and what to achieve
- The mindset analysis of AIAA and IEEE

The smarter AIAA
- The AI - Smart brain, IoT, e-devices
- The smart sensors for AIAA -scenarios, fabrication, challenges, and testings

Electric aviation
- Versatile, smarter and green
- The evolution of aero-engines - pistol, gas turbine, electric aero-engine
- The integration of aero-engines and aero-craft
- Delta VTOLer and STOL for B787
- Rotatable wing and VTOL operation

The RDF jet – a new electric aero-engine
- The features: small, light, thrust
- The architecture: motor, fan, jet
- The principle: rim driven, Tai Chi fan, duct, and jet

Aviation electric power grid
- Energy and weight
- Battery, LTG, and 3D HK SC

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Duan

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Springer

Preface

The initial motivation of this book is an over-30-page long article submitted to AIAA Journal, the top administrative academic magazine of American Institute of Astronautic and Aeronautic association. Unlike a purely technical paper which just focuses on a specific research topic, the editor feels hard to choose proper reviewer since its content covers a broad scope of disciplines both in AIAA and in IEEE, and it is not easy to find any experts who master both of them. He shared his thought with me, and in the mean time, I received the letter from Springer to encourage me to write a book. Indeed, considering both the content and the scope, the best output mode of this long article is a book. It is the comment from editors in AIAA and Springer who inspire me to write this book, talking about the integration of IEEE and AIAA, the two biggest engineering organizations in the world.

The book title *When AIAA Meets IEEE* is inspired after joining the AIAA Meeting in 2018 in Cincinnati, USA, an interactive meeting that AIAA invited IEEE for a joint conference called EATS. It is the first interactive meeting that an AIAA invite IEEE for a joint project of electric aircraft technologies to combine the two teams' efforts together. The author was deeply engaged these years with AIAA people to develop smart sensors for intelligent gas turbine engines and accumulated a lot of real-time experience of IEEE/AIAA working together. And I do feel the strong need of coordination to integrate these two teams together to achieve an engineering target on electric aviation. The differentiation of the mindset and the focus of interest of these two teams shall be properly addressed for their most efficient cooperation. In general, IEEE people needs to adjust their focus to fit the need of AIAA, while the AIAA people need to adapt the most advanced achievements in IEEE, especially in building intelligent aero-system and powerful battery for electrified aero-engines. AIAA people should be able to ask the correct questions on their designated need in smartness, power, weight, and robustness when communicating with IEEE fellows. A professional integration team shall be suggested to aid the communications on both sides to coordinate their necessity and feasibility.

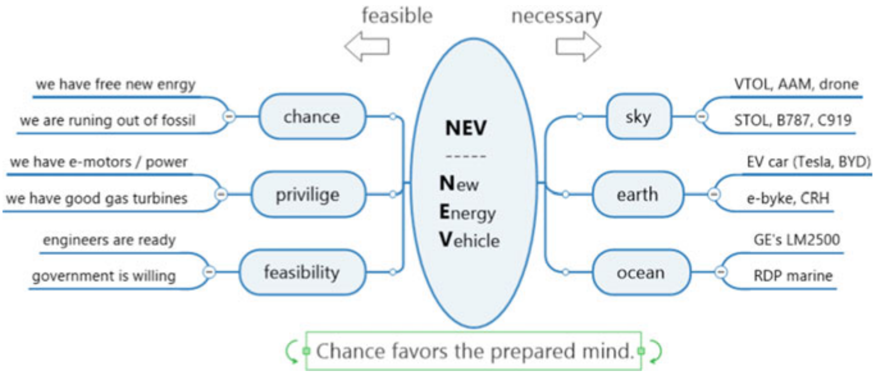
In the previous century, the key word of the AIAA is power; for the next century, the key word is smartness. Electric aero-engine and power are two crucial leading technologies, and both involve heavily the IEEE. The work-together of AIAA and IEEE people becomes a "MUST" in the future activities. While the first part of the book addresses IEEE people's working experience with AIAA, the second portion of the book explores the blueprint of electric aero-propulsion, involving two key technologies: rim-driven electric propulsion and mobile electric power grid. The privilege of this novel electric propulsion is investigated in comparison of the old-fashion propeller and the existing fuel-based gas turbine engines. Rim-driven aero-engines are much smaller and lighter. Multiple engines can be integrated in an aircraft design with a flexible vertical/horizontal propulsion orientation. New theories/methodologies are proposed and explored with some initial efforts made. As to the electric power, three major sources: battery, supercapacitor, and turbine gas generator are analyzed regarding the needs on power, energy, thrust from AIAA's angle and the power/energy density, efficiency, capability, price/maturity in IEEE's perspective.

When I start to write on the book, I feel a big challenge. The first challenge is the scope and the multi-disciplines involved since the AIAA and IEEE belong to totally two different categories of physics and cover so broad knowledge. Not only one needs to learn more knowledge but also needs to express it in more understandable manner. We try to use the verbal language other than the formal language to describe the technical terms whenever possible, and to use the glossary/index is to explain the specific technical jargons. Since the AA and EE cover two separate different physics categories, I most often use the first principles of physics to explain the technology/project from the root, like we did in Chap. 9 that electric motor is an origin of both electric generator and electric engine. The book is intending to lessen the burden of the readers of the intensive knowledge in vast fields by using the oral English rather than the official English.

The second challenge is to walk out from your own comfort zone which may make fool of yourself for the insufficient knowledge outside your profession. Besides, some readers may also feel uneasy when finding themselves outside the comfort zone at some point. The author, therefore, asks the pardon of the readers for some stupid naïves occurred occasionally in the book and offers you the courage you to engage into the new land like me. In fact, the author is intending to use this book to inspire you instead of using it as a textbook. The author was originally an IEEE fellow for nearly 20 years and then engaged in AIAA project in the past 10 years. The author appreciates the different mindsets of these two great minds from AIAA and IEEE people through these 30 years engagement on both sides. The author also feels the need for the effective and efficient integration of these two teams of people if they got to work together for a common goal. From necessity point of view, the intelligent aero-engine needs smart sensors, the electrified propulsion makes the aviation more efficient and sustainable. From feasibility point of view, advanced rim-driven brushless electric motor and advanced battery/supercapacitor achievements in electric automobiles shed the light for electrified niche aero-applications and smarter aviation scenarios such as short distance takeoff landing.

The author understands that some people may prefer to live in their comfortable zone instead of taking the challenge to step into another brand new career, just like most people prefer to park the car near the entrance of a shopping mall. It is the author's willingness to take the risk of making fool of himself, to make an initial effort to contribute some primitive thoughts for the integration of the two teams of people—the two world largest institutes of technology/engineering groups. The coordination of these two great minds, goals, and the ways of doing is highly necessary in order to make an efficient multi-disciplinary project such as the exemplified cases in this book—the IoT for intelligent aero-engine and electric propulsion for next generation electrified aviation, among the many others.

There are three main parts of this book. Part I explains the necessity and feasibility of the AIAA and IEEE cooperation. Part II discusses the use of smart sensor for an intelligent aero-engine. Among the Part II, Chap. 2 mainly explores the specific meanings of AI and how the sensors play an indispensable rules for intelligent AIAA. Then, we use Chaps. 3–5 to illustrate how to use the smarter methods to build the smart sensors to achieve the smarter gas turbine machines. Chapter 3 deals with the scenarios that the TFTC sensor can be used. Chapter 4 discusses the various methods to build them, and Chap. 5 discusses the specific tests that IEEE and AIAA people need to go through before the smart sensors being used infield. It is the author's motivation to use the true experience between the AIAA and IEEE people working together to encourage and to serve as a reference for the future IEEE/AIAA cooperation on electrified aviation engineering. As an intermission between Part II and Part III, Chap. 6 is an intermediate chapter to connect the AIAA and IEEE cooperation from previous to future, i.e., to use our six years' true experience of IEEE people with AIAA colleagues to explain the integrated process between the two groups of professionals, serving as a reference point for the future bigger cooperation. Electric propulsion and associated aviation electric power in Part III are much more challenging and more promising and may bring a more revolution to the whole aviation enterprise. In Part III, we discussed the smarter and the green aviation by the innovative design from e-engines, e-power to e-planes. Although electricity provides power for the e-aviation, the electricity is just a medium but not the final energy resource. The ultimate human energy comes from the solar, wind, tidal, and other green and sustainable natures. New energy vehicle offers new generation of human transportations from ground, ocean to sky with chance, privilege, and feasibility as shown in chart below—a blueprint of the feasibility (the left) versus necessities (the right) of future NEV.



Specifically in Chap. 7, we discuss the e-aviation from the first principle of physics, i.e., how to achieve a clever and smarter aviation, the significance of the greener takeoff and landing, and how to achieve this by vertical e-propulsion. Vertical thrust from e-engines leverages the weight of an airplane either to achieve a VTOL or STOL. Vertical takeoff and landing offer the vast scope of aviation mobility. Short takeoff and landing for larger airliners save lot of airport resources and reduce the airport pollution both from noise and from the hostile gases. Chapter 8 compares the few generations of the aero-engines from propeller to jet, gas turbine, and gas turbine fan, as well as the evolution of the electric motors from the DC brush to AC brushless. From these previous technologies, we are intending to extract the useful experience and lessons for the future development of advanced electric propulsion. In Chap. 9, we introduce a new e-propulsion called rim-driven fan (RDF) jet, a lightweight and small yet more efficient electric propulsion unit as the future electric aero-engine. Chapter 10 discusses the electric power grid suitable to provide enough electricity to drive the RDF jets such as battery, supercapacitor, and lightweight gas generator. Chapter 11 discusses the integrated design of the e-engines and e-airplanes, i.e., how to integrate the multi-electric engines into an aircraft. The key technology is the vertical and horizontal thrust transformation by rotatable wings to keep the optimal performance for both vertical thrust and horizontal propulsion.

The author deeply appreciates the academic and research platform provided by Shanghai Jiaotong University over the past 10 years, especially the cooperation and support of the team. Specifically, the author thanks Prof. Ding Guifu, Zhang Yafei, Han Tao, Fu Xuecheng, Cheng Xiulan, Wang Ying, and other teachers in these years. The author also thanks the other cooperative supports on all levels, such as Li Jibao, Li Jie, Hong Zhiliang, Qian Lingyi, Zheng Fangfang, Shao Jing, Wu Shaohui, Zhang Baowen, Tian Shuqing, and other comrades in AECC. The author also thanks the other colleagues outside the school such as Lin Yuzhen, Cao Xueqiang, Zou Binglin, Wang Ruijun, in Beihang University Wuhan Polytechnic University and

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Shanghai, China Franklin Li Duan

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当航空航天与电力电子相遇

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Part I
Astronautics/Aeronautics Versus Electricity/Electronics

AIAA is on the scale of kilometers, and the IEEE is the world of nanometers. The range of AIAA is from 1000 m to 1000 km, and the scale of IEEE is 1 nm to 1 mm. One is powerful, and the other is delicate. It is a wonderful thing to connect the two worlds together. Two contemporary bridges connecting them are the intelligent aero-engine and electric aviation. They connect the "far and near", they connect "strong and smart".

While there are many interactive activities between AIAA and IEEE, in this book, two hot topics are discussed and addressed as bridges to connect the two groups together. One is the AI's applications on intelligent aero-engine where the AI is greatly facilitated by IEEE, and the other one is electrified aviation where the electric propulsion, aviation electrical power grid and electric control play the key rules, which are also greatly facilitated by IEEE. We use the electronics to make the aero engines more intelligent, we use the electricity to make the aviation smarter.

Chapter 1
When AIAA Is Meeting IEEE—How to Interact and What to Achieve

AIAA refers to American Institute of Aeronautics and Astronautics, and IEEE refers to Institute of Electrical and Electronics Engineers. The "AA" in AIAA is astronautics (space) and aeronautics (aviation), and the "EE" in IEEE is electricity (powerful) and electronics (smart). AIAA is more government-driven, and IEEE is more product/commercial-driven; AIAA used to be more national, and IEEE is always more international. In this book, both terms refer to broader meanings than just the two institutions. The terms AIAA and IEEE in this book contain three meanings: organization/institute, science/technology, and professions/people.

IEEE and AIAA are the two world's largest engineering associations or institutes. Other than the AIAA and IEEE, American Society of Mechanical Engineers (ASME) and Materials Research Society (MRS) are two world's highly announced institutes which also relate to aerospace and aerospace industries. They are associated with AIAA very closely since the airplane and aero-engines are the 3 + 1: mechanical, material, thermal plus the aero-/astro-system and design.

AIAA and IEEE also refer to two distinct scientific categories. Not only they belong to different physics. In physics, we have six basic categories: electromagnetism, thermal dynamics, mechanical dynamics, vibration and wave, micro-nano science, field theory. AIAA mainly involves thermal and mechanical dynamics, while IEEE mainly involves the rest fields.

AIAA people may have different mindsets/points of interest compared those of IEEE people. For example, AIAA people like to say: more reliable and reliable …, more repeatable and repeatable …, while IEEE people like the wording: newer, the first time, cheaper … AIAA people are more focusing on reliability and endurance, while IEEE people may care more about expense and marketing. However, both believe that the technology itself is not the final success—much more effort is still needed through team efforts to transform technology into engineering/marketing.

The purpose of these two people meeting together is mainly that the IEEE helps the AIAA get smarter by electrification in two ways. One is using "electronics", and the other is using "electricity". One is tiny and delicate, and the other is strong and

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powerful. One is to make the AIAA more intelligent by smart sensors, and the other is to make the AIAA wiser by using electric propulsions.

This book is intended to help the AIAA and IEEE people to form a cooperation team for a common goal. Recently, there have been strong interactive activities of these two teams regarding intelligent aero-engines and electrified propulsion [1]. To effectively communicate between the two groups of people, the differentiation of the mindset and the focus of interest are analyzed in this book using two distinct showcases. One is the smart sensors built by IEEE's method to test the high temperature for various AIAA scenarios. The other is to use electrified propulsion for future aviation. The first example uses our six-year true working experience with AIAA's groups on developing TFTC sensors to illustrate the differentiation on mindsets and the coordination process on achieving a target. The second showcase is to explore the blueprint of the next generation of aero-propulsion, involving two key technologies: rim-driven electric jet and mobile electric power grid. The privilege of this novel rim-driven motor with inner blades is investigated in comparison to the old-time propeller and the concurrent turbine gas engines. Rim-driven engines are much smaller and can be multiple for flexible vertical/horizontal propulsion. New theories to evaluate the torque and magnetic interactions are proposed for the first time with some initial efforts made. Regarding the electric power, three major sources, battery, supercapacitor, and turbine gas generator, are analyzed regarding the needs of various aero-mobile scenarios on power, energy, and thrust from the AIAA's angle and the PE density, efficiency, capability, price/maturity from IEEE's perspective. In general, IEEE people need to adjust their focus to fit the need of AIAA, while the AIAA people need to explore and adapt the advancements from IEEE, especially in building intelligent aero-systems and powerful aviation electric power grids for electrified aero-engines. AIAA people should be able to ask the righteous questions on their designated need in smartness, power, weight, and robustness when communicating with IEEE fellows. A professional integration team is suggested to aid the communications on both sides to coordinate their necessity and feasibility and to ensure the cooperation plan executed along the road.

In this chapter, a primitive review of these two organizations and the initial integration efforts on the above two topics are given. The mindset differentiation and the manner to express data of the AIAA and IEEE people are analyzed and appreciated during the cooperative process.

1.1 The AIAA

The outer arrow in the AIAA logo represents the astronautics referring to flying out and toward the space; the inner arrow represents the aeronautics such as an aircraft carrying people around the earth. The propulsion of the aircraft is turbine jet + turbofan, while the outer space propulsion mainly relies on the rocket.

Figure 1.1 illustrates the scope and features of the AIAA organization. In general, the AIAA organization is quite concentrated and organized. AIAA has just four annual forums, which are highly focused and application-oriented [2]. There are three flags indicating the relevant hot spots associated in this book.

Another AIAA-related topic is unidentified flying objects. The UFO, if exists, may rely on gravity field modulations other than the rocket since it appears so quietly, together with advanced stealth technology because even the radars cannot detect it, which indicates that UFO can shield itself from large range spectra of wavelengths. At this moment, it still belongs to the scientific frictions, yet it reminds people of the analogy that Jules Verne predicted the submarine 20 years ahead before being used in Marine in his novel "Twenty Thousand Leagues under the Sea".

1.1.1 The Scope of AIAA

The AIAA institute comprises the following journals to cover a few distinct areas of expertise [3] (Table 1.1).

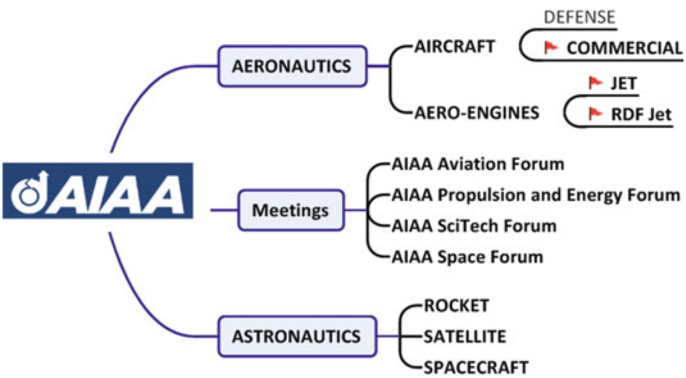

Fig. 1.1 Features of AIAA

Table 1.1 Relevant AIAA publications

*	AIAA Journal
	Journal of Aerospace Information Systems
	Journal of Air Transportation
*	Journal of Aircraft
*	Journal of Guidance, Control, and Dynamics
*	Journal of Propulsion and Power
	Journal of Spacecraft and Rockets
*	Journal of Thermophysics and Heat Transfer

In this book, the related topics are marked with "*" signs, i.e., smart sensors for propulsion and the airplanes. When AIAA is meeting IEEE, one needs to realize the pragmatism is a key which means that the cooperation must be highly project driven instead of academic; otherwise, it is very hard to make the coeffort be fruitful. There were quite a few unsuccessful projects due to the diversified efforts. We use the E-Fan X as an example to explain this defocused cooperation consequences. On Apr 27, 2020, E-Fan X, a joint effort of IEEE and AIAA on the electrification of airplanes of the Airbus/Rolls-Royce group, was canceled after just three years cooperation (the project was launched in 2017 [4]). The goal was to explore hybrid electric propulsion for commercial aviation. The due date of its maiden flight was in 2021. Obviously, the ambition seems impractical in the four-year span, and very importantly, the goal covers too many areas and topics that lack sufficient resources from many professionals. Specifically, the 20-pax commercial aircraft relates to hybrid power architectures, high-voltage systems, battery technologies, aircraft design, and enough flight experiments. Each one of them is a large and underdeveloped project that is still in the R&D stage. It could be more suitable to develop a new simple electric propulsor that we proposed as an RDF jet in Chap. 9. Therefore, it is better to be pragmatic when IEEE is working with AIAA on a new project. To cooperate with AIAA people more efficiently, the IEEE people also need to obtain some knowledge from AIAA's perspectives. Since their professions were not the AIAA, their efforts to become involved in AIAA should also be AIAA-focused and project-oriented. For example, they just need to know the thermo-related details in AIAA when developing smart sensors for gas turbines which involves high-temperature operations. They may ignore the theories in aerodynamics from this perspective—the relevant knowledge that needs to be added from the AIAA is not that many.

For example, AIAA has two immediate needs from IEEE at this moment: (1) the smart sensors to optimize aero-engine operations and monitor its conditions; (2) the electric propulsion including the motor and power. Here, we use the word "motor" instead of engine because the electric motor includes both the engine and the generator. They follow the same physics principle but renders two different needs in parallel: electric engine/propulsion and electric power from the lightweight electric generator.

1.1.2 Smart Engines by Smart Sensors

Smart sensors are a newly proposed idea to improve engine efficiency and to optimize engine design. For example, the efficiency of the aero-engine follows the Brayton thermal cycle:

$$\eta = \frac{W}{Q_{2-3}} = 1 - \frac{Q_{4-0}}{Q_{2-3}} = 1 - \frac{T_4 - T_0}{T_3 - T_2} \tag{1.1}$$

Increasing the pre-turbine temperature T_3 is crucial to enhance the eta and thrust. Generally, the thrust increases by 10–15% when the T_3 increases by 100 °C. To maintain the thermodynamic efficiency, the T_2 (T_0: input air, T_4: the jet air, T_2: after the compressor, T_3: pre-turbine) must also increase, that is, the boost ratio of the compressor increases. Therefore, the development of turbojet engines mainly focuses on two things: increasing the temperature in front of the turbine and increasing the boost ratio of the compressor.

Unfortunately, turbine material cannot bear such a high temperature, and a series of cooling holes are needed. Too much cooling air dramatically reduces the efficiency; therefore, the cooling effect needs to be evaluated. What is the efficiency of the cooling by these cooling holes? It is anticipated that cone-shaped cooling holes are more efficient. How effective can it be? The cooling effect can be described as:

$$\Theta = (T_\infty - T)/(T_\infty - T_\mathrm{c}) \tag{1.2}$$

where T_∞ is the mainstream temperature, T is the wall temperature, and T_c is the cold air temperature. To keep the engine working safely, one needs to keep the surface temperature T below the safety spec, e.g., 1000 °C. Traditionally, the cooling effect of the cooling gas from the cooling hole is very difficult to measure. This is mainly because of the impossibility of accurately measuring the wall temperature T in Formula (1.2). Usually, we apply more cooling air to keep it safe. Excessive cooling certainly lowers the engine efficiency greatly, but this has to be done since safety is the number one priority in aero-engine system. By using the MEMS technology, we can make a tiny temperature sensor just on the site of the cooling hole to get this T value in Eq. (1.2), so that we can optimize our blade design accordingly.

One distinct showcase that we have achieved is shown in Fig. 1.2—the cooling effect evaluation of different cooling holes. We have made special cooling holes on the turbine blade using laser drilling together with the conventional holes and use the MEMS sensors to compare their cooling effects. How to evaluate the cooling effect of this special hole with the conventional cooling holes? MEMS sensor is the best solution for this. Such measurement and comparison can only be made using our thin-film micro-sensors since the conventional wired thermocouples are adjust too big to fit in such a tiny spot on turbine blade. Figure 1.2 illustrates the temperature measurement on such a tiny spot (0.5 mm) near the cooling hole using MEMS micro-fabrication technique.

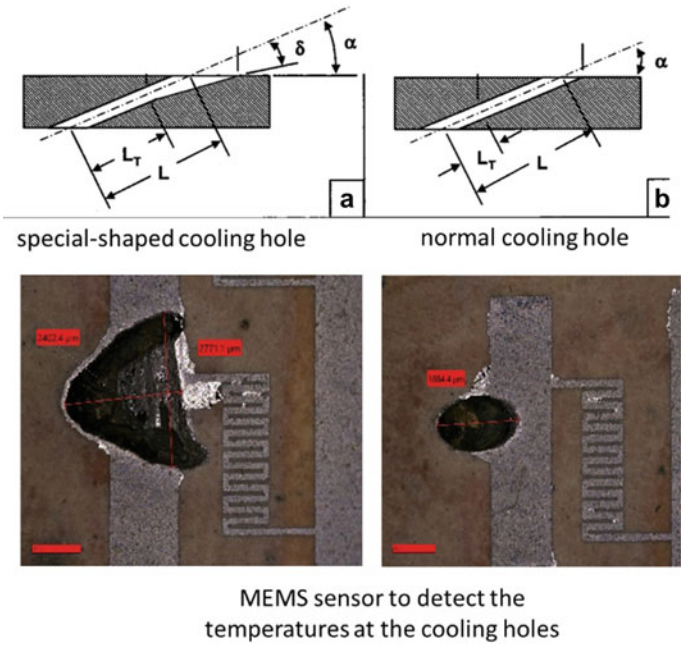

Fig. 1.2 To test the cooling effect of different cooling holes by using MEMS sensors

More details are presented in Chap. 3.

1.1.3 *Electrified Green Aviation*

For larger commercial aircraft, reducing airport pollution is an important issue that still lacks an effective solution. It is just the fact that an airplane needs more energy to takeoff, and when its engine is in full throttle, the airport receives a much higher amount of pollution. When the airplane is landing, the engine is still on with sub-combustion state, exhausting more NO_x gases (Chap. 7). Vertical takeoff and landing (VTOL) is therefore becoming a very hot topic in recent AIAA activities. The word VTOL is almost equivalent to eVTOL, i.e., electric-driven vertical takeoff. Electric propulsion creates clean thrust and can help to shorten the takeoff/landing distance, therefore saving airport resources. Electric propulsion, including electric engines and electric power, makes greener takeoff/landing possible.

From the application scenarios, electrified VTOL also enables advanced air mobility (AAM), a versatile small-scale mobile aero-applications. From the airplane

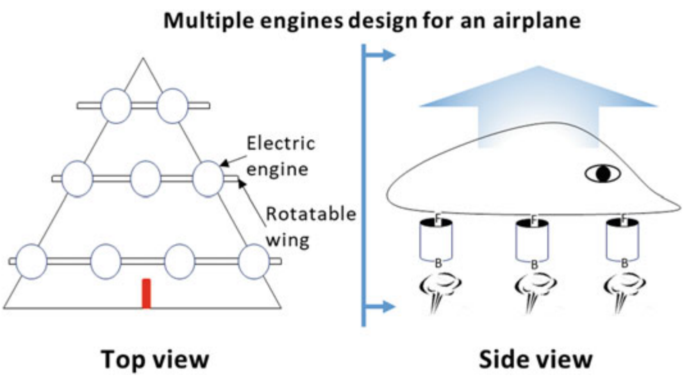

Fig. 1.3 Integrated delta e-plane with nine RDF jets (left: top view, right: side view)

design perspective, multiple rotatable electric propulsions enable the distributed electric propulsion (DEP) concept to become true, which enables the integrated design of airplanes with multiple engines for the most optimized aero-dynamic performance and flexibility of a modern airplane, either for the pure-electric small aircraft or as a supplement to the big commercial aircraft.

Electric engines are small, light and can be made multiple, providing a green and much more flexible propulsion for abundant mobile air application scenarios. Below is an example of using nine RDF jet electric engines to provide the flexible vertical and horizontal thrust of a delta-shaped aircraft. More details will be presented in Chaps. 7 and 11 (Fig. 1.3).

1.2 The IEEE

IEEE

Coincidentally, the IEEE logo is also composed of two distinct arrows. The up straight arrow refers to electricity, while the circling arrow refers to electronics. The electricity represents the "powerful" side of IEEE, which comprises the electric power and electric motor, and electronics studies the inner operations of electrons, which brings about the "around-the-earth" communications technology (the computer and internet, the IoT, and 5G).

As shown in Fig. 1.4, IEEE has much more diversified societies [5] compared with AIAA—more than 1900 annual conferences/events worldwide on much diversified cutting-edge contents. The relevant hot spots associated with smarter AIAA in this book are indicated by the "sunny" flag signs.

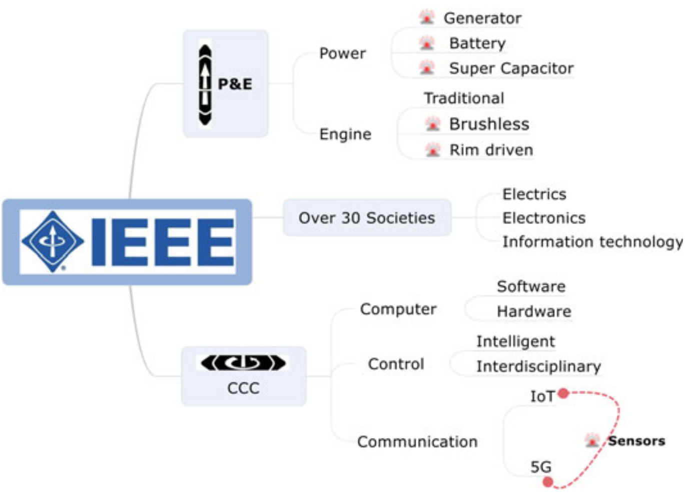

Fig. 1.4 Scope and organization of IEEE

1.2.1 The Scope of IEEE

The scope for IEEE is vast compared to AIAA. In general, it has two basic categories, strong “E” and weak “e”. Strong “E” involves electricity, i.e., the electric power and electric motor. Electric aviation are most often involved in the strong “E”, both the powers and engines. The weak “e” is related to the electron operations in the solid, i.e., the electric device and electric circuits, which usually do not involve high voltage, large current, and high power. There is a “3C” feature in electronic engineering: computer, control, and communication. The electronic engineering helps the global communication by computers, internet, and IoT.

From a–z, IEEE has the following societies as in Table 1.2.

Although the scope is large, the relevant IEEE societies to our topics in AIAA regarding IoT and electric aviation are just the few (in Table 1.2 marked with the * signs). They are basically around the two categories: MEMS micro-fabrication and sensors, electric motors and electric power.

1.2.2 MEMS Technology and Micro-fabrication

Micro-scale manufacturing from MEMS technology originated from 50 years of development in the integrated circuit (IC) industry from the Silicon Valley back to the 1970s. Since then, many industries have borrowed micro-manufacturing methods to fulfill their specific needs. For example, in our case, which will be discussed in Chaps. 4 and 5, we use the modified micro-method to build the smart MEMS sensor on the top of the turbine blade to measure the high temperature in aero-engine systems.

Table 1.2 IEEE has many academic and professional committees

	Aerospace and Electronic Systems Society
	Antennas and Propagation Society
	Broadcast Technology Society
	Circuits and Systems Society
	Communications Society
	Computational Intelligence Society
	Computer Society
	Consumer Technology Society
*	Control Systems Society
*	Dielectrics and Electrical Insulation Society
	Education Society
*	Electromagnetic Compatibility Society
	Electron Devices Society
	Electronics Packaging Society
	Engineering in Medicine and Biology Society
	Geoscience and Remote Sensing Society
*	Industrial Electronics Society
	Industry Applications Society
	Information Theory Society
	Instrumentation and Measurement Society
	Intelligent Transportation Systems Society
*	Magnetics Society
	Microwave Theory and Techniques Society
	Nuclear and Plasma Sciences Society
	Oceanic Engineering Society
	Photonics Society
*	Power Electronics Society
*	Power and Energy Society
	Product Safety Engineering Society
	Professional Communication Society
	Reliability Society
*	Robotics and Automation Society
	Signal Processing Society
	Society on Social Implications of Technology
	Solid-State Circuits Society
	Systems, Man, and Cybernetics Society
	Technology/Engineering Management Society
	Ultrasonics, Ferroelectrics, Frequency Control Society
	Vehicular Technology Society

Figure 1.5 indicates our capability to embed the very thin-film (just 1 μm thick) sensor in any shape (in this case, a school logo) on the curved blade surface. The minimum line width can be no smaller than 20 μm.

Such micro-sensor is capable to measure the surface temperature on turbine blade over 1000 °C. The thermal resistor detector sensor (RTD) on the surface of the turbine blade is made by using the micro-fabrication method borrowed from IC technology. More details are in Chaps. 3–5.

The use of the micro-technology to build smart micro-sensors for AIAA application is just one example of the AIAA/IEEE cooperation. To help the future AIAA/IEEE integration, Fig. 1.6 illustrates the main categories of the electronic societies in IEEE, which may help to build relationships with future AIAA applications.

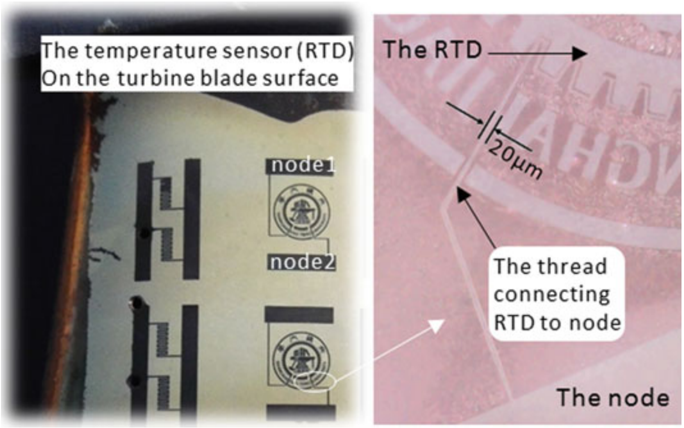

Fig. 1.5 Illustration of the micro-sensor built on the surface of the turbine blade using the modified school logo as a RTD pattern

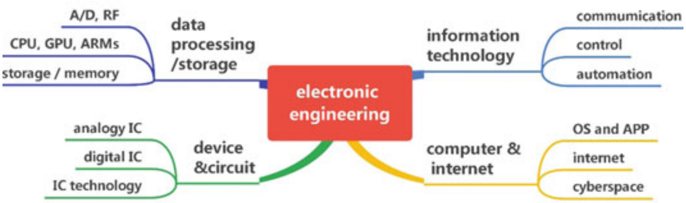

Fig. 1.6 Fields in IEEE for relevant AIAA applications

1.2.3 Electric Motor and Electric Power

Electrified aviation requires both electrical motors and electrical powers, which need help from IEEE people. The keywords here are lightweight and high power density both from the engine and the power supply. From the electric engines' perspective, Fig. 1.7 lists the possible alternatives of current electric motors used for electric airplanes. Tesla uses EM motors that do not need any permanent magnets (PM) and generate electromagnetic (EM) rotation purely by electric induction. Compared to PM-type motors, EM motors are less weight-efficient. A switch reluctance electric motor is another option for electric engines [6]. The three types of motor architectures can be combined and integrated such that the Tesla Model 3 car uses IPM-SynRM—a combination of permanent magnetic and reluctance electric technologies [7, 8].

A brushless DC motor (BLDC) is the most promising choice for electric propulsion with the best overall motor performance. PM brushless motor is a very hot spot in the current modern electric motor industry and is broadly used in EV car, UAS, and robot. Among the two types of brushless motors shown in Table 1.3, the BLDC type is more suitable considering its lightweight and large power-to-weight (PWR) ratio feature. However, more efforts are still needed to enhance its overall efficiency on propulsion for airplanes. We have proposed the rim-driven brushless motor for a more efficient high torque driver as the electric jet propulsion. This will be elaborated further in Chaps. 9–11.

For the electric power suppliers, Fig. 1.8 lists the electricity-related fields from IEEE's perspective, which consists of three main parts: electricity creation, storage, and transfer. The AIAA-related fields are marked with star signs, which will be further discussed in Chap. 10. The promising options for mobile electric power for aviation are lightweight gas turbine electric generators and 3D HK supercapacitors. Li batteries are the most mature technology borrowed from the electric car (EV) industry and can be used for quick-market planes and R&D purposes. For electricity transfer, electricity manipulation using SiC-based IGBTs is the key technology for high-power brushless electric motor control. Although the fossil fuel power generation is still the main stream electric power in the power grid, it is expected that in the future,

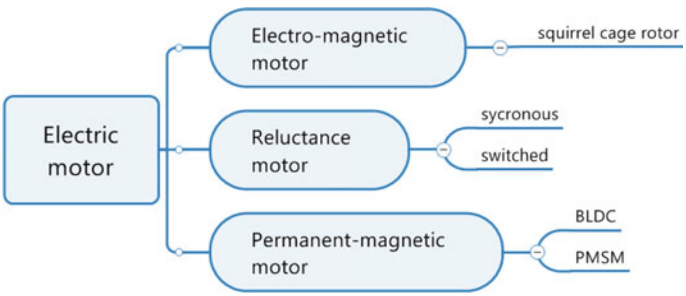

Fig. 1.7 Three typical electric motors. EM: electromagnetic, SRM: reluctance motor, PM: permanent magnetic

Table 1.3 Pros and cons of two brushless electric motors

Classification	Permanent magnet brush DC motor	Permanent magnet brushless motor	AC induction motor
Time, user	Old motor	BYD, *aero-engine, UAV*	Tesla
Stator	Permanent magnet	Electromagnet, multi-winding	Electromagnet, multi-winding
Rotor	Electromagnet, multi-winding	*Permanent magnet*	Electromagnet, squirrel cage winding
Electronic controller	Not necessary except to adjust the speed	*Must have*	Not necessary except to adjust the speed
Operating voltage	Low	*High, IGBT*	High
Efficiency	Lower	*High*, rotor has almost no loss	Low, rotor loss
Power density	Lower, rotor is not easy to dissipate heat	*High*, stator winding is easy to dissipate heat	Lower, rotor has loss and heating
Reliability	Low because of brush	*Higher*, mainly determined by bearing	High
Maintenance	Regular cleaning and maintenance needed	*Less* frequently maintained	Less frequently maintained
Cost	High, permanent magnet materials	High, permanent magnet materials/controllers	Low cost
	Permanent magnet brushless motor		
	PMSM	BLDC	
Driving mode	Sine wave driven	Square wave driven	
Torque		Higher *	
Power density		Higher *	
Control accuracy	Higher		
Purpose	More precise drives, robot	High power drives, high PWR	

PMSM Permanent magnet synchronous motor; *BLDC* brushless DC motor

most of the electric energies will be the "new energies" from the "free" resources of sun, wind, and river. The word "EV" will become the "NEV" (more details in Sect. 7.3). The new energy is transferred either via ultra-high-voltage synchronous AC (UHVAC) or extra high-voltage asynchronous AC (EHVAC) superpower grid lines [9].

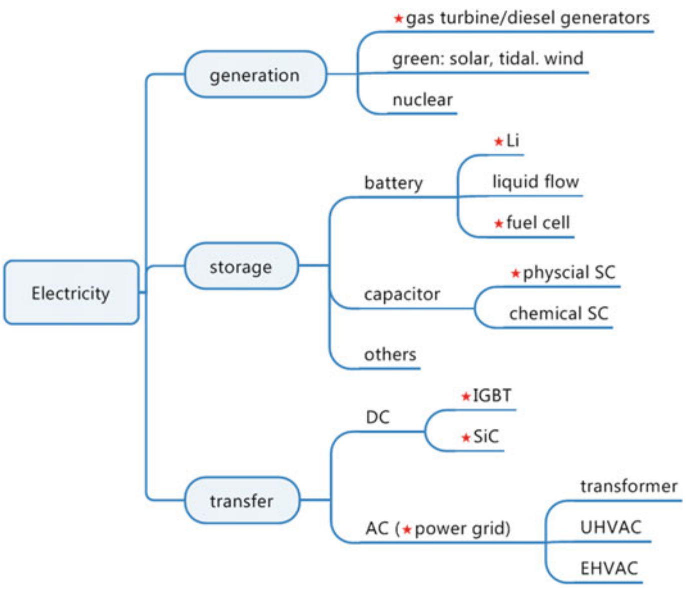

Fig. 1.8 Three key components regarding to the electric power supplier

1.3 To Integrate IEEE to AIAA

Electronic panels are already exist in front of the pilot in the airplane. This IEEE's work is associated with the knowledge of the basic electronics of electric circuits and electric controls and is also widely used in all fields. This is not the topic that we are addressing in this book.

Starting from 2018, there is a noticeable milestone of AIAA/IEEE interaction. In the AIAA Propulsion and Energy Forum in Cincinnati, Ohio, USA, AIAA first invited IEEE to open up joint section Electric Aircraft Technologies Symposium (EATS), inviting the IEEE colleagues for joint efforts to add more electric ingredients in AIAA fields. It is a good starting point of communication between the world's two largest Sci-Tech families. Electrical propulsion and smart sensors are the two promising kids of this "marriage". Since then, EATS has continued every year until now and is expected to continue for quite a long time due to the intrinsic mutual needs on both sides.

Just before this book released, on Sept 21, 2022, Honeywell hosted an "Air Mobility Summit 2022" at Washington, DC, in Honeywell's office at 101 Constitution Avenue Northwest [10]. In this summit, they discussed:

(1) How this new technology (urban air mobility, unmanned aircraft system, regional air mobility) helps with maintaining US global competitiveness, creating new and expanding economic benefits for society and building a more sustainable world.

(2) In detail on all-electric air taxis, uncrewed cargo delivery drones, move transportation from the road to the air with electrically powered vertical takeoff and landing aircraft for sustainable, high-speed air mobility.
(3) With the attendees include policymakers, regulators, industry trade associations, UAS, UAM, and RAM technology leaders, operators, key suppliers, and other stakeholders.
(4) To see, touch, and interact with the experts and hands-on technology immersion.
(5) The enabling technology for the industry with several eVTOL vehicle mock-ups on display and hear from some of the world's greatest minds behind this new technology.

It is seen that this IEEE/AIAA integration continues and is becoming more and more prosperous. To mingle the two great minds together to establish a new playground is an exciting game in front of us.

1.3.1 Mindset Difference of AIAA/IEEE Engineers

Other than the academic differences, AIAA and IEEE people have different habit of thinking—not only their IQ is different, but also their EQ. Generally speaking, IEEE covers more and broader fields and needs to deal with more variety of people/culture, hence needs more EQ than AIAA people. In order for AIAA and IEEE people communicating more effectively, it is worthwhile to understand their tiny differences in mindsets and habits.

IEEE people may have a more academic focus mindset, and AIAA people are more project-oriented. To a certain extent, AIAA is the customer of IEEE. The interaction between the two merely integrates IEEE's achievements into AIAA's engineering scenario. IEEE people need to adjust their mindset and point of interest to fit the needs of AIAA. The feature of the data shall be more application-oriented rather than purely academic-focused. For example, when developing a high-temperature sensor, IEEE people may concentrate on its performance and capability, but the AIAA people not only require the sensor to be capable of measuring the temperature but also place a stringent request on the repeatability, stability, and high-temperature endurance.

We use Chaps. 4–6 to explain this integration process, hoping to shed some insight into the future interactive activities between the two teams. Chapters 7–11 discuss electrified aviation, specifically electric propulsion, power, and integrated airplane/engine design.

1.3.2 *Two Cutting-Edge of AIAA/IEEE Fields*

There are two hot spots between the AIAA and IEEE interactions: the smarter aero-engines and the more electrified airplanes. As we know there are two different approaches in aero-industry: (1) technology/product is ready and we are waiting/looking for its user/market, (2) market has been designed/planned and we are seeking for the associated resource/technology. Below, we explain these two types of approaches: one is from bottom to top, and the other is from top to bottom.

(1) IEEE technology ready for AIAA—MEMS
Sensor technology from the micro-fabrication method is a mature technique and has been used extensively in the IoT for years. Where to use this technology to help AIAA? When we find an AIAA opportunity, then how to modify the current technology to fit in AIAA scenario? Chapters 4 and 5 address the details of this bottom to the top procedures to explain how "the technology goes the first, then we are looking for its playground" works?

(2) VTOL and green aviation—electric propulsion
This is the top-down approach. Vertical takeoff and landing (VTOL) is an advanced and clever way of airplane/propulsion. This need has been foreseen, designed, and planned in many large aviation organizations, and we are sincerely looking for partners to make it happen. IEEE is an ideal partner since the best VTOL is electric jet, and both the electric engine and electric power are in its territory. In Chaps. 7–11, the blueprint of this need from AIAA and the relevant technologies from IEEE are depicted.

The intelligent aero-engine and electric aviation are two cutting points of the AIAA/IEEE cooperation. The first joint effort (smart sensor for gas turbine engine) is relatively easier. The second goal (electric propulsion including engine and power) is tougher yet more promising. This book will focus on two concurrent hot topics: (1) IEEE helps AIAA more intelligently with smart sensors, and (2) electrical propulsions for aviation together with advanced electric power.

(1) More intelligent
In the past, aero/astro-enterprises were seeking capability and powerfulness but now are focusing on smartness and efficiency. On the other hand, IEEE has made tremendous achievements in the past 40 years and is looking for its playground. It is just the right timing to combine their willingness—to make the aero-engine more cost-effective and more intelligent.

(2) Electrical propulsion
With the advent of Tesla all-electric vehicles [11] and the emerging need for advanced air mobility (AAM) [12], electrical rim-driven Tai Chi jet engine and affordable lightweight electric power (LTG and 3D HK SC) have shed the light on the new generation of aero-propulsions. Full electric aircraft involving miscellaneous airmobile operations, such as 1–500 kg delivery UAS, 3-man VTOLer as rescuer plane, provides both the necessity and the feasibility for AIAA/IEEE cooperation.

1.3.3 The Corporations of AIAA/IEEE Communities

The gas turbine engine by using the smart sensors developed by IEEE people is the first tempting cooperation with AIAA. The rim-driven fan (RDF) jet is the key proposal for the next generation electric propulsion. They are the joint efforts of the AIAA and IEEE, the world's two largest engineering families. The integration of AIAA and IEEE is the interdisciplinary interaction between the two groups of smart people—a teamwork uniting both minds for both needs by both people. Mindset merging is highly needed as detailed in Chap. 6, which serves as a link from the corporate interaction experience of AIAA/IEEE on developing the smart sensors from Chaps. 3–5 to extrapolate the promising future of AIAA/IEEE cooperations in electrified aviation from Chaps. 7–11. That is, to use our six-year true experience of coworking between the IEEE and AIAA colleagues in Part 2 (Chaps. 3–5) to explain the process of the corporation between the two groups of people, serving as a reference point for the future bigger cooperation—the electrified aviation in Part 3 (Chaps. 7–11). Electric propulsion and associated aviation electric power are much more challenging and more promising and may bring a more revolution to the whole aviation enterprise.

More topics are also discussed in Chap. 6 regarding to: the mindset difference, influence of the different culture on international cooperation, 2D versus 3D thinking, the third way, the need of the dream keeper, etc. It is hoping that by combining the efforts of IEEE and AIAA, the next generation of hybrid/full-electric aero-engines will come true, just as the first Toyota's Prius hybrid car released in 1997 becomes the well-adopted EV cars with Elon Musk's Tesla or Wang ChuanFu's BYD electric vehicle after 20 years of efforts (from 1997 to 2022). It took over 20 years to get the electric power/motor ready for cars, and it may take 10 years to fulfill the electrified aviation.

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Part II
The Intelligent AIAA—Smart Sensor

$\rightarrow$ AI is becoming popular which is brought about by IEEE.
  $\rightarrow$ How to apply the AI in AIAA?
  $\rightarrow$ A few showcases or exemplifications.

Chapter 2
Artificial Intelligence

Artificial intelligence (AI) has become a popular term very recently, and it is not yet clearly classified or explained. Just from the surface meaning, AI refers to the simulation of human intelligence by machines that are programmed to think like humans and mimic their actions. Let us take the example of a monkey to see a banana on the roof beam, and there is a ladder sitting on the floor. A human being knows to move the ladder to the wall and climb to the roof to fetch the banana. Initially, the monkey may not know this, but when he sees the human doing this, he can imitate the human to do the same. Therefore, intelligence comes first from imitation. Simple imitation is the first and preliminary stage of AI. Currently, people use the term AI to cover many intelligent activities. The deeper AI actually involves comprehensive thinking and many other actions/options/outcomes. AI involves multi-dimensional sensing capabilities and much broader actions beyond humans, including smart brains and clouds, the Internet of Things, and robotics. Such a classification of AI helps us to find the relevant enabling technologies.

However, AI itself may not originate from the technology but from imaginations. For example, iPhone has changed people's lives, but the idea and outlook of the iPhone were at first just configured in Steve Job's mind. Then, he was seeking the associated technologies, the RF, the touch screen, the iPad, the iPod, etc. Some of them are already existing, and he just needed to integrate them into the iPhone; some need to be developed, such as an accurate touch screen and protocols. The iPhone was imagined at first, and the combination of the relevant technologies came afterward. The iPhone as a smartphone involves many sensors and sensor fusions. From the technology's perspective, AI involves multiple disciplines, including physics, chemistry, biology, etc. Among them, the IEEE is the greatest enabler. Almost all the AI activities involve the IEEE. For example, the concept of sensors is to convert any non-electrical signal into an electric signal so that one can use electronic circuits and computers to manipulate these sensors' signals and make the proper reactions. In addition, most of the IC fabrication technologies are borrowed by MEMS to build the various sensors by making use of the matured Silicon Valleys' integrated circuits techniques.

F. L. Duan, *When AIAA Meets IEEE*,
https://doi.org/10.1007/978-981-19-8394-8_2

Intermission

Chapter 6
The Mindset Analysis of AIAA and IEEE

This chapter serves as an intermission like the long music drama "Sound of Music", intending to connect the previous session to the next session. This chapter intends to connect the AIAA and IEEE interactions from previous to future. From the corporative intimate interaction experience of AIAA and IEEE people on developing a specific project done—the smart IEEE sensor to test the surface temperature of the turbine blade in AIAA, we extrapolates this cooperation to the promising future of AIAA/IEEE in electrified aviation. In Part 2 (Chaps. 3–5), we use our six years' true experience of IEEE people with AIAA colleagues to explain the integrated process between the two groups of professionals, serving as a reference point for the future bigger cooperation—the electrified aviation in Part 3 (Chaps. 7–11). Electric propulsion and associated aviation electric power in Part 3 is much more challenging and more promising and may bring a more revolution to the whole aviation enterprise.

6.1 The Necessity of AIAA/IEEE Working Together

Initially, either AIAA or IEEE goes its own way of engineering and innovation because they belong to two independent branches in physics. AIAA involves mechanics, thermal dynamics, and material science/technology, and IEEE addresses electrical and electronic science/engineering. AIAA has two aspects, astronautics, and aeronautics, as does the IEEE, electricity, and electronics.

From 1960–1970, electronic control started to help the aviation industry with the advent of mature electric motors and transistors. The main help from IEEE to AIAA was mainly to provide electric power for the airplane and electric equipment from the electrical aspect of IEEE. From the perspective of electronics in IEEE, the control and automation from the devices and circuits made the aero-machines easier to operate and manipulate like the front control panels in front a pilot.

Since then, both AIAA and IEEE have made a great deal of achievements. Due to the advent of artificial intelligence (AI) and electric vehicle (EV), many useful

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https://doi.org/10.1007/978-981-19-8394-8_6

technologies in IEEE were recognized by AIAA people to fit their need for advanced aviation purpose, for example, to use electric power shorten the takeoff distance of the big airliner. To achieve this goal, AIAA people need to work together with IEEE people, and this coworking not only involves technology expertise but also the man-to-man communications, namely, the IQ + EQ (Sect. 6.2.3) interlaced process. The motivation of this book is the integration of IEEE and AIAA, the two largest engineering organizations in the world, for more interactive and deeper cooperation involving the most recent advanced progress of both parties.

Recently, there have been strong interactive activities of these two teams regarding intelligent aero-engines and electrified propulsion [1]. Other than the activities from the academic and technical aspects, there exists the differentiation of the mindsets of AIAA and IEEE, together with their different technical habits and the multi-cultural differences since more and more future projects will be joint international for sharing costs/talents. Understanding these differences helps AIAA/IEEE people work together more efficiently. Part 2 (Chaps. 3–5) discussed the smart sensors built by the IEEE people to test the high temperature for various AIAA scenarios. This is the true experience from 2013–2022 of our IEEE team to work the AIAA people to develop smart sensors for jet engines. Not only this is still an active project between the AIAA/IEEE, here, we use this 10-year true working experience to illustrate the difference in mindsets, habits, preference and others. Our purpose is to use it as a learning curve for future deeper and more comprehensive topic—electrified aviation. Electric power and electric propulsion are two key technologies to enable electric aviation, and they all belong to the fields of IEEE. Both AIAA and IEEE people need to work together on drawing the blueprint of the next generation of aero-propulsion, the rim-driven Taichi fan jet as electric propulsion, and the 3D supercapacitor plus the lightweight gas generator as electric power that we will address in the following chapters. This new e-engine and its privilege is investigated in comparison to the old-fashioned propeller and the concurrent turbine gas engines. Rim-driven engines are small, light and compact, which are rotatable for flexible vertical/horizontal propulsion—a distinct difference from either the big jet engines or propeller drives.

From our previous learning curve of IEEE colleagues with AIAA fellows on developing the smart sensors embedded on turbine blades, we found that IEEE people need to adjust their focus to fit the need of AIAA, while the AIAA people need the eagerness to learn and adapt the new technologies in IEEE, especially in building intelligent aero-systems and powerful electric motors for electricity generation and propulsion. AIAA people need to learn how to define the problem for IEEE colleagues to solve and focus their efforts upon, i.e., to ask the right questions toward IEEE people. In many cases, being able to ask the right question is the rightful start of in innovation. For this, it is really worthwhile to read our previous book "The Introductory Engineering" published in Shanghai Jiao Tong University Press in 2019 on how to define a right question (the "IPO–Input–Process–Output" section in [3]). Since the AIAA/IEEE integration is not only a professional cooperation and involves a tremendous amount of integration efforts, a professional team may be necessary to aid the communications on both sides to coordinate their necessity and feasibility.

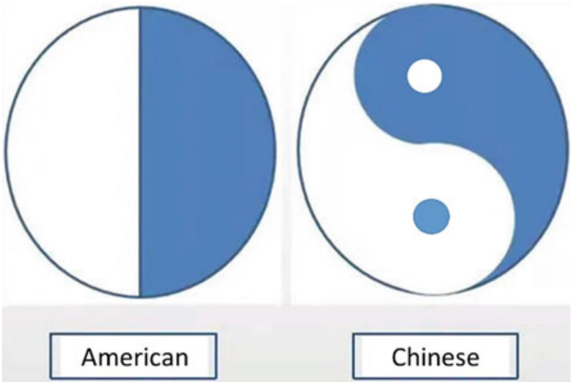

Fig. 6.3 Vivid illustration of American and Chinese

expression. The Westerners are bold, open, and direct. To apply it to our fan blade design in our RDF jet (Chap. 9), the Taichi blade converts the confronting air to a smooth tangential flow and then jet as a thrust.

It is just not as fair to argue which is better but to say which is more appropriate or your preference—it is like the relationship between shoes and feet. You may be an American, but you may prefer a Chinese style or vice versa. This personal feature should be considered looking for your career. When a graduate student looks for a job, he needs to know which style is more suitable, either the Chinese culture or American spirit. Observe yourself and see which app you like to use: iPhone or Huawei, whether you are a rule-driven, like the simplicity, or you are a person who is good at finding opportunities between the lines. When you are in cooperation with international colleagues, you need to be aware of this cultural difference, which you may never experience before, and to try to adapt but do not expect to change—it is difficult and unnecessary. In America, it is impolite to ask which religion you believe because this may cause unnecessary disputes, and it is actually not arguable. The same principle applies to cultural differences. Culture is not arguable but must be addressed when different people mingle together. One should focus on the commonality that both want to achieve the same goals sincerely, and both have good motivations on it. It is just the way they do things are different. It is just as pragmatic as to learn, to appreciate, to respect each other, and be adaptable in order for a win–win result.

China's system is relatively flexible, including the laws/rules and ways to excise them. The Chinese are always good at finding the 3rd path without violating the rules. The 3rd way method is very useful for innovation, which will be further elaborated in Sect. 1.3.2.

6.2.3 2D Versus 3D Thinking

Stephen Covey proposed plenary quadrants regarding the time management of urgency versus importance [2]. This method is very effective in improving the efficiency of the task and responsibility of the team as well as the individual. In contrast, we propose 3D task management by incorporating the Chinese strategy of not only considering the objective side of the task but also taking into account the subjective aspect.

Stephen Covey prioritizes tasks by placing them into four quadrants in a 2D plane. He drew an *X*-axis representing the urgency and a *Y*-axis that measures the significance (Fig. 6.4). Stephen Covey's 1, 2, 3, and 4 quadrants are explained as follows:

Urgency refers to tasks or responsibilities requiring immediate action or attention, and importance refers to those with high significance or value to the final goals. The objective of Steven Covey's four-quadrant systems is to focus on improving both personal growth and professional accomplishment. Q1 is the top priority.

- Quadrant 1: Urgent and important
- Quadrant 2: Not urgent but important
- Quadrant 3: Urgent but not important
- Quadrant 4: Not urgent and not important.

Q1 involves responsibilities or tasks related to critical results and requires urgent attention. Q1 jobs have the following qualities: impending deadlines, direct relation to time-sensitive goals, and/or involve alleviating immediate risk.

Q2 involves the related capabilities to achieve the overall goals and to enhance your work force. Q2 quality requires delicate planning and long-term perseverance.

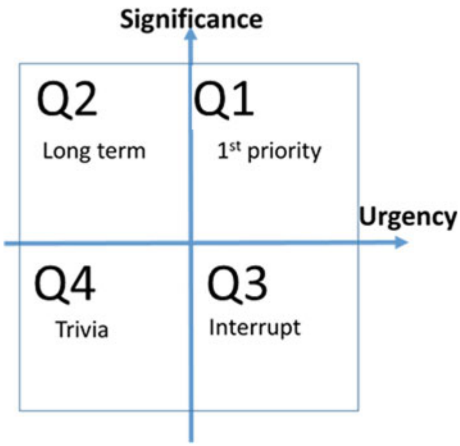

Fig. 6.4 Redrawn from Covey Leadership Center, Inc.

Q3 is urgent and assume some form of importance in the moment, which are likely reduced or removed from your workflow such as: some poor planning of items in Q1 and Q2, interrupting productivity or distractions.

Q4 is more likely able to be removed completely or reduced. It seems meaningless to list Q4 here because who is going to deal with the things which is neither important nor urgent? But, in reality, many of us very often dwell inside the quadrant 4 unconsciously or habitually. It is important to identify which items belong to Q4 consciously, especially when you are deeply engaged in some project. The conscious awareness is personal capability based on one's accumulated work experience. Q4 items are not directly related to neither overall nor time-sensitive goals, and our time shall not be wasted in that quadrant.

The benefits of using Covey's time management matrix include the following:

- Better productivity: help to organize and prioritize your task and to complete more and the most vital tasks in the same amount of time.
- Clear habits: help you to develop good habits of focusing only on Q1 and Q2 items.
- Work-life balance: help you to find time both for improving your working efficiency and to build up the workforce in the long run.
- Improved planning skills: effective people are proactive and understand the value of investing their time and energy into Q2 activities. Effective people respond to opportunities to do what's important, instead of reacting to urgent needs. When things come up, it is easier to determine what is important and what isn't once you have a clear goal and personal mission statement.

Stephen's four directions of emergency and essentiality may also have it shortcoming. From the teamwork point of view, one must consider both IQ and EQ. Team work is IQ + EQ, where both IQ and EQ have extended meanings here [3]. IQ not only represents intellectual quality but also includes the learning and adapting abilities, the way to organize your knowledge trees, be capable to find the 3rd path, etc. EQ not only refers to emotional quality but also the ability to be positive and active, passionate and compassionate, integrity and perseverance, etc.

In fact, there exists a third dimension: the timing must be right, such that "I am just in a good mood". Shown in Fig. 6.5, the best is the first quadrant in a 3D XYZ matrix. When being asked to do a favor in a wrong time, such as in a bad mood, fully occupied by something, or in a worry some state, thing will not get done either, and the bad trace may leave a bad memory affecting later-on communication. A good deed shall happen at a specific time and a specific place with specific people, i.e., the target is important, urgent and best timing to do it. If such timing is not yet ready, you may either wait or manage to create that opportunity. Trying to do it forcibly may just get things even worse. So, be patient!

To get the something done, one needs to control the proper balance of the three factors: urgency, significance, and the good timing. The Chinese call it (a tempted translation: chance, privilege, feasibility).

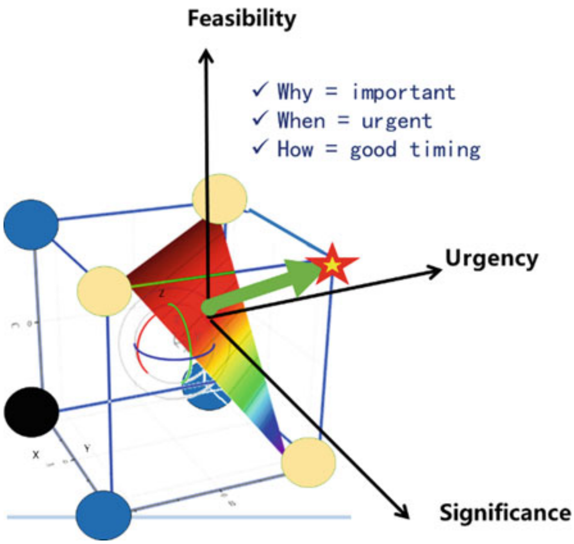

Fig. 6.5 Three-dimensional quadrants in the task management of a project

> *天时地利与人和*

it is more or less similar to the Western's saying (Louis Pasteur, a nineteenth century French chemist)

> *Chance favors the prepared mind*

Chinese people know that it is crucial to have the "3": the right time, the right place, and the right people in order to get one thing done. In old times, when a Chinese team was trying to win a war, they used the "天时地利与人和" theory; the resonance of the "3" is crucial to win a war. The physical situation, the necessity of fighting, and the readiness of the military workforce, corresponding but not limited to: war field conditions such as mountains and rivers, the motivation of fighting, and troops and weapons. They believe that just the physical or objective readiness is not enough. Currently, most human innovative efforts are not just AI work. Team work involves many emotions, such as passion, motivation, and willingness (EQs), together with their intelligence capabilities (IQs).

During the AIAA and IEEE cooperation work, although the technical details are very important and are favorites by both groups of people, it is relatively their weakness of not being good at "putting yourself in someone's shoes", i.e., to make an effort to imagine how they feel or act if you were in the same shoes. For example, imagine you are a sales person, you may have two options to improve yourself:

- What is the drawback of my product? What are the drawbacks of my survey? How can I improve them?
- What does a customer want? What are their needs? How can their needs be related to what we have?

To be honest, most of the engineers/graduates in the previous century favor asking the first types of questions, which is more suitable for performing dedicated work. However, in the twenty-first century, how customers feel and experience of your service becomes the 1st priority. To a certain extent, AIAA is the customer, and IEEE is the vendor. The cooperative work between them requires more intimacy. Purely objective-oriented Steven's four quadrants is not as advanced as the 3D quadrants by considering both the IQ and EQ. One must consider the best "mood" to obtain the best results, especially when dealing with international colleagues.

6.3 The Connection of AIAA/IEEE People

The main challenge of the AIAA and IEEE cooperation is originated from our traditional education pattern in college. Traditionally, our education system is scientific based but not the project based. For example, we often say "I am a student in the Department of Physics", but we seldom say that "I am a student who majors on electric propulsion". The physics is a science; the e-propulsion is a project, and there is no such department in the college. It is also very hard to arrange and manage the classes and textbooks for this. Not many universities like to challenge this like Shanghai Jiao Tong University in China, who dares to open the AI, 5G, and Micro/Nano as a Department or Institute. It is a very challenging job to find proper teachers who must be good at the hot and technological spots like IoT, UAS. What Jiaoda did is to seek for the graduate advisors who are good at these projects to deliver the lectures/practice in this class. Our new book "The Engineering Man" serves as a reference text book for them and to the up-to-date, this is the only book of its kind in the worldwide college bookshelf [3].

Both AIAA and IEEE people were trained professionally based upon the traditional college training programs. Traditional education system for college and for graduate students is the scientific-based education but not the project-based training. The scientific-based education is focusing on one specific field and then be good at it. It focuses on the depth instead of the width. Students graduated in this traditional training program are good at one distinct scientific field. But, in order to combine electronics with mechanics to fulfill an interdiscipline project, we are short of the professionals who are good at both fields. For a project-driven topic which combines a few scientific fields, such as electronics, mechanics, and material engineering, we need talents who are able to combine them organically in order to achieve a new product. Take the iPhone as example, the iPhone is a combination of many engineering achievements, such as electric circuits, RF electronics, computers, Internet, sensors, etc., even if all these are still within IEEE categories. Electric aero-propulsion involves more diversified physics fields covering both electrics and mechanics, which is almost impossible to find one professional who master both knowledge.

Therefore, the most crucial issue of the AIAA and IEEE cooperation resolves the conflicting targets between the traditional scientific based education and project oriented engineering education. Electrical science and aeronautic science belong to totally two different categories, and nobody is talented enough to master both. Besides one professional on one specific field does not want to take the risk to get laughed at in the new fields, especially when they become a pronounced professor in their comfort zones. Therefore, the integration of the multi-field project between the AIAA and IEEE becomes extremely difficult. There must be a certain methodology of strategy to handle this new issue, such that we have tried in Shanghai Jiao Tong University by establish a broader platform to accommodate the four major engineering schools: mechanical, electrical, material, and nautical science, considering in future such a multi-discipline phenomenon will become quite popular in many projects, such as the artificial intelligence (AI), the 5G (which we don't exactly know how to correctly define it), involving the professionals belonging to different physics fields, the chemistry and the biology. A new text book is tempted with many newer ideas on future college education with the original book name "To Be an Engineering Man" The word "Engineering" here has much broadly meanings and covers almost all the projects/activities which involved both the IQ and EQ, the only exceptions of which are the Albert Einstein and Leonardo da Vinci, etc., who just shut off themselves in their room to maneuver their own mind without cooperating with the outside world.

Another key factor for the AIAA and IEEE cooperation is the communication skill. Both sides should try to use the plain and oral language as possible to explain the technical terms. Avoid using the technical dragons or complicated technical terms as possible during the communication. Besides, try to use the analogy, common sense, and the first principles to explain the things.

As for a distinct project such as developing a dedicated RDF e-engine, it is highly suggested that there must be "a dream keeper" which is also a project coordinator and a project investigator (PI). He or she is a leader of the project such as the Steve Jobs for the iPhone. This PI should process both the engineering talents and management talents. Historically, the program manager is the professional MBA people. The shortcoming is that they have never get the engineering training neither be professional on any specific scientific field. Their mindset is management or economy but not the science and engineering. To better coordinate both AIAA and IEEE people, the preferred choice that he or she used to be a professional in some specific engineering, but he or she is also good at management and social communication. This is much better than just hiring a professional CEO as a pure program manager. Many professional MBA program manager in Silicon Valley are not graduated from the engineering schools but from the economics or MBA schools. There certainly a few unsuccessful cases that the company becomes a money machine instead of an enchanting innovation workforce. They are good at management, but they are short of the engineering habits/passion which build the basic instincts for the engineering project.

6.3.1 Customer Versus Vendor

Basically, to achieve a smarter AIAA by the technology from IEEE, IEEE functions as a vendor who serves AIAA as a customer. For IEEE, it is the technology waiting for the proper application (from bottom to top); for AIAA, it is the application looking for the suitable technology (from top to bottom). Regarding this customer/vendor relationship, let us use the example of Tesla and BYD, the two modern popular EV companies, to explain the difference between the two technological approaches: from top to bottom and from bottom to top. The battery and engine technologies from both companies are also highly related to our contents in Chaps. 7–11, electrified aviation.

Tesla and BYD are both developing and manufacturing electric cars but follow two different paths. Tesla starts from the design, i.e., an EV architecture. It is a "top-to-bottom" approach in which the design goes first and then to start finding the relevant and available technologies, and then combining them together to form a new product. It is new idea driven and then collects the necessary resources. BYD is different. It follows the "technology seeking for the product" approach. Even the brand name "BYD" was coined randomly at the very beginning of trademark registration in China, for the easiness of passing the trademark agency in China; now, the word "BYD" becomes "Build Your Dream" when the company gets prosperous nowadays. BYD was NOT a car manufacturer and almost had no experience nor the experts for automobiles. BYD was initially a battery company that had a solid background in developing a lithium iron phosphate battery ($LiFePO_4$). When the battery technology got matured on the market, the CEO of BYD decided to join the EV business to make the EV cars. To be honest, Li-ion batteries are the key for EVs, but a car is still too different from a battery itself since a car involves automobile architecture, mechanics, and electric engines. The early days of the CEO, Mr. Wang Chuanfu faced truly a big challenge, but he made it. In contrast, Tesla uses the mature ternary lithium battery system from Japan, which only packs the existing 18,650 standard cells together to form a battery package. It is much easier for Tesla to enter the EV market by borrowing the existing battery technology from Japanese vendors and e-engines from others However, from the battery's perspective, Tesla's technical background is not as strong and solid, and this weakness starts to reveal when both of them are competing the battery bottleneck right now. Tesla was not a professional battery company, and they just tried to modify the 18,650 (18,650 = ϕ18 mm in diameter and 65 mm long) standard battery into 4680 (ϕ46 mm $\times$ L80 mm), but this did not resolve the volume/weight efficiency from the root as BYD does. BYD is a professional battery company who is able to reconstruct the battery system from the root—layer-by-layer architecture instead of just packing the 18,650 one-by-one, saving a lot of space and avoiding many safety issues. Tesla just took a shortcut to circumvent the existing shortcomings, while BYD was able to enhance the system's ability from the root.

Both Tesla and BYD are successful in the EV market now, and both have their pros and cons. Likewise, either from AIAA's looking down to IEEE for technology, or from IEEE's going up to AIAA for playground, both approaches can make a success. Overall, it is the electronics who make AIAA more intelligent, and it is the electric motor and power who make the electrified aviation become true. However, a lot of integration journey must be gone through like we did in Chaps. 3–5, and we will continue this legacy in Chaps. 7–11.

6.3.2 The 3rd Way

When dealing with the conjunction joints between two professions, such as AIAA and IEEE, many innovations are involved, and the ability to find the third path is highly needed. Many Chinese people are good at finding the 3rd way in a dilemma. We use three stories to illustrate "the 3rd way" to obtain some insight into the third path.

- Story 1. In ancient China, there were many droughts. The irrigation of crops mainly depended on rain from the sky or manual irrigation either from the afar river or from the well. Other than the first kind which is totally depending on the heaven and fate, both methods were hard to fulfill, and there was not sufficient water to irrigate all the farmland. The ancient Chinese farmer found the third way to deal with this. The farmer dug out a small amount of soil at the bottom of the seedlings, poured a little bit water into it, and then buried it with dry soils. From basic physics or from common sense, we can easily understand why he does this way. Water buried under the soil provides nutrients to the plant and is not easily dried out by the sun. This delicate method of irrigation by leaking water into the soil to moisten its roots saves much water compared to sprinkling water on the leaves of crops, the conventional method of watering flowers. This is a "have-to-be" approach to achieve the optimal effect of irrigation; when you have the rich water you don't have to do this way. This is a 3rd way to deal with a seemingly impossible situation.
- Story 2. Another story to find the third path is from a Chinese TV series called "Top Secretes". The students are not allowed to take their notes out of the camp after listening to the Soviet military instructor, so how can they review their class work and pass through the exams? How can a person be so smart to remember every technical detail in a two-hour class? These guys did find a third way. The 30 students invent a strategy that each remembers only 1/30 of the class contents taught by the Soviet teacher, and after they came back, they reiterate the class contents and write them down into notes and share with each other. In this way, they incredibly passed the exam successfully. Since they did this secretly, the top officers and teachers felt it hard to believe how they can get such a good grade!

Even for teachers themselves, the used-to-be top students, could not do this. How could these soldiers who had not even graduated from junior high school have such a good talents? They certainly doubt that they had cheated the exam, but this is a military camp, and there is no chance of cheating in the whole process. However, it is quite plausible when this secretion is revealed in the end. There always exists a third path called "incredible"!

- Story 3 is the "third answering". When your boss asks you, "are you free now"? What would be the right answer? If you answer "yes", the boss may have the impression that you have nothing to do all day. If you answer "no", the boss will think you are arrogant and even ignore his request. Then, what you should say except yes or no? The 3rd way! You neither say "Yes" nor "No". You can say, "I'll come over right away". It is my business whether I'm free or not and I don't have to tell you that. What I need to do is do what you need, i.e., to come over to help. This answer circumvents the dilemma that may cause unnecessary misunderstandings.

Now, did you appreciate the beauty of the third word?

3rd way is important for innovation. The third way is a synonym of "a new idea". There are two popular ways to find a third way, "finding a gap and expanding it" and "finding a thin thread and thickening it".

(1) The microscope is the example of the 1st kind. You cannot see anything virtually on piece of smooth glass. Is there any gap on the glass? With a microscope and enough magnification, you can see the seams on the smooth glass surface. Likewise, in a very well-studied science topic, there always exists a gap to dig into and see more interesting things inside. This is how we enlarge the gap and open a new ground.

(2) "Find a thread and thicken it" is the method used to connect two or more interdisciplines to form a new science topic to study and expand it to a new playground. Micro/nanoscience involves technology in the micro-world, and the geometric scale is between 10^{-9} and 10^{-6} m. Aerospace is a technology in the macro-world, with a scale ranging above 10^{+4} m. Both are high-tech cutting-edge technologies, with a scale difference of more than 15 orders of magnitude. It is a wonderful thing to connect the two careers and build a bridge in between. Smart sensors for aero-engines built in the MEMS method in IEEE and then used for aero-engine optimization and health monitoring for AIAA are the linking bridges that connect two nodes together. It is a nearly zero-to-one (0-to-1) achievement after 6 years of endeavor since we first discovered the weak link (the thread) between the two. Then, we keep on working this project and expand it into a success story that we have successfully developed smart thin-film thermocouple sensors to measure the high temperature inside the gas turbine system. This is the example of "finding a thread and thickening it" to bridge the AIAA and IEEE.

"Be good at finding the 3rd way" examples above are from Chinese but not limited to Chinese. It is a habit of thinking that may not depend on where you are and who you are. However, one has to say there are more such happenings in China because this land cultivates this habit: to adapt and to survive in a stringent situation. The PRC and the USA have similar amounts of land but different ratios of resources per capita. The population is 15/4, and there is less arable land area in China than in the United States. Historically, there were fewer wars involved in the US than in other countries in the world. The situations help the Chinese be more alert and be good at finding a way among the "impossible" (in fact Impossible = I m possible).

6.3.3 A Dream Keeper

A dream keeper is a coordinator who should have enough authority to govern the resources on both the AIAA and IEEE sides to push things forward. The reason is that during the cooperation of AIAA and IEEE project, there are certain gray areas that do not have a distinct responsibility. Such a situation happens much more frequently compared to either AIAA or IEEE dealing with their own expertise. Let us use one example, the cooling effect test for gas turbine machines, to illustrate how this happens and why a perseverant PI (principal investigator) is necessary.

The target is to verify and use the TFTCs to replace the cumbersome wire TCs for the turbine blade cooling effect test. The IEEE is responsible for building the TFTCs on the blade and connecting them into wires. AIAA people are responsible for running the engine and reading the data. Initially, there is a gap—who and how to connect the wires and extend them to the outside data collector for thermovoltage reading and process the data into the valid temperature reading. This area does not belong to either side of AIAA and IEEE, and it is not the expertise of either side. AIAA people used to delegate this job to a third-party vendor, but now such a vendor does not exist. A dedicated PI is needed to look for a 3rd way to resolve this issue and fill in this gap. It takes much more effort, time, and patience as expected, and he or she must coordinates all the process. He/she must have the authority to get involved in the detailed engagement as well. Without enough passion, endurance, and perseverance of the dream keeper and without entitled authorities, it is hard to get things done!

A healthy ecosystem is also needed and must be cultivated. We should not always punish the failure and never encourage trial-on-error. For example, when you are doing things, you have a chance to make mistakes. Whenever you got mistakes, you got punishment, and your success is ignored. On the other hand, if I do nothing, I commit no errors, and I don't have any punishment. Which one you may choose? The logical answer is very clear. A good dream keeper should be aware of this basic logic and try to build a healthy ecosystem to activate the team members with more passionate to pursue the project.

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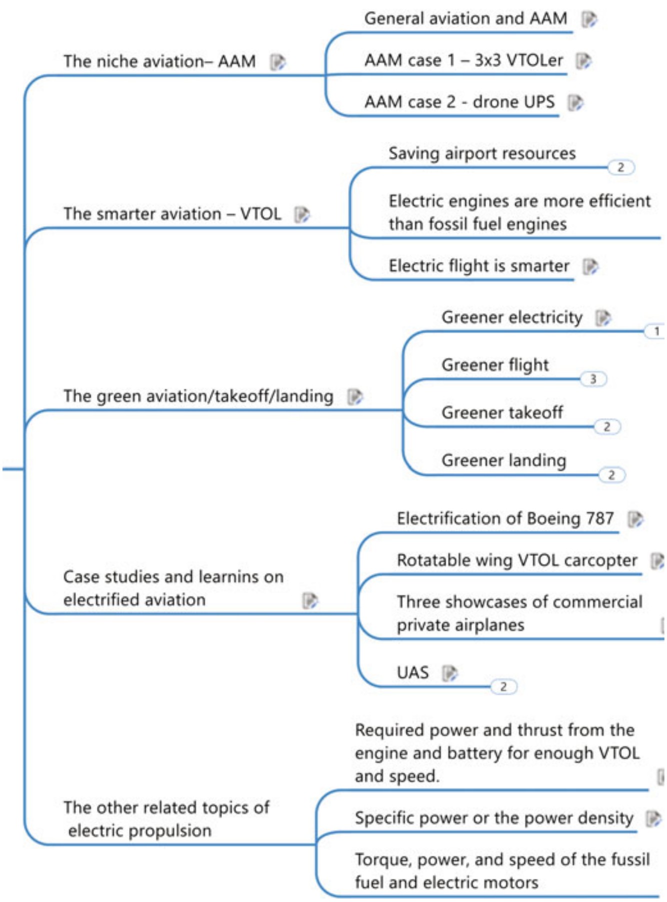
Part II
The Intelligent AIAA—Smart Sensor

→ AI is becoming popular which is brought about by IEEE.
  → How to apply the AI in AIAA?
  → A few showcases or exemplifications.

Chapter 7
Why Electric Aviation—Versatile, Smarter, and Green

The outline of this chapter is:



F. L. Duan, *When AIAA Meets IEEE*,
https://doi.org/10.1007/978-981-19-8394-8_7

In the Part I of this book, we use the IEEE's people's experience in developing smart sensors for AIAA fellows on high-temperature measurements of gas turbine engines, intending to explain the difference in their mindset and serves as a reference point for the very promising future of the AIAA + IEEE coproject, i.e., the electrified aviation. Obviously, IEEE's involvement is highly necessary since the e-aviation is highly electrified, and AIAA needs the expertise in electric motors and electric power from IEEE. From AIAA's perspective, electric propulsion has two distinct playgrounds: one is the eVTOL for small-scale AAM aviation, and the other is the e-STOL for large airliners. Both require an effective electric propulsion engine and high-quality electric power. From IEEE's perspective, there are two key technologies involved: one is the engine, and the other is the power. In this book, a new electric aero-engine—the RDF jet, and two powerful electric power suppliers—3D HK SC and LTG are proposed to fit in the AIAA's needs for e-aviation. These are the main topics in the following chapters in Part II.

The last 20th AD was a revolutionary century of human civilization containing many disruptive inventions; one is the airplane starting from the Wright Brothers in 1903. The main focus of the whole twentieth century is the capability for aviation, the big continental airliners, and the advance jet fighters. In twenty-first century, the key words are efficiency and smartness, such as electric propulsion and airplanes. The value of developing electrified aircraft does not lie in chasing the powerfulness but seeking for the smartness, i.e., the versatile mobile aviation (AAM [1]) for small-scale aviation and the clever takeoff/landing for large aircraft (STOL [2]). Pure electric aircraft is of indispensable significance for various civil and mobile aviation needs and for low-carbon green flight. For example, a 20-passenger minivan-type aircraft of 1000 m height, 400 km 3-h flight has a larger market share than a 400-passenger continental flight. Shorter takeoff aided by an electric engine to leverage gravity is a more optimized aircraft operation compared to the powerful yet noisy gas turbine propulsion. The developing work on electrified RDF jet engine in this article is intended to fit these two scenarios for flexible and smarter aviation.

Electrification of an airplane mainly relies on the engine, namely, the RDF jet, a small and lightweight rim-driven fan jet that is compact in size for easy and flexible orientation adjustment, which is indispensable for vertical takeoff/landing (VTOL) operation. RDF jets can be used as a supplement to the existing gas turbine or as an independent electric engine for UASs and small/mid-sized commune/drone aircrafts. Its smallness and flexibility offer many opportunities for various AAM scenarios as well for the best airplane redesign by integrating multiple e-engines with airplane (the distributed electric propulsion concept) for the best aero-dynamics performance.

In this introductory chapter, we discuss electric aviation from the application point of view, focusing on three key words: AAM, smarter, and green.

7.1 The Niche Aviation—AAM

In order to appreciate the value of term "AAM", let's at first compare its difference with "General Aviation", a well-accepted term in the aviation industry. The concept of general aviation from Wikimedia is as follows:

> *General aviation refers to aviation activities other than military, police, customs and public air transport flights, including operational flights in industry, agriculture, forestry, fishery, mining and construction, and flight activities in medical and health, rescue and disaster relief, meteorological exploration, marine monitoring, scientific experiments, remote sensing mapping, education and training, culture and sports, tourism and sightseeing. The aircraft used for these activities are collectively referred to as general-purpose aircraft. There are approximately 300000 general-purpose aircrafts in the world, and the number of general-purpose aircraft accounts for more than 90% of all civil aircraft.*

The focus of this definition is on *application scenarios*. One similar wording in general aviation is urban air mobility (UAM). UAM is recognized more by the public, but it also focuses on application and less on its technical aspects. Moore [3] once presented the concept of the on-demand air mobility, where the user can specify the departure place, destination, and departure time to best fit the private flights of general aircraft, charter flight, air taxi, and other operations. Comparing to the UAM, the term AAM has different focus.

Different from the above application-oriented definitions, the main focus of the term advanced air mobility (AAM) is "*technology*". NASA/NBAA defines the AAM term as follows:

> *AAM is a new* concept of air transportation ***using*** electric vertical takeoff and landing (VTOL) *aircraft to move people and cargo between places – local, regional, intraregional, urban – not currently or easily served by surface transportation or existing aviation modes. AAM* ***uses*** revolutionary new aircraft that are only just now becoming possible. (from: https://www.nasa.gov/aam/)

According to the above description, the word AAM focuses on its *technical features*. AAM technology implies the new concept of VTOL. Vertical takeoff and landing is a very advanced and ideal flight concept and is increasingly recognized by "aviation people" as the keyword "eVTOL", since the vertical takeoff/landing is most likely achieved by electric aero-engines driven by electric power. AAM technology fits in various "niche" occasions of the "air mobilities". AAM aims at highly specialized needs, such as a 3 $\times$ 3 VTOLer (3-men 3-m triangular e-aircraft) as a rescue plane for emergency or a catering drone for Amazon/eBay. Electrified aircrafting and aero-engines enable these more versatile, more mobile, more flexible scenarios. Let's review the general aviation and AAM in their technical details as follows.

7.1.1 General Aviation Versus AAM

The counterpart of general aviation is the mainstream aviation of military and commercial airplanes. Here, we use the method in the IC industry as a comparison that is, dividing the IC market into one main category and others as another category. In the integrated circuits marketplace, the main products are CPU and DRAM—the two key components for each computer with the largest market shares. The other category contains all sorts other ICs, such as interface circuits, buses, drivers, videos, audios… Similarly, we classify military and public flights into one aviation category. The other category is general aviation. Such a classification method may not be necessarily as scientific but is more practical to integrate the electric participation in the aviation technology.

General Aviation

General aviation covers a wide range of fields. The three main categories of electrically driven general aviation include purpose, scale, and technology, as shown in Fig. 7.1.

(1) The first category is from the perspective of usage, for private use or for public service. Private aviation refers to the air traffic and air vehicle used by individuals mainly as entertainment (now) and commune vehicle (future). Here, it should be mentioned that there are many synonyms of flying vehicles. One tends to define the flying object as an airplane, such as VTOLer, carcopter, and car-type aircraft, and the other defines it as automobiles, such as skycars and flying cars. Whether aircraft or car depends on the use and range. In general, the flight range of aircraft is relatively long, which generally refers to cross-continental and provincial transportation. The mileage of cars is relatively small, which may generally refer to indoor and urban transportation. At the current stage, the private aircraft is a luxury personal entertainment toy for high-income people. In the future, private aircraft will replace current cars as a popular personal transportation vehicle. The most prominent advantage is that it can avoid ground traffic. The VTOLer is most suitable for less than 500 kg weight and 300 km range. Its goal is to replace the current car as an ordinary means of transportation from home to the most nearby metro railway station and then to take the metro to downtown office. This is a very promising new marketplace, which has already appeared in science fiction novels. Imagination is an early arrival of the future reality. This car-type VTOLer is purely electric with mileage just enough to fly a person from home to shopping mall, maybe just a hundred kilometers away.

At the current stage, most of them are still using propellers driven by Li batteries. The price ranges from 300 K to 1 million dollars. The propeller drive is either

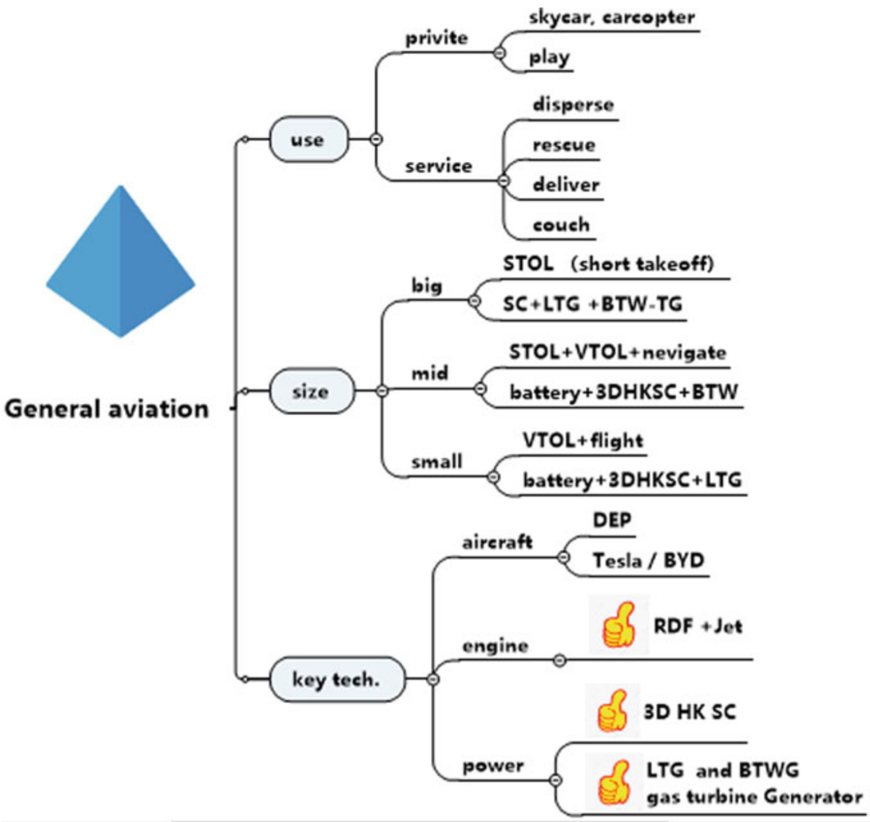


Fig. 7.1 The architecture of the general aviation industry

designed as helicopter type to hover in the air or by turboprop type for horizontal flying. The first kind of propeller is designed for maximum lift to conquer gravity, and the second kind is designed for high horizontal speeding. Both technologies are very mature but are not exchangeable. In comparison, turbofan technology makes it easier to adopt the rotatable wing technique to adjust its horizontal/vertical propulsion for navigation and vertical takeoff, yet further development work is needed.

As for the public service aircraft, its application fields are much broader and more extensive. There are four major fields. The first is dispersers, such as spraying pesticides/seed planting and mountain forest fire fighting. The second is an ambulance aircraft, which can replace the current helicopter. For example, the three-person ambulance aircraft (which we will discuss) is a 3-m VTOLer compared with the traditional 10-m helicopter, fitting the niche landing for rescue. The flight range is within 100 km to send the wounded to the nearest public hospital. The third type is cargo aircraft, which have a large market share and can be used as EMS/DHL and Amazon/eBay services. The delivery drone saves human payload and has less safety concerns, which has a huge future market places esp. in China with the very complicated geographies. The fourth type is training aircraft for coaching a pilot, which is generally a two-seater aircraft used to train aerial vehicle drivers or to test their aerial driving license. In terms of the current technology maturity level, all electric-driven unmanned aerial vehicles of less than 100 kg are already in the market, such as sky camera (DJI Mini 3 Pro) and farming drones (DJI Agras T40).

(2) The second category is the scale. The size of the aircraft determines which type of power is used, pure electric or hybrid? For large trunk jetliners, the contribution of the electric RDF jet engine is to leverage the MGTOW to reduce the takeoff distance and to slow down the jetliner by electric reverse thrust during landing. These two intelligent operations can greatly save airport resources and reduce the airport noise/pollution. The mid-sized aircraft has the largest portion of air traffic shares such as local traveling from city to city/from state to state. More frequent 20-passenge van-type aircraft are most appropriate to fit in this scenario. Such van-type aircraft must be hybrid powered for both enough range (~300 km) and the capability of vertical takeoff/landing. For the small car-airplane with a 2-seater weighting less than 1 ton, pure electric driving and VTOL are quite possible with a maximum journey of 100 km powered by current Li battery. If equipped with the LTG using kerosene as fuel to generate aero-electricity, such small aircraft can be made as a supersonic VTOLer capable of long-range continental private flight as Boom's XB-1 supersonic high-speed jet [4]. The difference lies in that such VTOL jet uses the kerosene to generate electricity for RDF jet to provide the thrust instead of turbojet, and it is also capable of vertical takeoff/landing.

(3) From the technology perspective, there are three major aspects: aircraft, engine, and power, which are the three key topics that we will address in Chaps. 9–11. One of the greatest features of electrified aviation is that the e-aircraft design is different from traditional airplane with dual or four engines. Electric engines are small and can be made multiple (more than 4), allowing more flexible and optimized engine/aircraft integration, namely, the DEP concept (distributed electric propulsion). Multiple electric engines can be synchronized by electricity and evenly distributed along the airplanes in different locations for the best aerodynamic performance. For example, the 3D orientation of each RDF jet offers the flexibility to maneuver the airplane moment by different rotation of the jet stream. Obviously, the RDF jet engine is the key for DEP, which is our second key technology elaborated in Chap. 9. The third key technology is the electricity to power this RDF jet engine. In Chap. 10, we review the various electric power options, such as Li and fuel cell batteries and ordinary supercapacitors, together with various fuel generators. Although Li batteries and FCs have made great contributions to the new energy automobile industry, such as Tesla and BYD, they are not as powerful enough when used for airplanes, esp. for VTOL purpose. We have to develop new energy sources, such as the 3D HK SC together with the lightweight hybrid generator as the ultimate aviation electric power source.

AAM

Figure 7.2 illustrates the AAM market places, the applications, and the technologies. The key AAM technology is VTOL. Vertical takeoff and landing offer tremendous advantages, and air mobilities and VTOL itself is a disruptive technology, which involves revolution e-engine and e-power. This certainly takes time to happen and the best fit-to-market option currently is the Li battery-powered propeller-driven 2-seat small airplane such as in RR's SOI and Eviation's Alice and DJI's camera shooting and agriculture farming UAS.

- The unmanned aerial system uses multiple propellers to hover in the air as well as a navigation powered with a Li battery. Lightweight (~ 30 kg) is its great advantage, which shall not exceed 100 kg.
- Propeller driving is not sufficient for the VTOL operation of heavier aircraft. Most flying or sky cars use Li battery-driven propellers to achieve horizontal takeoff and navigation. Generally, the marketplace is a 1–2-seat aircraft with a weight less than 1 ton, a height of 1000 m, and a speed of 500 mph. Most flying cars just

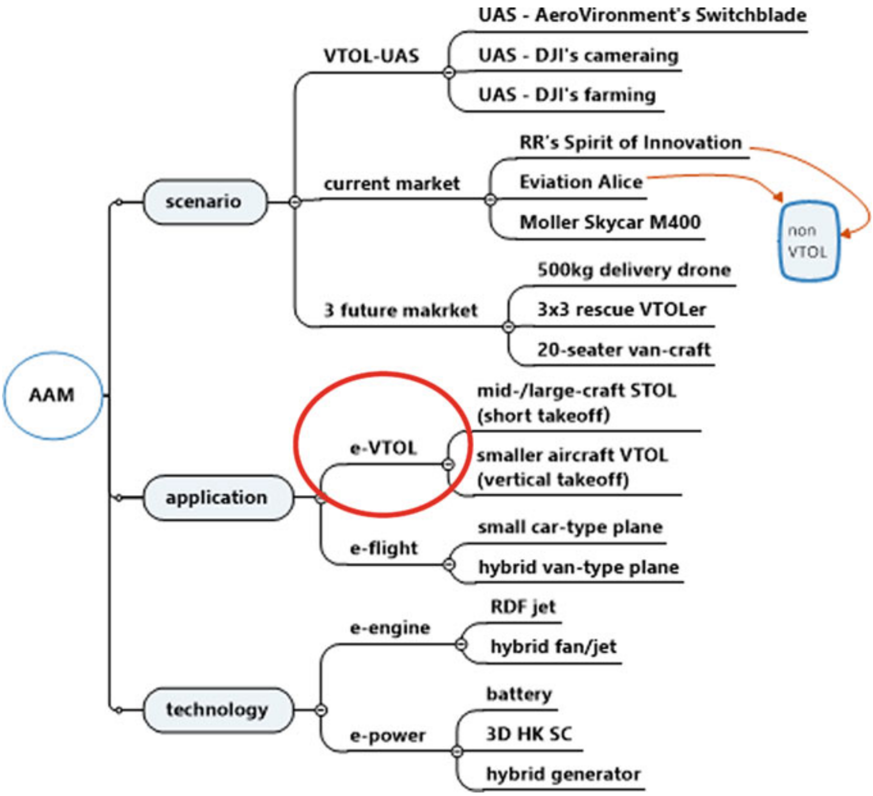


Fig. 7.2 The map of the advanced air mobility (AAM)

have a prototype to demonstrate/show off as an ad. The price range is between 300 K and 1 million dollars.

- Most of the private one seat electric airplanes carry less than 500 kg Li battery for power lasting 2 h for an ~ 300 km journey. XB-1 and other supersonic private jets are kerosene powered for long-lasting continental flight—from London to Washington DC in just 3 h. In the long-run kerosene-powered hybrid generator, LTG together with high-power output 3D HK SC offers a future alternative VTOL plus long-journey private hybrid electric aircraft.

In the following, we give two example cases of AAM: a 3 × 3 VTOLer rescue aircraft intending to replace the helicopter and drone delivery aircraft for Internet shopping—the IoTs.

7.1.2 AAM Case 1—3 × 3 VTOLer

It is a 3-m, 3-men, 3-engine aircraft as an emergency rescue vertical takeoff/landing "car-copter". The three-person VTOL ambulance has its prominent application as a general aviation application. Its unique advantage is that it does not occupy too much space during vertical takeoff, a distinct difference from current helicopter technology, which can take off vertically but occupy too much space (30 m in diameter) or ordinary small aircraft with folding wings but need a runway for landing/takeoff. This VTOL ambulance can land/takeoff in a narrow space and fly 80 km with a 50-kg Li battery for VTOL and 60 kg of kerosene for hybrid power to navigate. Patients can be sent from the accident scene to the nearest local hospital. The flight altitude is 1 km with a cruising speed of ~ 500 kmh. With such an altitude and speed, the flight journey is quite comfortable since this is basically an open-space flight with fresh air. The horizontal and vertical propulsion of the 3 × 3 3-seater triangular plane mainly relies on the unique advantage of the RDF jets (Fig. 7.3).

7.1.3 AAM Case 2—Drone UPS

The express cargo fly activates a nation's vitality:

The mobile cargo flyers

- *To activate the national mobility*
- *To boost the national economy*
- *To circulate the national currency.*

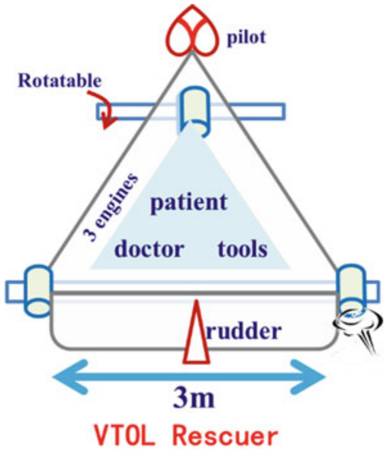


Fig. 7.3 3-men, 3-engine, 3-m 3 × 3 VTOLer rescue plane

Drone delivery makes the IoT become true. The IoT is a popular word after the "Internet"—to share the physical things in addition to the sharing the "mind things". The "Internet of Things" is communication in physical form based on visual/audio information from the Internet. For example, one can see and hear that a cake is tasty on eBay, yet the information conveyed on the "Internet" is just the message, not the taste. Through purchase and delivery, one can taste the real cake with their tongues—this is the "Thing". This is the original meaning of the IoT—delivering the wholesome experience with human's five senses: seeing, hearing, tasting, smelling, and feeling, with five organs: eye, ear, tongue, nose, and skin, instead of just sharing visual and audio information. A mid-sized drone can be used to serve the routine localized package delivery of UPS, EMS, DHL for Amazon, eBay in the US and Taobao and jd.com in China, which basically covers every corner of the land in the country. The business covers shipping, freight, logistics, and the supply chain. The drone delivery helps to activate the national economy and national IoT communication. Compared to conventional delivery services, drone delivery is fast and prompt, point to point. Compared to helicopter delivery services, it is much more economical and convenient (Fig. 7.4).

This triangular unmanned VTOLer is a handy drone delivery tool. The VTOL can be achieved by adjusting the RDF jet vertically and pushing the jet to the ground. After vertical takeoff, the electric aero-engines gradually turn to 45° to make the aircraft navigate while maintaining the aircraft hover in the air by vertical thrust and lift/drag ratio. The takeoff is directly driven by the battery and supercapacitor. It is feasible to carry 500-kg aircraft (lightweight airplane 140 kg, payload 200 kg, three electric engines $3 \times 20 = 60$ kg, battery and fuel 100 kg) for nearly a hundred miles, or a few tons weight larger delivery drone with hybrid electric power aided by lightweight gas turbine generator. The delivery distance can also be extended to 600 km.

The RDF jet also helps e-STOL for large commercial aircraft to achieve a smarter and greener aviation as follows.

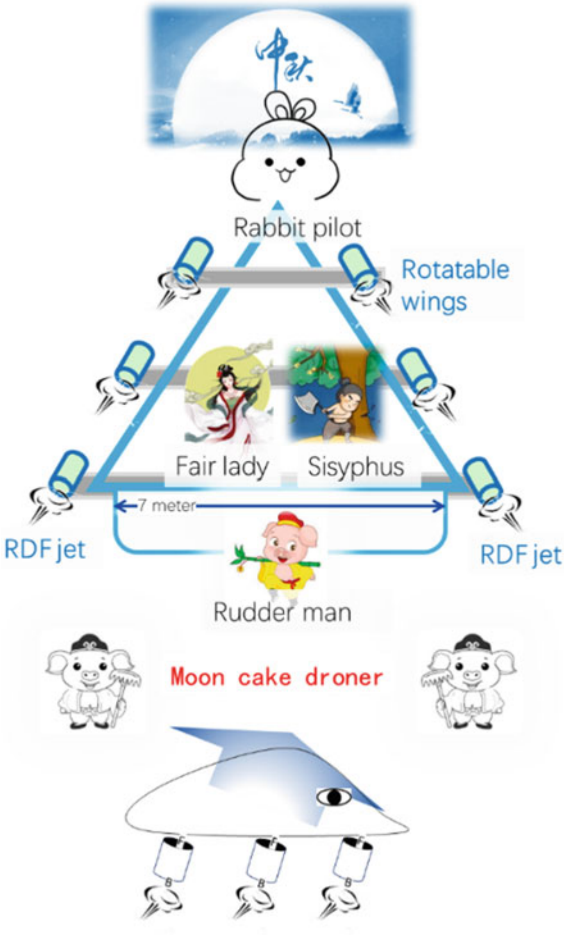


Fig. 7.4 Figurative 7-m moon-cake[1] delivery drone powered by 9 RDF jets (2 + 3 + 4 on each row)

7.2 The Smarter Aviation—STOL

VTOL stands for vertical takeoff and landing and has two synonyms electric vertical takeoff and landing (eVTOL) and short takeoff and landing (STOL) for large aircraft where it is not practical to conquer the gravity of 300 tons weight. To lift over

[1] This aircraft follows the Chinese fair tales that there are a few figures on moon, the beautiful goddess Change, a Chinese Sisyphus called Wugang, a rabbit of Change and a piggy as a steersman. Wugang is cutting a tree which automatically heals itself just like Sisyphus who is the loading a stone to a mountain top but rolling down again and again, as a punishment labor. In addition, the mid-moon festival is Chinese traditional holiday and people eat mooncakes on Aug 15 night (lunar calendar) to share the same bright moon afar (in Ancient Chinese far away friends/relatives cannot see each other so they use the moon as a remote mirror). This figure in this chart is just a parable that these four figures bought the mooncakes from the earth and flying back to the moon have a home festival party.

100 ton airliner requires more than 100 MW power, and the maximal power of one GEnX is just 45 MW. Two GEnX aero engines cannot lift this airplane vertically but can easily take off the airplane by horizontal acceleration. The VTOL also implies rotatable wing architecture that allows electric engines to rotate at various angles for flexible horizontal and vertical propulsion. In short, the VTOL is a comprehensive technology that does not rely on propulsion alone as the conventional fixed wing engine.

Vertical takeoff is a more advanced concept than the conventional Bernoulli's takeoff. Horizontal takeoff relies on the acceleration to use the wing to lift the airplane, needing a runway which brings about the friction (the heavier the aircraft, the more obvious) energy loss. Taking a 100 t aircraft as an example, the takeoff speed is 270 km/h (75 m/s); the required power is ~ 15 MW, and the friction power (to overcome) is 7.5 MW. Therefore, the power required for takeoff is approximately 23 MW. It takes 32.5 s to accelerate to takeoff; the takeoff distance is ~ 1000 m; the takeoff power consumption is ~ 200 MJ (= 56 kWh), and the friction power consumption is 100 MJ. So, the total takeoff power consumption is 300 MJ. For vertical takeoff, the power is $mgV_{\perp}$. Suppose the rising speed $V_{\perp}$ is 1 m/s; then, for a 100-ton aircraft, the power required is 1 MW, and the work done to 10-m height is $W = \mathrm{FS} = 11$ MJ, which is much less than the energy consumed by horizontal takeoff and requires much less takeoff space.

However, to achieve a VTOL for this big aircraft, one needs to conquer the weight of 100 ton, which requires a 1000 kN thrust. This is not applicable even with the current gas turbine propulsion technology. One GEnX engine delivers 300 kN thrust, and four of them are needed to lift this airplane vertically. But, there is an intrinsic drawback of fixed wing GEnX which cannot rotate 90 degrees from vertical to horizontal. The rotatable wing technology does not fit to rotate a big and heavy gas turbine engine but quite applicable to shift the small, light multiple electric engines from vertical propulsion to horizontal.

Besides, the working principle of vertical lift up takeoff is different from horizontal acceleration takeoff. VTOL requires thrust, and horizontal takeoff requires speed. To compare the power needs of horizontal versus vertical force, we use the current automobile and aircraft as a comparison:

- The aircraft taking off needs to overcome gravity, so the vertical acceleration force must be above 9.8 m/s^2.
- For an automobile, to accelerate from 0 to 100 kmh in one minute, the acceleration rate is just 1.67 m/s^2; for an airplane, the takeoff speed is 75 m/s (270 km/h). To accelerate from 0 to75 m/s in 30 s, the acceleration is only 2.5 m/s^2, far less than 9.8 m/s^2.

Therefore, comparing the horizontal versus vertical takeoff for bigger airplanes, horizontal acceleration requires far less power than the vertical force needed for VTOL. It is pragmatic to rely on the wing to achieve this indirect takeoff at the current being for heavy aircraft. It is not as practical to VTOL an aircraft of more than 10t MGTOW. However, STOL is quite feasible with e-propulsion, which is discussed further in a later section.

7.2.1 Saving Airport Resources

The airport resources refer to space/time, noise, and pollution, i.e., how much space and how long an airplane stays before taking off or moves to inventory, the noise level during takeoff, and the harmful emissions during the takeoff/landing process. The *active time/space* of an aircraft in the airport during landing and takeoff is the determining factor of the overall noise and pollution level as well as the airport occupancy. VTOL and STOL help to save time and space during takeoff/landing, to reduce the emission and noise level by shortening this duration in takeoff and to reduce the emission intensity during landing. Let us first analyze the energy consumption, emissions and air pollution in the whole flight journey.

Energy Consumption

Aircraft engines use aviation kerosene as fuel to provide power. Various kinds of air pollutants are emitted during combustion, impacting human health and the environment. The emission level of NOx of A320 (150 seats) during one 90-min flight (1350 km) is approximately equal to the emission level of a compact car traveling 86,000 km. The emission level of cars and airplanes is comparable per person/per km (150 * 1350 = 172,000 persons km for airplane versus 86,000 * 2 = 202,500 persons km for car). However, the airplane uses more fuels and emission intensity during the takeoff, and landing process is higher (Fig. 7.5). First, the amount of engine fuel and emissions is proportional to the thrust, which is full during takeoff and nearly 1/5 during navigation. Therefore, although the takeoff time is short, the emission brought to the airport due to the full thrust is at a very high level. The aircraft uses the maximum thrust to taxis and accelerates on the runway. At this time, the fuel flow rapidly rises to the maximum value, reaching 262.8 kg min^{-1}, compared to the average of 40.7 kg min^{-1} during flight. The takeoff and ramping span is 15.1 min, and the fuel consumption is 615.7 kg. During the landing phase, the engine thrust increases briefly, and the instantaneous maximum fuel flow reaches 74.2 kg min^{-1}. At this time, the engine uses the reverse thrust to decelerate to shorten the landing distance. The total flight time during landing is 9.0 min, and the fuel consumption is 215.4 kg [5].

Table 7.1 lists the fuel consumption at each stage in the whole journey of the A320's 90-min flight. The total flight time is 2 h 32 min; the fuel consumption is 6332.1 kg, and the flight distance is 1647 km.

The Noise Level

The noise level of the airport refers to the intensity and duration of the decibel levels versus distance, and the accumulated noise of air traffic of takeoff and landing. In general, the take-off time lasts approximately 0.8 min, and touch down takes 1 min. The engine is in full thrust during takeoff, with the highest noise level ~ 140 dB. When you are within 50 m of the takeoff plane, the noise level is ~ 110 dB, which is extremely harmful to health. Table 7.2 shows a few typical noise levels at various scenes.

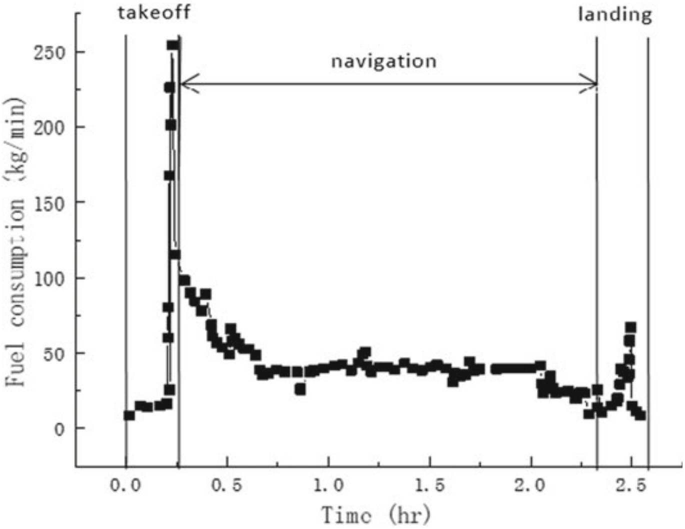


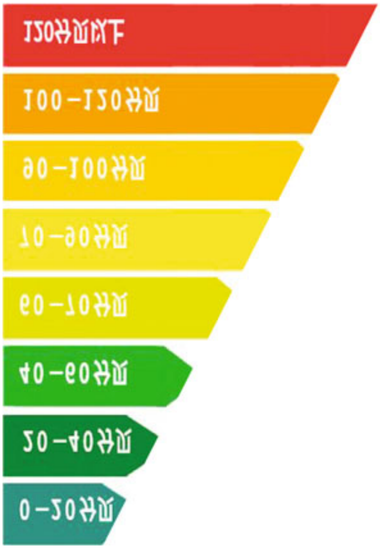
Fig. 7.5 Fuel flow during flight

Table 7.1 Flight time and fuel consumption analysis

Aviation stage		Duration (min)	Fuel consumption (kg)
Takeoff	Taxiing	12.4	182.2
	Takeoff	0.8	151.5
	Ramping to 1000 m	1.8	282.1
Flight	Ramping from 1000 to 10,000 m	21.1	1565.4
	Navigation	86.6	3519.9
	Descending from 10,000 m	20	415.6
Landing	From 1000 to 0 m	5.9	157.4
	Touch-down	1	29.4
	Taxiing	2.2	28.6
Total		151.8	6332.1

It is usually difficult to reduce the noise intensity during landing and takeoff since a large airliner must use the full thrust for takeoff and the reverse thrust in landing. However, reducing the takeoff duration is quite possible by making use of electric-driven jets that we proposed in Chap. 9 to leverage the takeoff weight for shorter takeoff distances. For landing, reverse thrust from the gas turbine machine can be replaced by the electrified jet thrust.

Table 7.2 Noise levels at different distance from the takeoff aircraft with the corresponding scenes

Distance (m)	Noise (dB)	Level (scene)	
0	143		
50	109	110 dB, damaging	
150	99		
450	90	90 dB, noisy street	
950	83		
3950	71	70 dB, noisy talking	
28,950	54		
33,950	52	50 dB, meeting room	
		20–40 dB, whisper	
		0–20 dB, silence	

7.2.2 *Electric Engine Is More Efficient*

Compared to fossil fuel mechanical/thermal engines, the efficiency of electric motor is higher. First, there is no thermal energy loss in e-engines. Second, the structure of the e-motor is relatively simpler—there is no gearbox to shift speed and no energy loss in the transmission. The motor speed is continuously adjustable, which only depends on the input electric current. The efficiency of the motor is just to convert the input voltage and current into the mechanical torque and rotation. The conversion efficiency can reach 90% or higher.

The electricity itself can be generated more efficiently as well. Currently, more and more electricity are from sustainable resources such as solar and windmills. In China, green energy has already account for nearly half (more details are provided in Sect. 7.3.1). Such green electricity stored in batteries and supercapacitors can be used to drive electric engines, a very worthwhile approach compared to fossil fuel gas turbine engines. Of course, some electricity may also come from power plants, but its efficiency can be targeted at ~ 40%. Compared with many individual combustion engines running around the world, the centralized electric generation from large power plants still has higher overall efficiency and fewer emissions of pollutants/greenhouse gases.

Additionally, electric engines are more prompt because they are electric driven instead of going through a gradual thermal combustion ramping process. This is because the power output mode of the engine is different. Fossil engines need to reach a certain speed to output the maximum torque. The electric engine can reach the maximum torque in an instant when the maximum input voltage and current are applied. For example, Tesla Model 3 has 275 horsepower and 1745 kg vehicle in weight. Its 100-m acceleration has reached 5.6 s. The Cadillac ATS with 276 horsepower and 1550 kg weight needs 6.2 s for the same acceleration.

The electric engine is clean and not as "dirty" as the fossil fuel engine since there is no exhaustion involved. Electric vehicles have zero tailpipe emissions, leaving the air cleaner as you drive. EV cars produce no emissions as compared to fossil fuel cars, especially as the electric grid becomes more renewable. The same truth applied for the airplanes since the electrified takeoff reduces many airport contaminations (more in Sect. 7.3).

7.2.3 Electric Flight Is Smarter

The smart flight is the "medium scope" flight, both from the range and from the pax. The large flight such as a 400-seat overseas commercial flight is not as economical compare to a few flexible 20 pax flights. Besides, the majority of flights are from ~ 500 km in range with ~ 50 passenger. Electrification plays a more efficient role in this scenario.

Figure 7.6 shows the flight traffic versus the mileage, and an impressive share of the flights is taken for short distances with a flight journey of 500 km range and 1–2 h duration [6]. As seen from the chart, close to 50% of all domestic flights cover distances of less than 500 km. These distances correspond to the operational range where the fossil fuels planes are the less efficient due to the higher takeoff and landing portion compared to cruising. Figure 7.6 also implies that it would be easier to reduce CO_2 emissions by using electrified takeoff/landing by replacing or decarbonizing the conventional gas turbine airliners in these short flights. The potential savings of less than 500-km flights by electrified air vehicles represent most of the CO_2 reductions.

Another interesting example of short-distance flight is in China. There used to be an interesting question asked by Chinese: Why don't we build a bridge over Dalian and Yantai? Dalian and Yantai are two very important coastal cities in China (Fig. 7.7) belonging to two large provinces: Liaoning and Shandong. Interestingly, although they are so close in distance, they are not connected inland due to a short ocean channel in between such as the Suez Canal. Both Dalian and Yantai are node cities with diverse transportation hubs connecting other inland cities, major ports, etc. In fact, the Chinese did not establish a bridging to connect these two cities is not they are not capable build high and long oversea bridge nor under sea canal, but due to the massive big shipping traffic passing through this canal everyday, since there are many important cities inside the canal connecting the inland to the Pacific Ocean. Through the scientific analysis of the geological situation, it is just not as scientific logical to connect these two cities either by underground channels or via a bridge across the Yangtze River. Since it is just 100 miles distance, it is a very promising plan to use the aero-vehicles to connect these two cities considering the short-range

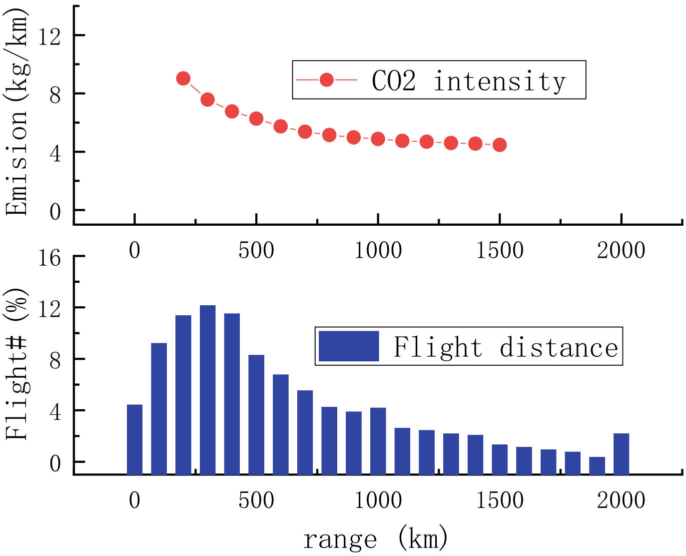


Fig. 7.6 The statistics of the most frequent flights and related CO_2 emission levels

feature of the electric aircraft, which happens to be in within 100 miles using the matured Li batteries. If one drives a car between these two cities, he has to drive around a big circle of over 1000 km (see Fig. 7.7 left). Not only in China, similar geographical situations worldwide can take a similar advantage by electric vehicles to connect two locations.

The Chinese philosophy is always seeking the "middle way", allowing more room to maneuver left or right, to shift either to the faster lane or slower lane on a highway. In this case, the middle way is the ~ 500-km flight with ~ 50 pax—the most frequent aviation traffic that the electric airplanes can fit in to maintain a proper balance between the performance versus efficiency. From the strategic level, small and medium-sized aircraft with medium thrust is always preferred for the best

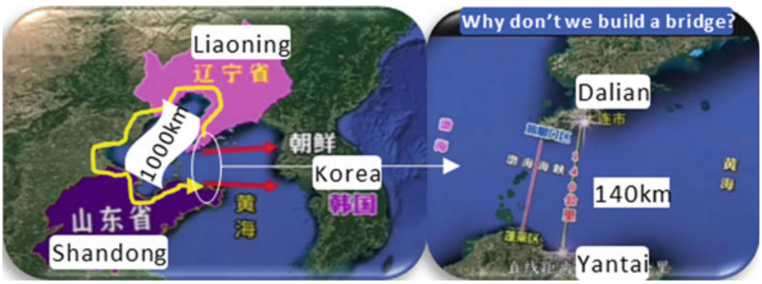


Fig. 7.7 Geographical site which is most suitable for electric aero-communications

economy. Most of the time, the 400 seats of large aircraft are not fully occupied and not as cost-effective as several adjustable-scheduled 20 seats van aircraft.

7.3 The Green Aviation—Less CO_2

What is "green"? "Green" refers to less carbon dioxide and methane in the air under the background of energy conservation and sustainability. There are two "greener" ways: one is passive, and the other is active. The passive way, for example, is to make CO_2 disappear by carbon neutralization, i.e., the focus is to solve a problem. The active way is to reduce the emission, i.e., to prevent a problem from happening. One is curing a disease while the other is to avoid it. The advantage of the second choice is obvious. Electrification is the active solution. Green electric aircraft technology has gradually become a hot topic f under the background of recent global warming, the abrupt climate change, and the reduction of fossil fuel resources [7, 8] Small and medium-sized aircraft and electric aircraft have low energy consumption and a high utilization rate, which is of great benefit to energy conservation and emission reduction. In addition, express drone aircraft is a hot market place in the near future, which will greatly enhance the IoT capability. It is especially cost-effective to use electric aircraft for fuel savings and emission reduction!

7.3.1 Greener Electricity

Electricity itself is becoming cheaper and more green in the coming century with the advent of more sustainable electricity generation such as solar, wind, and tidal. Figure 7.8 shows the electricity generation of China and America, the two largest vendors and users of electric power. The amount of electric generation has continued to grow since China opened its door to the outside world in 1978 by President Den XiaoPing. In addition, an increasing amount of electricity comes from renewable energy rather than from fossil. Renewable energy accounts for as much as 20% of total electricity generation in the States. The total power generation of the US in 2021 is ~ 4.1 trillion kWh, and the renewable energy power generation, including hydropower, solar power, wind power, and biomass power generation, is ~ 800 billion kWh. In particular, "solar power generation" is expected to become the main renewable energy source in the United States. In China, the total power generation in 2021 is approximately 8.112 trillion kWh, and the power generation from renewable energy is 2.485 trillion kWh, accounting for 30.6%. The power generation from wind power, solar energy, and biomass energy is 586.67, 300.9, and 148 billion kWh, respectively.

The Final Chapter of Green Energy

The ultimate green energy generation of mankind must be the full use of solar energy, tidal energy, and wind energy. The ultimate green energy storage should use the

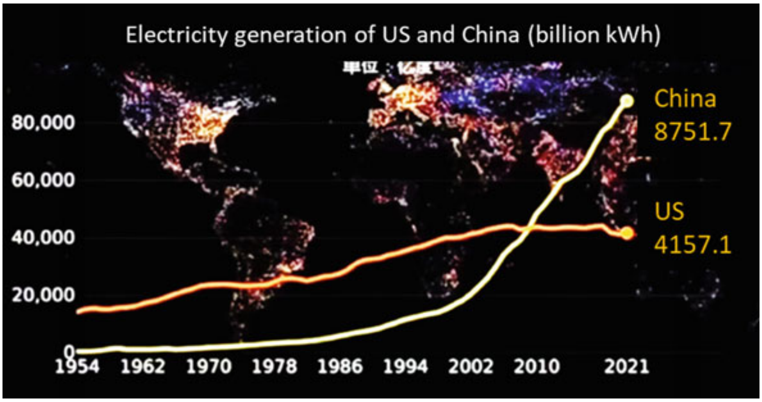


Fig. 7.8 Electricity generation of the US and China

above energies to hydrolyze water to extract hydrogen, storing hydrogen as fuel instead of fossil fuels, and using hydrogen fuel to create electricity from fuel cells. The byproduct is the H_2O, the water. That is the ideal way of green power. The real green energy solution is to use hydrogen as an energy storage fuel instead of using a Li battery and/or fossil fuel.

That is why Japanese people prefer to develop FC instead of Li battery cars although Toyota was the first to introduce the Prius hybrid car to the market as early as 1997. Japan has not participated in the development of Li battery EVs in recent years; part of the reason is due to Japanese understanding of clean energy and its own national conditions. Unlike the US or China, which have boundless resources, Japan is an island country and is seeking its self-feeding independence. According to Japan's philosophy, Li battery is never considered as clean energy because the battery production and recycling still cause a great deal of pollution to the environment. They firmly believe that Li batteries are only a temporary substitute to deal with the oil crisis. The hydrogen is the final chapter of the green energy, despite the current bottleneck of the hydrogen generation technique. Although there are boundless hydrogen in H_2O, it is just take too much electricity to separate it from water right now, and it is just a question of time when the breakthrough come into being.

7.3.2 Greener Flight

Greener Trip

Table 7.3 compares the cost of trips per capita by airplanes, gasoline cars, and electric cars in China and in the US as well as Chinese advanced CRH train, the cheapest and most effective cool public transportation taking full advantage of Chinese landscape geography. In China, taking CRH trains costs only ¥0.0022 per person per km, the cheapest long-journey travel in the world. Additionally, as seen in the table, it is more economical to drive electric cars in China than gasoline cars, and the expense of electric car traveling is only 1/9–1/5, because Chinese electricity is cheaper than that in the US and Chinese gasoline is more expensive than that in the US. Using EV car to replace fossil fuel car is partially driven by the government policies in China in the future, to shift from fossil fuels to purely electric vehicles. It is wise national strategy in the long run. Table 7.3 also contains many other useful info for future technology and policy judgment.

Greener Journey

One can also see from the above table that speed affects the efficiency of the high-speed trains—just reducing the traveling speed from 350 to 250 kmh saves 33% of the energy. This also applies for airplanes. Figure 7.9 shows the best navigation speed corresponding to the $L/D_{\max}$ ratios for airplanes traveling at different stages (with different weights of the airplane due to the kerosene consumption) [9]. It is thus concluded that more delicate tune-ups during the flight can save the energies to achieve a greener journey other than the above policies/strategic approaches.

Greener Strategy

The government is responsible for directing the overall orientation of the greener policy by taking full advantage of the nation's geographical and cultural situations. For example, in China, the CRH high-speed train is a wise decision for public traveling as well as for logistics deliveries in comparison to airplanes. It is both cheaper and green, just ¥0.0022/paxkm, less than 1% of traveling expense of the airplane and

Table 7.3 Comparison of the trip prices in the US and China by airplane, trains, gas car, and electric car

	E-motorbike	Motorbike	Tesla car	BMW car	China hi-speed train	Boeing 787	RR's e-plane
	Electric	Fossil	Electric	Fossil	Electric	Fossil	Electric
kWh/km, capita	0.048	0.110	0.072	0.193	0.003@250kmh 0.0045@350kmh	0.16	0.130
kWh/km, total	0.048	0.110	0.143	0.386	19.2@250kmh 27.4@350kmh	32	0.130
Passengers	1	1	2	2	600	200	1
¥/kWh/China	0.478	1.95	0.478	1.95	0.478	1.95	0.478
¥/kWh/US	0.86	1.34	0.86	1.34		1.34	0.86
¥/km capita/China	0.0229	0.2145	0.0342	0.3764	0.0022	0.3120	0.0621
¥/km capita/US	0.0413	0.1474	0.0615	0.2586		0.2144	0.1118
Notes	1 man	1 man	2 men	2 men	8 carriages, 600 passengers	200 passengers	1 man

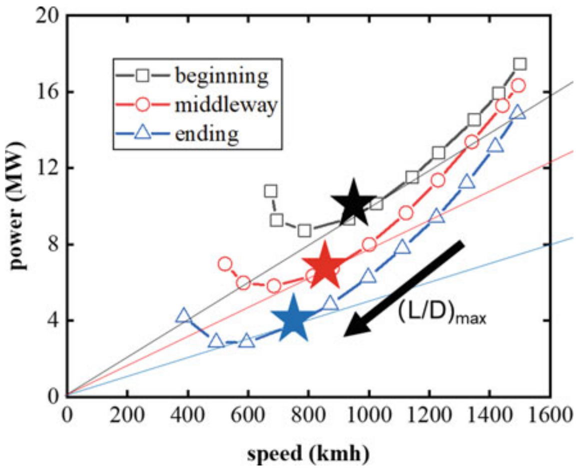


Fig. 7.9 Illustration of different $(L/D)_{\max}$ ratios (at the points of tangency) when fuel is consumed in the journey

less than 10% of electric cars. The railway station security checking is also much easier than in the airport. The loading time is also much shorter—no-ticket/check-in is required.

From a strategic point of view, unless purely necessary such as continental long-range travels, large aircraft is not as efficient to operate as smaller aircraft. Large thrust consumes much more power than medium thrust, and continental flights are less frequent than domestic travels. Through the analysis of the markets and air flows, medium-scale local flight processes a large portion of air traffic, and electric planes fit into this scenario more efficiently.

7.3.3 Greener Takeoff

Background: Pollution from Takeoff

The air pollution during takeoff/landing is higher and more intense since the engine is in full thrust and emissions are on the ground with concentrated airplane traffic (Fig. 7.10). NO_x (nitrogen oxides) is the main pollutant from engine's full thrust emissions, a poisonous gas derived from nitrogen and oxygen combustion under high pressure and temperatures during takeoff. NO_x contains nitric oxide (NO) and a smaller percentage of more poisonous nitrogen dioxide (NO_2); both are poisonous gases that contribute to acid rain and suffocating smog. In the takeoff phase, during the low-speed coasting process after the engine is started, the NO_x emission index increases from 0.96 to 8.10 g kg^{-1}. When entering the takeoff process with full thrust, the engine temperature rises, and the NO_x emission rises. The instantaneous maximum value exceeds 114.00 g kg^{-1}, with an average of approximately 105.80 g kg^{-1}, which is much higher than the rest of the flight.

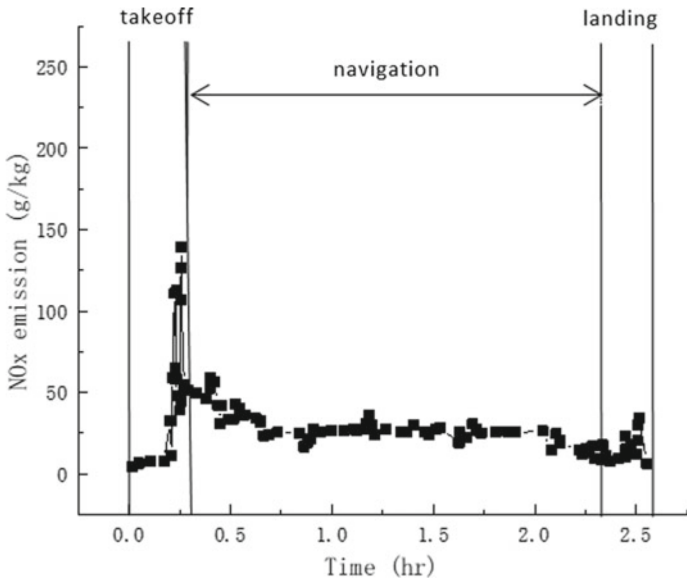


Fig. 7.10 NO_x levels in takeoff, navigation, and landing

The landing takeoff cycle (LTO) of the A320 series aircraft is 215 per day, accounting for approximately 40% of the total LTO of the airport. Based on this calculation, the NO_x emitted from the A320 series aircraft at Baiyun Airport in Guangzhou, China, is almost equivalent to the sum of 270,000 cars in a single day. Airport pollution is heavy and intense and usually requires a large space to digest other than its requirements on takeoff/landing distances.

Table 7.4 shows the details of fuel consumption rate of the engines together with the thrust and duration of the takeoff/landing of two typical engines, the small-scale AE3007 (32 kN thrust, 717 kg weight), and large jet engine CF6 (300 kN thrust, 4.9 tons weight) series. The proportions of aircraft engine NOx emissions are 28.16%, 38.60%, 8.46%, and 4.10% for the four modes of LTO: takeoff, climb, approach, and taxiing, respectively.

Greener Takeoff Methodology—VTOL and STOL

For larger aircraft, it is not practical for vertical takeoff since lifting up a 100-ton airliner aircraft requires 1000-kN engine thrust. However, shorter takeoff is feasible to offer an optimized and advanced takeoff process by reducing the amount of on the acceleration runway. Taking a 10-ton aircraft as an example, the friction loss accounts for 1/3 of the total takeoff energy. This takeoff loss can be avoided by shorter takeoff. Table 7.5 evaluates the takeoff distance savings for different planes by using RDF jets to leverage the weight of the airplane. For a 20-ton airplane equipped with 9 RDF jets, only, 500 m are needed for takeoff, half of the takeoff distance without vertical lift and half of the friction energy loss in takeoff.

Table 7.4 Throttle and fuel consumption of the four LTO stages

Mode of operation	Thrust throttle (%)	Duration (min)	Fuel consumption rate (kg/s)	Aero-engine
Takeoff	100	0.7	0.383	AE3007A1
			2.581	CF6-80C2A5
Ramping	85	2.2	0.318	AE3007A1
			2.082	CF6-80C2A5
Descending	30	4.0	0.113	AE3007A1
			0.687	CF6-80C2A5
Taxiing	7	26.0	0.046	AE3007A1
			0.207	CF6-80C2A5

The weight of large aircraft can be reduced with vertical thrust from rim-driven jet thrusters, hence shortening the takeoff distance and reducing the emission of harmful gases. For a rough estimate, takeoff distance S, duration, acceleration a, speed V thrust F, friction force f and coefficient k, takeoff weight m follow:

$$S = \frac{1}{2}at^2 \tag{7.1}$$

$$V = at \tag{7.2}$$

$$F - f = ma \tag{7.3}$$

$$f = mgk \tag{7.4}$$

We have

$$S = \frac{1}{2}\left(\frac{V^2}{F - mgk}\right) * m \tag{7.5}$$

For an ordinary commercial airplane, the takeoff speed is 270 kmh; the takeoff distance is 1000 m, and the takeoff time is 30 s. The thrust F must be large enough to accelerate the airplane to the takeoff speed within the runway distance S. That renders different aero-engines with different levels of maximum thrust (e.g., two engines with 290-kN thrust each). The takeoff distance S is proportional to the takeoff weight of the airplane. Using 9 RDF jets with a maximum vertical thrust of 10 tons, the weight is reduced by 1/5 for a 50-ton airliner. Ignoring the friction, the takeoff distance savings of the 50-ton aircraft are 1/5 * 1000 m = 200 m. In Table 7.5, we estimate the takeoff savings on distance for three weight airplanes under different thrust levels but assume the same takeoff distance of 1000 m including the friction loss at the friction coefficient $k = 0.01$.

Table 7.5 Reduced takeoff distance by vertical thrust for three airliners

RDF jet thrust (kg)	20 ton airplane			50 ton airplane			100 ton airplane		
	Reduced weight (kg)	Takeoff distance (m)	Takeoff saving (%)	Reduced weight (kg)	Takeoff distance (m)	Takeoff saving (%)	Reduced weight (kg)	Takeoff distance (m)	Takeoff saving
0	20,000	1004		50,000	1001		100,000	1004	
2000	18,000	901	10.3	48,000	959	4.1	98,000	984	2.0
4000	16,000	798	20.5	46,000	918	8.3	96,000	963	4.1
6000	14,000	696	30.7	44,000	877	12.4	94,000	942	6.2
8000	12,000	594	40.8	42,000	836	16.5	92,000	921	8.2
10,000	10,000	493	50.9	40,000	795	20.6	90,000	901	10.3
	Thrust	*58 kN*		*Thrust*	*146 kN*		*Thrust*	*290 kN*	

In summary, the STOL is the best approach for greener takeoff, saving airport space and time by using the vertical thrust to reduce the MGTOW. The Beijing airport traffic every day has ~ 22,920 takeoffs. A 10–50% takeoff distance reduction is a considerable amount of saving for CO_2 emissions and airport resources.

7.3.4 Greener Landing

Background: Pollution from Landing

The engine cannot be shut off during aircraft landing for safety concerns. Besides, many models still need the engine power to provide the reverse thrust to decelerate the plane during the landing. Moreover, the aircraft needs some power for taxiing and connecting taxiways.

When the aircraft is approaching the runway and preparing to land, the engine throttle is gradually reduced. In the final stage of landing, the engine throttle is at the minimum (idle) position. The combustion stability and economy of the engine are poor under the idle state. There are three main reasons for this: first, the small supercharging ratio of the engine at idle makes the thermal efficiency of the engine low and the economy poor. Second, the combustion chamber efficiency is low in the idle state. At idle conditions, the inlet temperature and pressure decrease, and the mixture is relatively lean, resulting in a lower flame temperature in the combustion chamber, which increases the emissions of carbon monoxide and hydrocarbons, both of which are products of incomplete combustion. Nearly, 50% of pollutants are discharged when the aircraft is in taxiing/idle mode. It is indicated that when the engine operates at low thrust, the emission index is relatively high, producing more emissions per unit of fuel consumed. Taking Beijing Capital Airport as an example, when the sliding time decreases from 26 to 22 min, the total amount of gaseous pollutant emissions is reduced by 6%. From an environmental point of view, the general approach is to reduce the duration of the on-state of gas turbine engines during landing.

CO is more prominent during landing, as shown in Fig. 7.11 although its content is not as high as NO_x in Fig. 7.11 during the takeoff. CO is more harmful than NO_x. The most common symptoms of CO exposure are fatigue, headaches, and dizziness due to inadequate oxygen delivery to the brain. This can lead to serious tissue damage or even death. In the landing phase during the approaching phase, the engine's low fuel flow operation and the reversed thrust cause the increasing CO emission index. In addition, the duration of this CO pollution is longer, causing more serious airport pollution than NO_x pollution during takeoff.

Greener Landing Methodology—Electric Reverse Thrust

Traditionally, the reverse thrust technique is applied for landing deceleration. The speed of the aircraft during landing is ~ 250 kmh, and the taxiing distance is between 2000 and 3000 m. This consumes many airport resources. Deceleration is the basic

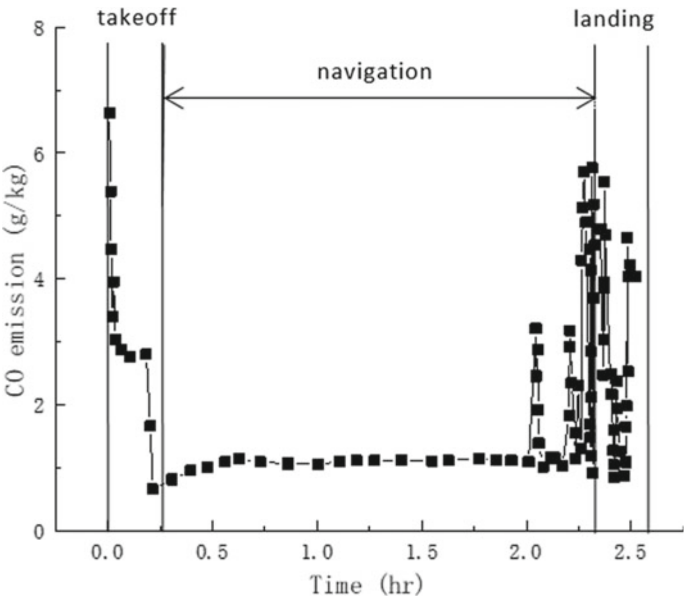


Fig. 7.11 CO levels in takeoff, navigation, and landing

solution to enhance the airport landing efficiency. The conventional deceleration methods are wheel braking and reverse thrust (Fig. 7.12), and the reverse thrust is the more effective and powerful and preferred. The drawback of this deceleration is its highest level of CO emission for landing compared to other LTO stages due to its low fuel rate combustion and reverse thrust. Such pollutant and noisy deceleration can be replaced by electric reverse thrusters. Multiple RDF jet can provide ~ 100 kN thrust just equivalent to a Boeing 787 reverse thruster deceleration force (Suppose the approaching speed is 250 kmh and the taxiing distance is 2500 m, the landing time is thereby 71 s, and the deceleration rate is approximately 1 ms^{-2}. Suppose the MGTOW of Boeing 787 is 200 tons, the fuel is almost exhausted after the journey; the aircraft weight at landing is 100 tons, and the decelerating force is close to 100 kN.)

Replacing the on-state gas turbine engine with an electric reverse thruster avoids much CO contamination from the commercial airliners—a large contribution to the greener landing.

In summary, green airports are more crucial since contamination is intense in the takeoff and landing periods. The peak and major levels of CO and NO_x are larger in the takeoff/landing stages than in the flight stage. In addition, airports are concentrated places for airplanes, and these accumulated effects exacerbate air pollution. Taking advantage of the rotatable wings to shift the electric jets vertically and backwardly can greatly enhance the airport takeoff/landing efficiency and reduce the associated airport pollution of NO_x and CO poisonous gases. The power to drive these electric engines may come from cleaner and quieter rechargeable electricity resources such

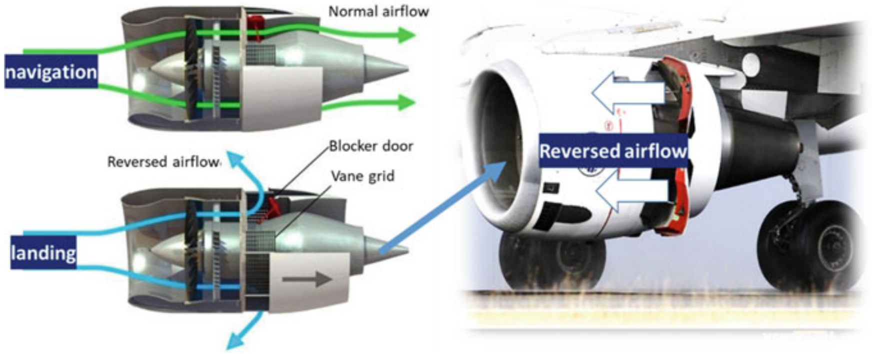


Fig. 7.12 Reverse thrust of the jet engine for landing

as Li battery and fuel cell battery. But, the best power is our 3D supercapacitor, which is lightweight, powerful, and safe aero-electricity storage media. The electric power is discharged in takeoff and will be recharged by the BTW generator from the existing gas turbine engine (more in Chap. 10) and then use this recharged electricity for clean and quiet landing. This clever arrangement of takeoff and landing is much more economical and much cleaner.

7.4 Case Studies/The Learnings

Table 7.6 compares the features, pros and cons of a few typical cases of the e-aviation together with our proposed e-aircraft/propulsion platform. There are two kinds of efforts on electric aviation: one is targeting the commercial market, and the other is for R&D; one is for short-term profit, and the other is long-term technology. The former is highly market driven, such as the twin-seat private airplane equipped with propeller and lithium battery—the two mature existing yet let advanced technology. Mature technology is easy to implement and simple to use, but its function is not superior enough. The latter is technology leading, which is the main interest of our AIAA/IEEE technical experts. It should be noted that while developing technology, we must have a strong sense of engineering infield experimentation instead of purely theoretical argument.

The value of the first three airplanes lies in its infield test data, which can be used as reference points for later development work. It borrows the matured Li battery achievements from the mature electric car industry to test the flight principles of electric propulsion and airplanes. Nevertheless, even these early testing are still preliminary—the immigration from the car industry to the aero-experiment is not as smooth or as up-to-date during the initial integration efforts. For example, the range of the infield test of the RR's SoI e-plane is still far less than the estimated value.

Table 7.6 Review of electrification on airplanes

Showcase	Moller VTOL Skycar	Rolls-Royce SOI	Eviation Alice	Yuneec E430	Boeing 787	Delta VTOLer	20-seater aero-van	3 × 3 STOL for C919
Driven by: shaft/rim	Shaft	Shaft	Shaft	Shaft	Shaft	Rim	Rim	Rim
Power: battery/generator/SC	Generator	Battery	Battery/generator	Battery	Generator	Battery/SC	SC/LTG	SC/LTG
Generator: ethanol/diesel/gas turbine	Ethanol	na	Gas turbine	na	Diesel	na	Gas turbine	Gas turbine
Fuel: fossil/electricity/hybrid	Fossil	Electric	Hybrid	Electric	Fossil	Electric	Hybrid	Hybrid
E-engine	Duct fan	Propeller	Propeller	Propeller	APU	RDF jet	RDF jet	RDF jet
VTOL	y	n	n	n	STOL	y	y	y
Rotatable wing	y	n	n	n	n	y	y	y
L/D ratio	n	y	y	y	y	y	y	y
Weight	325 kg	1250 kg	6668 kg	470 kg	250 ton	500 kg	7 ton	73 ton
Size meter ($W \times L \times H$)	6.5 × 2.5 × 2.25	7 × 8 × 2	19 × 17 × 3	13.8 × 12.5 × 2	60 × 63 × 17	3 × 2 × 2	7 × 6 × 2	36 × 38 × 12
Pax	1	1	11	2	200	3	20	168
Prototype	y	y	y	y	y	n	n	n

Sufficient battery efficiency data and airplane efficiency are still lacking. Stronger teams and sponsorship are urgently needed for future work.

In addition, from the first principle of physics, the Li battery is not an ideal choice for aviation electricity, both from its capacity and safety point of view. The intrinsic-specific power of the battery is just too low, and if operated in high-power output mode, its safety and reliability/lifetime (recharging times) will be greatly affected. From this perspective, new electric power supply resources must be developed that are more suitable for aviation electricity.

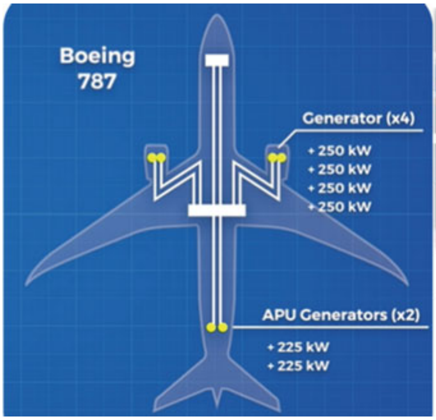
The value of the Moller's effort in Table 7.6 is its VTOL feature—it is the only manned VTOL infield test so far by successfully replacing the propeller with turbofan and with rotatable wings compared with other e-airplanes. This practical case, although far from being commercialized yet, serves as a good reference when developing the advanced eVTOL technologies. As for the Boeing 787's case, the value in a bold pace to adapt the new technologies, such as more electric engines, lightweight materials, and advanced aero-plane designs, with its superior R&D background support. These highly mature advanced technologies can be transplanted to electric engines, electric generators, and electric aircrafts.

In the following, we review the above electrification achievements from two perspectives. One is from the existing two mature cases from Boeing 787 and Honeywell, and the other is the three typical flying e-objects such as the Moller's VTOL carcopter, RR's SoI e-airplane, and DJI's agriculture UAS. The purpose of reviewing the existing process is for future advanced e-aviation technologies—to make traditional aviation more intelligent and effective. There are two key technology families involved in e-propulsion addressed in Chaps. 9 and 10 and advanced airplane/engine integration (DEP in Chap. 11).

7.4.1 Electrification of Boeing 787

Boeing 787 took advantage of new electrical engineering achievements to aid the existing aircraft (Fig. 7.13, from [10]). It is the first aircraft in history which makes the most electrification on the commercial airplane compared to its previous generations and other counterparts (Table in Fig. 7.13). In its first generations, it uses four 250 kW VSVF diesel generators to start the GEnX gas turbine engines during takeoff and two 225 kW engines from Honeywell for APU. The power over weight ratio of these generators is close to 1–2 kW/kg. For the recent generations, it uses four 250 kW generators weighing 95 kg (the specific power is 2.63 kW/kg).

What we learned from B787 electrification is although the power generation efficiency of diesel generator is lower than that of the gas turbine generator, its technology is simple, mature, and easy to implement. In B787's first introduction generation in 2011, the specific power is 1.25 kW/kg [11]. Currently, this ratio becomes 2.63 kW/kg (B787 in 2022). Boeing expects to achieve 5 kW/kg in 2030, and NASA has an even more ambitious goal achieve this specific power over 10 kW/kg [12].



Aricraft	Electic power used	Year	MTOW	Power /MTOW	Engine
B787-8	1000kW	2011	228 tons	4.387	Trent 1000/GEnx
A380	600kW	2007	575 tons	1.043	GP7000/Trent 900
B737NG	180kW	1998	79 tons	2.278	CFM56
A340	360kW	1993	277 tons	1.302	CFM56/Trent 500
B777	240kW	1995	247 tons	0.971	GE90
B767	240kW	1982	204 tons	1.176	CF6/RB211/PW4056

Fig. 7.13 Six diesel generators equipped on Boeing 787 plane with the maximum of 1.45 MW power right: electric power amount of different aircraft with introduction year

7.4.2 Rotatable Wing VTOL Carcopter

In 1991, Paul Moller completed his M400 Skycar after 50 years' endeavor in VTOL [13]. Compared with other flying cars, Muller focuses on its technological aspect rather than the commercial market. His great achievement is that he completed the vertical takeoff and landing using the rotatable wings (Fig. 7.14). It is the first practical case thus far to use a rotatable wing to adjust small-scale aero-engines to adjust the horizontal and vertical propulsion. During takeoff, the four engines project to the ground for the VTOL and turn to the proper angles for hover and navigate—some propulsion power holds the airplane in air, and some power moves the airplane forward. Four simple ethanol engines drive ducted fans to provide the thrust. This is the prototype that is closest to the future VTOL concept electric aircraft. Skycar M400 is designed for 4 people for duration of 5.9 h, passenger capacity 325 kg, aircraft weight 1 ton, speed 500 kmh, ethanol as fuel, and maximum range 1206 km. Engine maximum power is 45 kW, weight 22 kg, size 25 × 28 × 28 cm, displacement 530 cc, 24.5 L per hour. The aircraft size ($L \times W \times H$) is 6.5 m × 2.5 m × 2.25 m [14].

The value of this prototype is that it is a proven case to verify the working principle of a rotating wing by attaching a compact duct fan to it to achieve the VTOL instead of using rotating propellers without proven cases. Although this prototype is far from being adopted by marketing, its main focus on technical aspects is more important to us compared to most of the other developers who are still using propellers and other matured technologies to design a product on a planned roadmap. Of course, the disadvantages were the lack of strong sponsorship, such as the big airliners, and lack of the perseverant efforts of follow-ups. Its technology is more advanced but needs further R&D investment. In addition, it is not an electric aircraft; it is noisy and only weighs 500 kg. Despite all these drawbacks, its trial-and-error experience is much

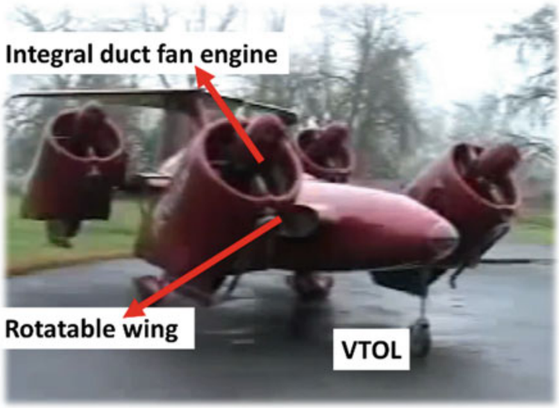


Fig. 7.14 Carcopter from Paul Moller

more worthwhile to study and follow-up when developing our e-propulsions using the RDF jet because they share many commonality.

7.4.3 *Three E-plane Cases*

There are many showcases of small Li battery-powered aircraft. The maximum takeoff weight is basically within 1.5 tons with less than 4 seats. Most of the time, people intend to identify electric aircraft with electric cars simply because they both use Li battery as electric power. However, there are still some differences in the battery features required for these two types of vehicles as listed in Table 7.7. The working conditions of existing Li batteries in electric airplanes are far more stringent than those of new energy automobiles. For example, the power output rate is much higher for electric aircraft, esp. during the takeoff. It is certainly the bottleneck of the battery from its first principle of physics—low specific power and lack of safety, esp. under high-power output. Li battery helps e-plane enters the e-aviation market faster, but it is not an ideal technology for aviation. In reality, as we see in the following real cases, the use of lithium battery technology borrowed from Tesla or BYD electric cars is not as professional and requires more delicate integration efforts. It is a big achievement of Rolls-Royce's Spirit of Innovation's test flight with its opened technical datasheet, where we can see that the actual flight mileage has not yet reached its expectation. Many tune-ups are still needed on the road of development.

Mobile aviation power is still the key bottleneck for electric aviation. In the long run, new electricity options must be developed other than Li batteries.

Real prototype test flights are still lacking to accumulate enough flight data to analyze for future R&D and commercial use. Here, we select only three cases—"Alice" from the Israeli/American Eviation Company, "Spirit of Innovation" from the British Rolls-Royce company, "E430" from a Chinese company. All cases have some infield flight data that can be used as reference for future studies. There are

Table 7.7 Li battery parameter comparison of EV car and EV plane

Parameters	Electric car	Flying car
Energy density (Wh/kg)	140–200	180–300
Discharge rate (C)	0.5–2	1–5
Peak power duration (S)	10–30	≥ 60
Number of cycles	1000–1500	≤ 500
Fast charging frequency (%)	10–50	≥ 90
Safety (%)	50	≥ 90

two prerequisites when we select the cases: they have deep research and development background support (for the perseverance and sustainability) and actual flight test prototypes (infield validation and technical datasheet). These models have good historical continuities and excellent supporting platforms, so they will not be like many "short life" cases. The battery is key bottleneck for all cases, and they need to work closely with concurrent EV vendors such as Tesla and BYD to catch up the newest battery developments (for example, 4680 battery in Tesla and Blade battery technology in BYD, more details in Chap. 10).

RR's Spirit of Innovation

Rolls-Royce's Spirit of Innovation [15] claimed in 2021 the first time that this SoI airplane flew more than 15 km at an average speed of 532.1 kmh and broke the world's highest electric aircraft speed record (600 kmh). It took 202 s to climb to 3000 m. The data of the RR aircraft are as follows: single-person aircraft, aircraft weight 1250 kg, 7 m (W) $\times$ 8 m (L) $\times$ 2 m (H), lithium battery weight 475 kg, power 74 kWh (= energy density 155 Wh/kg * 475 kg), power 237 kW (power density 500 W/kg * 475 kg). Three electric engines with a total power of 133 kW $\times$ 3 = 399 kW, 2200 rpm propeller, 750 V voltage.

The "Spirit of Innovation" is part of the ACCEL or "Accelerating the Electrification of Flight" project. Half of the project's funding is provided by the Aerospace Technology Institute (ATI), in partnership with the Department for Business, Energy & Industrial Strategy and Innovate UK. Its strong sponsorship background ensures that such an airplane plan has perseverant follow-up in the following years, and its real flight data provide valuable reference points for the following researchers.

Eviation's Alice

Unlike the RR's SoI, Eviation's Alice [16] electric airplane has not yet performed its infield flight and plan to make its first try from 2021 to 2022. It is a larger airplane with 11 seaters, all electric with 820 kWh lithium battery in total weight of 3720 kg. It covers an area of 19 m (W) $\times$ 17 m (L) $\times$ 3 m (H), with a maximum takeoff weight of 6668 kg. Table 7.8 lists its target parameters. It is our opinion that such plane has bigger ambition to achieve than RR's SoI which involves more technology challenges (much heavier aircraft which must involve the hybrid technology instead of pure Li battery). With such a goal in mind, the delivery year of 2022 is just too

Table 7.8 Key parameters of Alice's hybrid "van-aircraft"

Performance		Weights/power	
Max cruise speed	250 kts	MTOW	16,500 lbs
Max range	440 NM[a]	Payload	2500 lbs
Landing distance	2040 ft		
Take-off distance	2600 ft	Model	magni650
Climb rate	2000 ft/min	Max power	2×640 kW

[a]Target range, zero wind, no payload, IFR reserves

early considering the recent global situation. The more reasonable prototype delivery date shall be 2025–2030.

Chinese E430 Dual-Seat Electric Plane

Yuneec E430 [17] is a Chinese domestic two-seat electric aircraft, with a total takeoff mass of 470 kg (= battery 200 kg + two people 160 kg + aircraft and engine 110 kg). The lithium battery energy density is 200 Wh/kg, and the power density is 100 W/kg. The total energy carried with the airplane is 40 kWh with a maximum power of 20 kW. The cruise speed is 90 km/h, and the range is 227 km, so the flight time is 2 h and 30 min. The ordinary e-plane market in China is not as prominent compared to the unmanned e-aircraft for various mobile scenarios such as camera, delivery, and agricultures.

7.4.4 Unmanned Aero-system

UAS is one of the air mobilities in advanced air mobility (AAM). UAS opens a broad playground of market which brings about the vast versatile aerospace usages and needs the proper aero-administration rules when there are too many aero-vehicles in air. The keyword of UAS is the "unmanned" which implies much less safety concerns which involved stringent technical requirements such as robustness and reliability. There are two families of UAS. One is the vertical hovering ability, such as camera drones. The other is horizontal aero-machine, such as the Switch Blade series. From the thrust perspective, the first type focuses on the vertical lift ability similar to a helicopter, and the design rules are focusing overcoming the gravity. The second type is focusing on the acceleration for horizontal navigation as ordinary planes. The first type UAS seems to have more market places. In both UAS cases, the weight is the key factor to leverage the load of the engine as well as the battery. Such UAS is usually below 100 kg. At the current stage, none of them is capable of rotatable wings to accommodate both VTOL and horizontal navigation. Below, we analyze these two typical UAS. As a rough estimate:

- The horizontal speeding capability. The power need in the flight must match the power of the battery as well as the engine. For example, a UAS carrying a 0.25 kg

Li battery (150 Wh/kg and 400 W/kg) can provide a maximum 100 W power and 37.5 Wh energy. With a power/weight ratio of 1 kW/1 kg, a 0.1-kg electric motor can provide a power output of 100 W. The power needed to fly at 120 kmh (=33 ms) speed is $P = TV$, where the thrust $T = $ mg (L/D). With a designed thrust/weight ratio of 10, $P = 82.5$ W Therefore, 100 W of power from both the electric motor and battery is sufficient to support the navigation of this horizontal UAS airplane.
- The vertical hovering capability. With the special design of the propeller together with enough power output, the vertical thrust should overcome the gravity of the UAS. The power/weight ratio should be greater than 3.75 kg/kW, a typical value for a helicopter. For an electric UAS, this value can reach 7 kg/kW or higher. For example, to lift an agriculture drone of 90 kg, one needs at least 13 kW of power from the battery, i.e., at least 32.5 kg of Li battery with a power density of 400 W/kg is necessary to lift this 90-kg T40 agriculture UAS. This is the proven data from DJI.

Horizontal UAS

The two main characteristics of a horizontal flight UAS are the range and duration. The range R follows this formula, and the duration t is the energy E divided by the output power P

$$R = E\,\eta \frac{1}{g}\frac{L}{D}\frac{m_b}{m_a} \tag{7.6}$$

$$t = E/P \tag{7.7}$$

For example, the energy carried in SB300 with a 0.1-kg Li battery is $E = 15$ Wh. The power was assumed to be $P = TV = $ mg (L/D) $V = 125$ W. Then, $t = E/P = $ 7 min.

As discussed earlier, for a certain airplane, there exists a best navigation speed for the best efficiency with a max lift/drag ratio L/D. Therefore, the best design of the lift/drag ratio and optimized flight velocity is the key. It is noted that the L/D ratio is different during takeoff compared to the $L/D_{\max}$ in navigation. For example, B787 takeoff requires 60 tons of thrust to lift 240 tons of weight at a speed of 270 kmh, and $L/D = 1/4$. During the flight, the thrust used is 8 tons with a speed of 900 kmh to keep the airplane at 10,000 m altitude. The L/D ratio is $8/240 = 30$.

Table 7.9 lists the three typical UASs from AeroVironment unmanned aircraft systems [18]. It is noted here that only the switch blade 300 and 600 use electricity as the power; JUMP 20 UAS uses gasoline engines/fossil fuels as navigation power and MOGAS 190 cc electronic fuel injection (EFI) as its engine [19]. Unlike the DJI, this type of UAS is still a horizontal airplane which need some range to take off.

Vertical UAS

Table 7.9 Three typical small UAS (two one-time use)

	Fuel	E (Wh/kg)	Eta	mb (battery) (kg)	ma (MGTOW) (kg)	Range (estimated) (km)	Range (data) (km)	Endurance (min)
Switch blade300	Li battery	150	0.8	0.1	2.5	10.4	10	6.0
Switch blade600	Li battery	150	0.8	10	54	40.0	40	40
JUMP 20	Kerosene	2000	0.3	17	100	183.6	185	

DJI (Da Jiang Inc. [20]) is one of the leading Chinese drone companies founded in 2006 focusing on versatile drones. There are two typical application scenarios: camera drone for geometrical studies and agricultural drone spraying fertilizer and sowing seeds (Table 7.10).

Table 7.10 Small weight drones for agriculture and for camera shooting

	Parameters	DJI agricultural drone	DJI camera drone
Battery	mb (battery)	12 kg	0.12 kg
	P-density	1112 W/kg	1112 W/kg
	Max power	13,344.0 W	134.6 W
	Max lifted weight	93 kg	1 kg
	E-density	130 Wh/kg	130 Wh/kg
	Total energy	1560 Wh	16 Wh
	Duration	7 min	33 min
Airplane	I	30,000 mAh	3850 mAh
	V	52.0 V	7.4 V
	Used power	1560.0 W	28.5 W
	Duration	7 min	30 min
	ma (airplane)	50 kg	
	mp (payload)	40 kg	
	MGTOW	90 kg	0.25 kg
	Weight (ability)	93 kg	1 kg

DJI Agras T40. T40 drone is DJI's new flagship for *digital agriculture*. This high-endurance drone is optimized for agricultural application scenarios such as precision spraying fertilizers, spreading the seeds, and aerial surveying and mapping. Equipped with a coaxial twin-rotor design, the T40 farming drone boasts its spreading capacity of 50 kg and a spraying capacity of 40 kg. Effectively, this drone can spread 1.5 tons spray pesticides on a 320-acre field in an hour. The drone also features omni-directional radar and binocular vision to detect obstacles at a distance of up to 50 m. As such, DJI T40 can also be flown in complex terrain, such as orchard hills, by spraying up to 60 acres of fruit trees in an hour.

T40' has max MGTOW 90 kg (40-kg payload), size 2.8 m $\times$ 3.15 m $\times$ 0.78 m, can hover max 7 min with 1560 Wh energy and max battery power output 13.4 kW (full load). There are eight 18 cm propellers, each driven by a rotor with 4 kW, and the max electric engine power is 32 kW. To lift the 90-kg T40, the weight-to-power ratio must be higher than 90 kg/13.4 kW = 6.7 kg/kW. This ratio is higher than that of a typical kerosene-fuelled helicopter (3.75 kg/kW), indicating that the electric engine used in DJI possesses higher lift-to-power ratio than an ordinary machines.

DJI Mini 3 Pro. This tiny camera drone weighs only 0.25 kg, with 30 min hovering time, 18 km range, 21.6 kmh speed. The size is $L \times W \times H = 251$ mm $\times$ 362 mm $\times$ 70 mm. Li ion battery 3850 mAh, 0.121 kg, 7.4 V, 28.4 Wh, using slightly tilted rotating wings or a dedicated propeller to provide horizontal thrust.

What we learned from the above examples is that (1) they are unmanned flying objects, (2) they are within 100 kg weight, and (3) they are matured products.

7.5 The Distinct Topics of E-propulsion

The electronic propulsion for a VTOL aero-machine is a pretty comprehensive technology and process. We use Fig. 7.15 to illustrate their complex connections. A VTOLer must fly horizontally fast enough (speed) as well be able to vertically take off (weight). The engine/the battery must be good enough to provide enough thrust/power. Both the energy density and the amount of fuel should provide enough energies for a long-range flight.

7.5.1 Power Versus Thrust, Engine Versus Battery

First of all, both the engine and battery must be able to support enough power (in kW) as well as thrust (in kN). The power and thrusts are two different concepts. Enough output power is needed from the battery, and the engine must be able to accept this power, digest it, and convert it to propulsion energy either as a propeller or a turbofan. This acceptability is power of an engine. Therefore, both the battery (or other electric power supplier) and engine must be powerful enough. Besides, vertical takeoff thrust

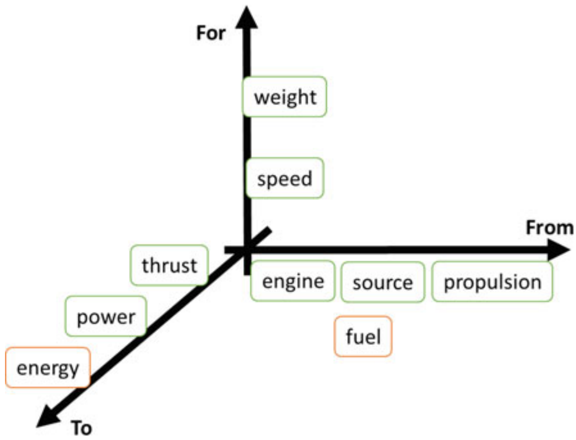


Fig. 7.15 E-propulsion system—from, to, and for

requirement is different from the horizontal thrust. The horizontal thrust is used for acceleration and then to use the wing to take off an airplane. The key ability is for the horizontal acceleration. The vertical thrust is to conquer the weight of the airplane, i.e., to overcome the gravity "mg". The latter needs more thrust and is harder to achieve than the former. For example, two GEnX engines can horizontally take off a Boeing 787, but it is almost impossible to lift this 200-ton airplane machine. As an advanced electric airplane, we prefer to call it a "VTOLer", which must possess both qualities: vertical lifting itself and enough horizontal speed.

VTOL is a pretty comprehensive technology, which involves both the power and the thrust from both engines and batteries for both horizontal speeding and for vertical lifting. As outlined in Fig. 7.16, the new e-aircraft is different from the previous generations in its integrated capabilities of both VTOL (e.g., ~ 7 tons weight) and horizontal flight high speed (e.g., ~ 600 kmh) via a rotatable wing.

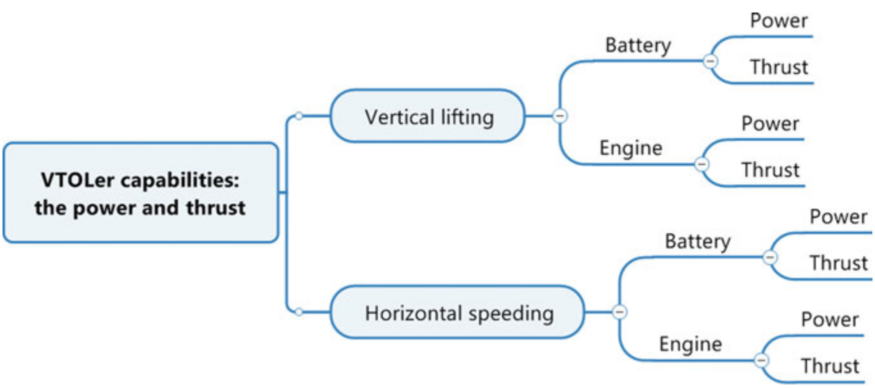


Fig. 7.16 A VTOLer must have both vertical and horizontal capabilities from both engine and battery for both power and thrust

Below, we discussed this matter one by one.

(1) **Vertical lifting**

The vertical takeoff requires both power and thrust. To raise the 700-kg aircraft with a speed of 1 m/s, the power needed is $P = \mathrm{FV} = \mathrm{mgv} = 7$ kW. On the other hand, the helicopter has a conventional rule that under enough helicopter thrust like a long propeller, the lift-to-weight ratio is 3.75 kg/kW. From this perspective, 187 kW of power is needed to raise a 700-kg VTOLer. On the other hand, the estimated lift-to-weight ratio of DJI's UAS can reach 7 kg/kW. Considering the thrust privilege of the RDF jet, this lift-to-weight ratio can be even higher. The needed power if using the 7 kg/kW is just 100 kW. In terms of lift-up strength, the vertical thrust must overweight of the 700-kg aircraft, i.e., 7 kN. Enough power/thrust must be provided both by battery/engine:

Battery

Assuming the battery weighs 400 kg in the 700-kg plane equipped with three ϕ30 RDF jet engines (Chap. 9), the max power of the battery is 160 kW (the power density of the Li battery is 400 Wh/kg), which meets the minimum requirement of 100 kW.

Engine

(1) Power: The power-to-weight ratio of the e-engine is 1–7 kW/kg. Three ϕ30 RDF jets weigh 60 kg which shall deliver 60–420-kW e-power, which can may meet the minimum requirement of 100-kW power margin provided enough power from battery/other electric suppliers.
(2) Thrust: Three ϕ30 RDF jets provide 3–18 kN depending on the amount of the feeding power from the battery. With enough battery power, the thrust can be greater than 7 kN weight, fulfilling the need for VTOL.

Therefore, the power/thrust from the battery/engine is good enough for vertical takeoff. After that, the RDF jets are rotated horizontally by rotatable wing to speed up the airplane, and eVTOLer relies on the lift-to-drag ratio to maintain its altitude.

(2) **Horizontal speeding**

The power needed to fly at 900 kmh (=250 ms) speed is $P = TV$, where the thrust $T = \mathrm{mg}\ (L/D)^{-1}$. For the 700-kg airplane with a thrust/weight ratio L/D of 30, the thrust needed is $T = 233$ N, and the power is $P = 58$ kW. Both these thrust and power shall be provided by battery and engine with enough amount.

Battery

The power of 400-kg battery (400 W/kg) is 160 kW, which is greater than need (58 kW). Assuming the energy density is 200 Wh/kg, then total energy of 400-kg battery is 80 kWh. If the airplane keeps flying at 900 kmh, the time span is 80/160 = 0.5 h; the range is 450 km.

Engine

Three ϕ30 RDF jets can deliver greater than 60 kW e-power, which can also fulfill the need of the minimum requirement of 58 kW. Besides, three ϕ30 RDF jets provide greater than 3-kN thrust, also greater than the thrust requirement.

Of course, the previous calculation is just a rough estimation of the ideal case, such as assuming the best level *L*/*D* ratio ~ 30 and no other energy losses. Yet, it is already seen that the main bottleneck for a VTOLer is the vertical takeoff, the potential powerfulness of engine and power when outputting the vertical thrust and related power in the lightweight. In our sample case above, this VTOLer potential is fairly easy to achieve since the airplane is still not heavy, just 700 kg. Besides, we carry a lot of battery (400-kg Li ion battery with the best level of energy density (200 Wh/kg) as the year of 2022 with the power density of 400 W/kg) in just 700-kg airplane, with a big assumption of lightweight aircraft and payload (just 300 kg of airplane, engine, and pilot).

7.5.2 Specific Power of E-engine

The specific power of an engine refers to the ratio of the power output versus the weight of an engine (kW/kg). It used not to a big deal for the vehicles traveling on the ground, but this parameter is very crucial for the aero-engines. Beside, even for ground vehicles like the modern EV cars, seeking the higher P/W ratio is also a key parameter when developing the advanced e-engines. Table 7.11 compares the power/weight ratios of various engines of fossil versus electric, car versus airplane.

Table 7.11 Specific power of typical engines

	Motor	Para			
		M (kg)	*W* (kW)	Power/weight (kW/kg)	Year of introduction
Cars	EA111	128	100	0.781	1974
	EA211	106	100	0.943	2012
	BMW740i's B57	334	294	0.880	2015
Air-planes	Diesel generator/B787	95	250	2.632	2021
	Honeywell aero-generator	127	1000	7.874	2021
	Gas turbine/CFM56-2-C	2104	13,000	6.179	2010
Electric engine	E-engine-old	7	1	0.143	1960
	E-engine-Tesla	134	340	2.537	2020
	E-engine-Lucid Air	73	502.5	6.884	2021

Most of the traditional fossil fuel car engines do not have a good PWR performance. In comparison, the ordinary aero-engines for aviation have a much better performance by considering the weight factor in engine design. Most of the gas turbine machines can reach the power-weight ratio about 7 kW/kg. In Boeing 787 first generations of diesel generators, the PWR is just 1 kW/kg. For the most recent B787, four 250 kW generators weighing 95 kg have been implemented with an improved PWR of 2.63 kW/kg. In the future, much better PWR electric engines will emerge according to their roadmap of development [21].

What we learned from B787 electrification is that when advanced aero-electric power generation technology is ready, diesel and other mature generators can be used with lightweight modifications to generate electricity on a small and medium scale. Although the power generation efficiency of a diesel generator is lower than that of a gas turbine, its technology is simple, mature, and easy to implement. In B787's first introduction generation in 2011, the specific power was 1.25 kW/kg [11]. Currently, this ratio will become 2.63 kW/kg in B787 in 2022. As seen, Honeywell already claimed its lightweight gas turbine generator (in 2021). Other companies are also working on developing large PWR machines such that Boeing expects to achieve 5 kW/kg in 2030, and NASA has an even more ambitious goal of achieving this specific power over 10 kW/kg [12, 22].

Big PWR E-motors

The early power-to-weight ratio of traditional electric motors is very low. About 7–12-kg heavy-duty motor is often required to output 1 kW of power (0.08–0.14 kW/kg). Driven by electric cars and other advanced robotic mobile devices, more and more advanced motor design technology are adopted to enhance the power-to-weight ratio (PWR in kW/kg). For example, the Tesla Model 3 Motor weighs 92 kg with 2.35 kW/kg PWR, and the weight of the Lucid Air motor is just 73 kg reaching a high PWR of 6.8 kW/kg. Lucid recently claims it permanent magnet motor integrated with an inverter; differential and transmission system with an ultra-high voltage 900 V power unit weighs only 74 kg with a max of 9.45 kW/kg PWR.

As seen, adopting a rare earth permanent magnet into electric motors is the key technology to increase the PWR. Rare earth permanent magnet motor systems are already in broad use in Chinese high-speed railways (CRHs). The manufacturing cost of rare earth permanent magnet (PM) motors is reduced by more than 20%; the weight is reduced by 50–80%; the volume is reduced by 80%, and the energy conversion efficiency is increased by 10–15%. Rare earth PM most often use Nd-Fe-B composites, and LaSeFeB can also be added into PM family to leverage the need for pure NdFeB rare earth materials. PM is an indispensable material for building rim-driven aviation engines (in Chap. 9). As a future roadmap for advanced electric propulsion of electric aviation by improving the power density and efficiency of motors, the realistic near-term target is to develop 50–300 kW electric motors with PWRs of 5–7 kW/kg and weights of 8–40 kg. For example, for an 8-kg rare earth PM electric engine with a PWR of 5 kW/kg, 48 such engines can deliver up to 2.24 MW for the DEP airplane with a total thrust of 5 tons. To achieve this goal, the integrated design of materials, structures, and systems is the key instead of the individualized efforts of the professionals in different fields in AIAA and IEEE. The mutual cooperation is highly necessary to achieve at highly interdiscipline goal of electrified aviation.

7.5.3 Torque, Power, and Speed of Electric Motor

Figure 7.17 compares the engine behaviors of the famous and matured EA 211 gasoline engine and an ordinary electric engine which is still on the road of developing for better PWR. Here, we just use this chart to compare the different performance behavior of the fossil engines versus electric engines. There are two distinct difference between two engines. For the electric engine, the maximum torque can be achieved even with the low rotating speed. In other words, the torque is only dependent on the amount of applied electric powers (the input current and voltage). With enough power supply, we can maintain the enough strength of the engine. The second difference is that the electric motor has a maximum constant power limit which is the product of the torque and speed. In other words, if the torque is too big, the engine cannot maintain the speed. Such a phenomenon will be elaborated in Chap. 9 that in the RDF e-engine; if the resistance level is too high (the torque is too big), the turbofan will slow down the speed and cause the lower air intake rate and then reduce the thrust. Such a phenomenon does not occur for gas turbofan with stronger power level. Due to the limited electricity output from battery, its power is just not enough to maintain the speed under high torque when driving a bigger fan size, i.e., the thrust cannot reach its expected value even with a larger fan size (Sect. 9.6, Table 9.3).

In summary, driven by the strong need of advanced and smarter electric-driven e-aviation industry, with the help of the most advanced e-generator and e-engine, the vertical VTOL aero-machines will soon become possible to fit in the vast air mobility needs in the very near future.

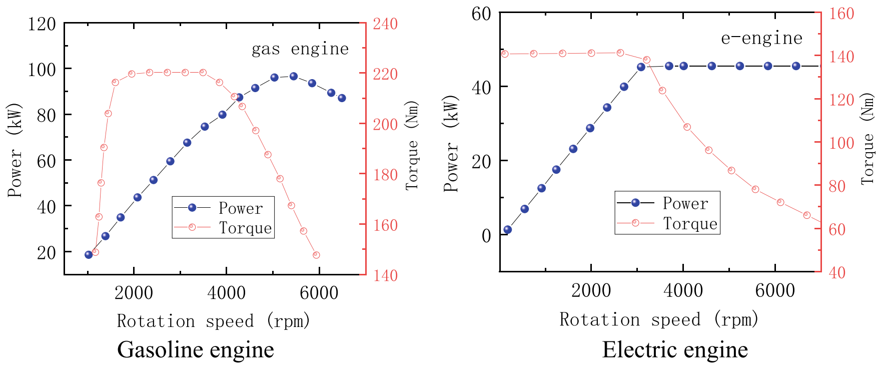


Fig. 7.17 Engine performance of typical gas engine and electric engine: torque, speed and power. Left: 220 Nm, 110 kW, 106 kg fossil engine. Right: 135 Nm, 50 kW, 200 kg, electric engine

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Chapter 8
The Evolution of Aero-engines

Engine is the heart of an airplane. In fact, in the aero-industry, the significance value of the engine is almost equivalent to the plane. That is why in the four AIAA Forums, there is a dedicated forum specifically for the aero-engine—the AIAA Forum on Propulsion and Energy. In the 2018 P&E Forum, the electric aero-engine was the hottest topic which attracts both the AIAA and IEEE people. Since then, electric propulsion keeps shedding new light to the next generation of aircraft propulsive force:

> *In terms of thrust, the power ranking is:*
>
> *Rocket > Turbine jet > Turbine fan > Electric aero-engine*
>
> *In regard to intelligence, the ranking becomes:*
>
> *Electric propulsion > Turbine-fan > Turbine jet > Rocket.*

An electric propulsion versus gas turbine engine is analogous to efficiency versus power. The value of developing electric aero-engine does not lie in chasing the powerfulness but in seeking for intelligence. Let's review the development of the aero-engines starting from the early days in order to get some insight from past to future.

The Evolution

As shown in Fig. 8.1, the first generation for aero-propulsion is a propeller driven by piston engine, such as the Spitfire fighter and Merlin engine in WW II. The second generation is the gas turbine and electric-driven propeller. Both technologies are matured and are being used right now. The future aero-engine shall be the clever combination of the re-engineered gas turbine (for example, big BPR gas turbofan GEnX) plus the advanced electric propulsion technology (RDF jet in Chap. 9).

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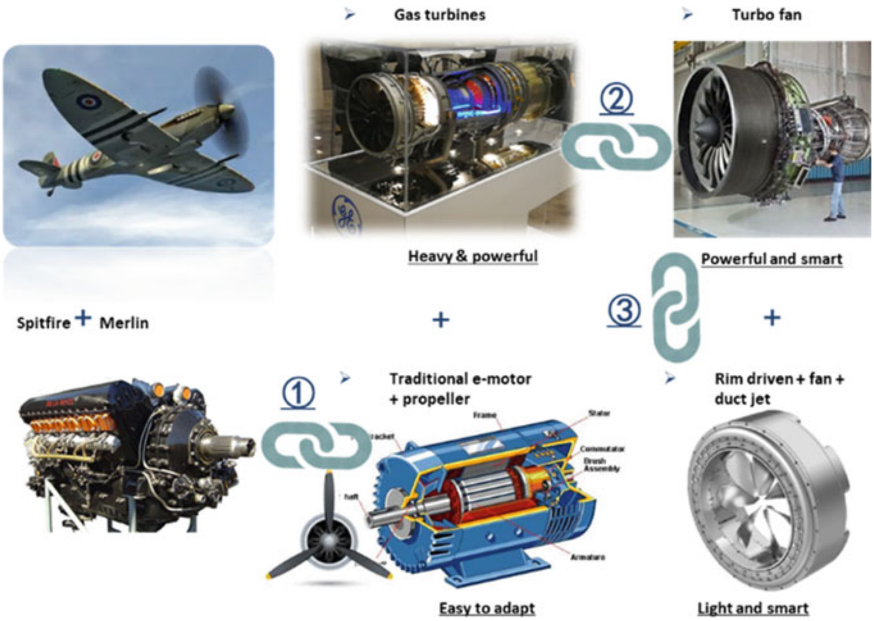

Fig. 8.1 Evolution of the aero-engine from past to future

The Road Map

A roadmap of future aero-engine is shown in Fig. 8.2. There are two separate paths: stronger/more efficient gas turbine engines and smaller/smarter electric aero-engines. Gas turbine engines are highly dependable on advanced technologies in mechanical, thermodynamic, and material engineering and stringent working ambient conditions (high temperature, high pressure, and intense stress). In contrast, electrified propulsion may circumvent these tough requirements. In these two paths, the first engine serves big size aircraft for continental and official purpose. We use larger bypass ratio to enhance the efficiency of gas turbofan engine and to use the electric propulsion to shorten the takeoff distance. The second aero-engine provides the propulsion for small aircraft serving the local, private, and versatile purposes. We use electric propulsion to achieve the integrated design of multiple engines/airplane (DEP) and to serve as the driving engine for 300-kg–10-ton VTOLers (aero-vehicles capable of both vertical takeoff and horizontal navigation with rotatable wings.

As to future electric power, there are three separate road maps (Fig. 8.3),

1. Li battery and diesel generator are two matured technologies which can be quickly used in propeller-based private airplanes and to help the electrification for big airplane as in B787. Battery-driven propeller plane is still in R&D stage and not yet fully commercialized. The main challenge is the range is too short and the less satisfied safety when adopting the Li battery from EV cars to airplanes. Even the EV cars are still in the developing stage of enhancing the Li battery efficiency

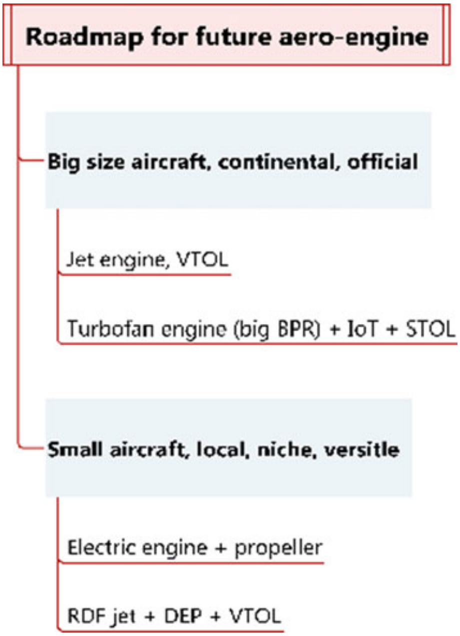

Fig. 8.2 Roadmap of future airplane propulsion

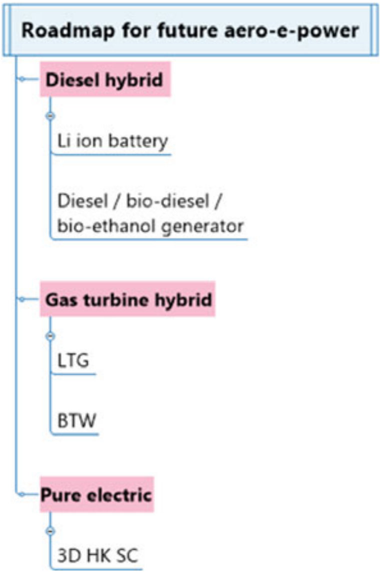

Fig. 8.3 Road maps for future aviation electric powers