frontiers | Frontiers in Aerospace Engineering

TYPE Field Grand Challenge
PUBLISHED 04 March 2024
DOI 10.3389/fpace.2024.1383934



OPEN ACCESS

EDITED AND REVIEWED BY
Matthew Oehlschlaeger,
Rensselaer Polytechnic Institute, United States

*CORRESPONDENCE
Ramesh K. Agarwal,
rka@wustl.edu

RECEIVED 08 February 2024
ACCEPTED 19 February 2024
PUBLISHED 04 March 2024

CITATION
Agarwal RK (2024), Grand challenges in aerospace engineering.
*Front. Aerosp. Eng.* 3:1383934.
doi: 10.3389/fpace.2024.1383934



# Grand challenges in aerospace engineering

Ramesh K. Agarwal*

Department of Mechanical Engineering and Materials Science, Washington University in St. Louis, St. Louis, MO, United States

KEYWORDS

**aerodynamics and flight mechanics, aircraft materials and structures, propulsion and energetics, guidance, navigation and control, intelligent aerospace systems, electronic aviation systems, aircraft engineering and design**

## Introduction

Since the historic first powered flight of a heavier-than-air aircraft (known as the Wright Flyer) on 17 December 1903 at Kill Devil Hills near Kitty Hawk, North Carolina, there has been a revolutionary transformation in technologies that have made the air travel around the globe possible for general masses by commercial aircraft such as B737 to B787 and A310 to A380 and this technological progress is continuing today. It is clear that the new generation of air vehicles would be built using new materials, low weight optimized structures of composite materials, advanced aerodynamic configurations with flow control, new propulsion concepts and technologies using fuels such as SAF, Synthetic fuels, hydrogen, batteries, etc. In addition, advanced and revolutionary navigation and control system and avionics are being developed, and advanced ATM and NEXTGEN are getting ready to manage the air space. The following sections describe the key challenges that need to be addressed in the six technology areas. The goal of the journal “Frontiers in Aerospace Engineering” is to attract high quality papers from researchers working in all these challenge areas and make them rapidly available on open access platform to the aerospace community after a rigorous peer review process. Papers on multi-disciplinary applications of various aerospace technologies as well as those addressing futuristic aerospace configurations/designs such as electric/hybrid and hydrogen-powered commercial subsonic/transonic aircraft, low boom supersonic aircraft, air-breathing hypersonic aircraft, and e-drones/UAV/MAVs are especially welcome.

## Challenge 1: aerodynamics and flight mechanics

This technical challenge includes both fundamental and applied aspects of aerodynamics (Cummings et al., 2015; Bertin and Cummings, 2021) and flight mechanics (Stengel, 2022) that promote their better understanding as they relate to the advance and futuristic aerospace systems including the environmentally responsible aerodynamic technologies and designs (Agarwal, 2009; Agarwal, 2012). The papers describing applications of aerodynamics fundamentals to new aerospace engineering systems technology by combining theoretical, experimental, and computational studies of multidisciplinary nature are especially sought. The topics covered by this challenge include, but are not limited to aerodynamics of streamline and bluff bodies, free- and wall-shear-flow stability, aerodynamic measurements, aerospace thermo-fluids experiments and simulations, laminar, transitional, turbulent and separated flows, jets, wakes and shear flows in general, passive, active and re-active flow control (Gad-el-Hak, 2000; Agarwal et al., 2006), open and closed loop control, actuator and sensors, reduced—order modeling and flow control, fluid-structure interaction and aero-elastic analysis and control (Collis et al., 2004), flight mechanics innovations, aerodynamics of the ground vehicles (Qu et al., 2014) and the marine vehicles (Qu et al., 2016), high-lift systems (Wild, 2022), Computational Fluid Dynamics (Anderson et al., 2020), turbulence and transition modeling and validation (Wilcox, 2006; Durbin, 2021), Large Eddy Simulation (LES) and Direct Numerical Simulations (DNS) (Jiang and Lai, 2017), applications to aircraft (Agarwal and Deese, 1990a; Agarwal, 1999) and rotorcraft (Agarwal and Deese, 1990b) and other air vehicles. Papers are also sought with applications of Machine Learning and Artificial Intelligence to aerodynamics (Vinuesa and Brunton, 2022). In the area of flight mechanics, papers are sought in the areas of nonlinear six-degree of freedom flight simulation, lateral, longitudinal and coupled aircraft motions, flight control design of all categories of aircraft, aircraft, and flying qualities and flight performance.

## Challenge 2: materials and structures

The demand of new materials and structures for aircraft and aerospace engineering industries has increased dramatically. High-strength, lightweight, non-corrosive, recyclable, ultra-violet (UV) and impact resistant properties are key factors for materials for new type of flying vehicles (Zhang et al., 2018) Advanced manufacturing processes including additive manufacturing, digital manufacturing and virtual-twin technologies provide new solutions for different types of space structures subject to harsh space environments (Blakey-Milner et al., 2021; Li et al., 2022). Nanotechnology supports the fundamental changes of materials and mechanical properties of metal and polymer-based composites to add values, in terms of better electrical, mechanical, thermal, and multifunctional properties of host materials for structures at different extreme temperature conditions (Ni et al., 2022). Electro-magnetic shielding properties of polymer-based composites could be altered by nanofillers for space re-entry vehicles (Van der Heijden, 2018). For small space structures, like cube satellites, metamaterials, deployable and morphing structures are of interest to space engineers and researchers. The development of full electric-driven and hydrogen/electric (hybrid) driven vertical takeoff and landing (eVTOL) or short take-off and landing (eSTOL) vehicles requires new materials to compensate the weight penalty from batteries (Dale et al., 2020). The ambient condition of flying vehicles at high altitude and space environment are low temperature, low pressure and full of radiation attacks that may deteriorate the properties of materials. Space debris and natural meteoroids moving at hyper-velocity can damage satellites and space stations easily due to accumulated high impact energy. Nano-structural design may be promising to dissipate energy to prevent catastrophic damages to the structures. To overcome these challenges ahead, designing and adopting new materials and structures for the aircrafts and space vehicles are crucial to support the growth of aerospace industry (Fleck et al., 2020).

In summary, the focus of this challenge is on the new materials and structures covering their fundamental properties to applications, multifunctional properties, advanced manufacturing processes, modelling and analysis, data-driven technologies including data-security in the manufacturing 4.0 network, additive manufacturing, digital/virtual twins, etc. Carbon-based materials that drive the development of high-temperature resistant composites, energy composites including supercapacitors, cryogenic fuel tanks and radiation-resistant coating layers for space structures also fall into this specialty. The papers in any of these areas are sought.

## Challenge 3: aerospace propulsion and energetics

An excellent summary of this challenge has already been published by Oehlschlaeger (2022) in Frontiers in Aerospace Engineering. Here, some of his observations are highlighted for the sake of completeness of this article.

Propulsion technologies are well established for low speed to supersonic air flight, payload launch to space, and missions within space. However, existing commercial systems have shortcomings in terms of their sustainability and often operational performance (range, speed, power density, safety, etc.). These shortcomings are being addressed through fundamental and applied research that seeks to overcome existing challenges to improve current technologies and develop new concepts.

Conventional aircraft propulsion is predominantly reliant on aviation fuels from fossil sources and has considerable impact on the environment, through the emission of greenhouse gases and air pollutants and generation of contrails (Nelson and Reddy, 2018). In response, there is ongoing research on the development of aircraft propulsion systems that are fully electric, hybrid-electric, and/or operate using hydrogen fuels or alternative fuels offering reduced environmental impact (electric, bio-derived, and synthetic fuels). Research and development efforts on next-generation of aircraft propulsion to address sustainability challenges are multi-disciplinary and involve the development of bio-chemical engineered fuels, fuel cells for efficient conversion of chemical energy to electricity, next-generation batteries, and new hybrid and electric concepts for distributed and embedded propulsion units such that the air vehicle geometries can be re-envisioned and optimized (Pelz et al., 2021).

Air-breathing hypersonic propulsion systems have been pursued for decades but are still in the research and development phase, owing to the inherent difficulties of designing robust systems capable of supersonic combustion and handling the hypersonic aero-thermodynamic environments. Research challenges in this the area of air-breathing hypersonic include the fundamental understanding of the supersonic-combustion such that the scramjet engines can be designed that operate on hydrogen or liquid fuels and are sufficiently compact and robust to be integrated into an air vehicle and operate for minutes to hours rather than seconds. Among the current research challenges relating to hypersonic vehicle propulsion include supersonic fuel-air mixing (Huang et al., 2019), combustion stabilization (Liu et al., 2020), materials and cooling systems offering thermal management and protection at the extreme conditions encountered, and the development of ground-based experimental facilities to test hypersonic concepts (Gu and and Olivier, 2020).

Electric space propulsion systems have seen rapid growth over the last several decades for a variety of applications, including Hall, ion, and electrothermal thrusters. However, significant research is ongoing to develop new electric propulsion concepts that improve specific impulse, efficiency, scalability, longevity, and reliability of these systems (Dale et al., 2020). Examples of electric propulsion concepts for space that are under research and development include electrospray arrays, radio frequency- or microwave-systems coupled with magnetic nozzles, pulsed inductive thrusters, magneto-plasma-dynamic (MPD) and nuclear thermal (NT) propulsion systems among others (O'Reilly et al., 2021). Research challenges for future electric space propulsion systems will address the need to improve the specific impulse and longevity of the high-thrust systems and the efficiency and reliability of low-thrust systems (Dale et al., 2020).

Commercial solid and liquid energetics for propulsion and munitions applications take a variety of forms and have been developed over a century or more; however, there are still significant research challenges in developing new energetic materials with improved properties and reduced environmental impact. These include the development of solid propellants and solid hybrid propulsion fuels utilizing additives that increase regression rate (Pang et al., 2021). Solid energetics for munitions applications are sought that are insensitive to thermal, mechanical, or electrical stimuli but have increased energy release rates relative to the incumbents (Anniyappan et al., 2020). For both munitions and propulsion applications, solid energetic formulations that take advantage of the nanomaterial features (Van der Heijden, 2018) or are additively manufactured are being developed (Fleck et al., 2020). Additionally, green monopropellants for space propulsion that offer reduced environmental impact and address safety concerns are areas of active research and development (Nossier et al., 2021).

The papers are sought in all the research and technology areas describe above.

## Challenge 4: guidance, navigation, and control (GNC)

The issues related to guidance, navigation, and control (GNC) are receiving increased attention in aerospace engineering research and applications (Stengel, 2022; Yan et al., 2023). One of the objectives of this challenge is to provide a platform to both the theoreticians and the practitioners to share their latest results and identify critical issues and challenges for further investigation in GNC. The papers are sought on new advances in GNC including the advanced dynamic modeling, fault management capabilities, reconfigurable and fault tolerant flight control (Yin et al., 2016), guidance and navigation systems and multi-sensor data fusion (Ye et al., 2023), sensor and actuator fault monitoring and diagnosis, detection and mitigation of anomalous events and threats, upset recovery and management of loss of control in-flight (LOC-I) regimes, safe flight envelope prediction and protection, new decision-making methods, model identification and optimization, and intelligent functionalities for trustworthy and evolvable autonomy for next-generation unmanned systems. With the advent of artificial intelligence and machine learning, unmanned systems (e.g., satellites, unmanned aerial vehicles, unmanned underwater vehicles, etc.) are playing an irreplaceable role in civil and military aviation. Navigation and control are of key importance to the unmanned system. Without navigation and control, the unmanned system would have no autonomy. There is a great push for new technological developments in the unmanned systems to meet the ever-higher safety, autonomy, and sustainability requirements. In these fields, the challenges and emerging needs continue to grow as individual systems evolve and operate with greater autonomy and intelligence within a networked and distributed cyber-physical environment. The papers are also sought that highlight developments in GNC areas that include sensors, actuators, communications, estimation, control as well as applications of AI and machine learning in GNC including the comprehensive reviews/surveys of these areas (Wu et al., 2021; Li et al., 2023).

## Challenge 5: intelligent aerospace systems

An excellent summary of this challenge has already been published by Cohen (2023) in Frontiers in Aerospace Engineering. Here, some of his observations are highlighted for the sake of completeness of this article.

The growing trends in Artificial Intelligence (AI) (Adadi and Berrada, 2018) coupled with increasingly autonomous aerospace systems bring about a major paradigm shift resulting in new opportunities that have the potential to radically extend the state of the art. These innovative technologies are pushing the market in new area such as the advanced air mobility which has an estimated global market value of USD 1.9 trillion in the next 25 years. Recent demonstrations by civilian space industry have opened avenues like space tourism and the investments in the long term deep space missions are growing. Autonomy (Clarke and Tomlin, 2020; Bartlett et al., 2023) is a key enabler and needs to be trustworthy (Baron et al., 2018; Kaur et al., 2022). It must synergize with human operators to augment performance and assure safety and reliability of operations. The goal of this challenge is to promote new advances in intelligent aerospace systems and technologies that incorporate exciting and relevant developments in the Industrial Revolution 4.0/5.0. The topics covered in this challenge, having a common theme of AI-Enabled Aerospace Systems, include but not limited to Systems Engineering of AI-Enabled Aerospace Systems, Responsible, Trustworthy, Transparent and Certifiable AI, Supervised, Semi-supervised and Unsupervised Explainable AI, Assured Autonomy for non-deterministic systems, Advanced Air Mobility, Cyber-attack Resilience, Real-time Learning and Adaptation, AI driven Prognostics and Health Management, Scalable, Robust, Large Collaborative Systems, Human-AI Teaming and Optimization, AI-Enabled Augmented Reality/Virtual Reality for Training and CONOPS development, etc. The papers are sought in all the above and related areas.

## Challenge 6: aircraft engineering and design

Aircraft Design Challenges are safety, long-haul flights, sustainability and capacity (Torenbeek, 2013). Modern aircraft designs have been driven by "higher, faster and farther" doctrine (Kundu et al., 2019). In traditional design paradigm, the goal has been continuous improvements in performance accompanied by continuous increase in complexity and cost (Raymer, 2006) which is now not acceptable to both the supplier and the customer; the requirement now is the continuous improvements in performance accompanied by the continuous increase in complexity with lower cost. Lean aircraft engineering concepts have been introduced to substantially reduce time, resources, and risk, and increase quality, utility, and supportability while reducing total ownership cost, and enable integrated product and process development (IPPD) concept across the full acquisition life cycle by using modeling and simulation to reduce life cycle cost (LCC) (Raj, 1998). Over the years, many methods have been developed to facilitate decision-making at various stages of design process—Computer-Aided Design (CAD). Finite Element Methods (FEM), and Computational Fluid Dynamics (CFD).

The traditional design consisted of three steps—Conceptual design, Preliminary design and Production design which resulted in long cycle time, high risk and high cost. Decisions were made in early stages using data from crude and simplistic analyses and much time was spent to reconcile design changes proposed by various engineering disciplines and the design, manufacturing, operations, and support were essentially segregated. The way forward is therefore to use an integrated approach which simultaneously considers all aspects including design, manufacturing, and support and considers all requirements and constraints from start thus reducing the need for design changes in the later stages by conducting cost/performance trade-offs early using more knowledge from modeling and simulation tools. This integrated approach shortens design cycle time and reduces risk and cost (Raj, 1998).

The way forward to meet the challenges is to introduce innovative technologies and develop an integrated, effective, and efficient process for the life cycle design of aircraft, known as systems engineering (SE). SE is a holistic approach to a product that comprises several components. Customer specifications, conceptual design, risk analysis, functional analysis and architecture, physical architecture, design analysis and synthesis, and trade studies and optimization, manufacturing, testing validation and verification, delivery, life cycle cost and management. Further, it involves interaction among traditional disciplines such as aerodynamics, structures and flight mechanics with people- and process-oriented disciplines such as management, manufacturing, and technology transfer. SE has become the state-of-the-art methodology for organizing and managing aerospace production. Typically, the research into SE provides a deeper understanding of the core principles and interactions and helps one to appreciate the required technical architecture for fully exploiting it as a process, rather than a series of events. There are major issues as regards to systems approach to aircraft design which include lack of basic scientific/practical models and tools for interfacing and integrating the components of SE and within a given component, for example, the life cycle cost and the basic models for linking the key drivers. The papers are sought in all aspects of SE for aircraft design as well as the advanced modeling and simulation tools required. The papers on the practical case studies of aircraft design are especially welcome.

## Author contributions

RA: Writing–original draft, Writing–review and editing.

## Acknowledgments

The author gratefully acknowledges the inputs and contributions from Prof. Cohen, Prof. Das, Prof. Oehlschlaeger, and Prof. Xiao.

## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

## Publisher's note



## References

Adadi, A., and Berrada, M. (2018). Peeking inside the black-box: a survey on explainable artificial intelligence (XAI). *IEEE Access* 6, 52138–52160. doi:10.1109/access.2018.2870052

Agarwal, R. K. (1999). Computational fluid dynamics of whole-body aircraft. *Annu. Rev. Fluid Mech.* 31, 125–169. doi:10.1146/annurev.fluid.31.1.125

Agarwal, R. K. (2009). Sustainable (green) aviation: challenges and opportunities. *SAE Int. J. Aerosp.* 2, 1–20. doi:10.4271/2009-01-3085

Agarwal, R. K. (2012). "Review of technologies for sustainable (green) aviation," in *Recent advances in aircraft technology*. Editor R. K. Agarwal (London, U.K.: Intech Press).

Agarwal, R. K., and Deese, J. E. (1990a). "Navier-Stokes calculations of the flow-field of a complete aircraft," in *Advances in computational fluid dynamics*. Editor W. G. Habashi (Springer-Verlag).

Agarwal, R. K., and Deese, J. E. (1990b). in *Euler/Navier-Stokes computation of the flow field of a helicopter rotor in hover and forward flight*. Editor P. A. Henne (Progress in Aeronautics, American Institute of Aeronautics and Astronautics), 125, 533–555.

Agarwal, R. K., Vadillo, J., Tan, Y., Cui, J., Guo, D., Jain, H., et al. (2006). "Flow control with synthetic and pulsed jets: applications to virtual aero-shaping, thrust-vectoring, and control of separation and cavity oscillations," in *Frontiers of computational fluid dynamics*. Editors D. A. Caughey and M. Hafez (World Scientific). Chapter 11.

Anderson, D. A., Tannehill, J. C., Pletcher, R. H., Munipalli, R., and Shankar, V. (2020). *Computational fluid mechanics and heat transfer (computational and physical processes in mechanics and thermal sciences)*. 4th Edition. Boca Raton, FL: CRC Press. 13: 978-0815357124.

Anniyappan, M., Talawar, M. B., Sinha, R. K., and Murthy, K. P. S. (2020). Review on advanced energetic materials for insensitive munition formulations. *Combust. Explos. Shock Waves* 56 (5), 495–519. doi:10.1134/s0010508220050019

Baron, A., Babiceanu, R. F., and Seker, R. (2018). "Trustworthiness requirements and models for aviation and aerospace systems," in Proc. 2018 Integr. Commun. Navigation (Herndon, VA, USA. (Herndon, VA: ICNS (Published in IEEE Xplore)).

Bartlett, P., Chamberlain, L., Singh, S., and Coblenz, L. (2023). A near-term path to assured aerial autonomy. *SAE Int. J. Aerosp.* 16 (3). doi:10.4271/01-16-03-0020

Bertin, J. J., and Cummings, R. M. (2021). *Aerodynamics for engineers*. 6th edition. Cambridge University Press. -13 þ: 978-1009098625.

Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., et al. (2021) Metal additive manufacturing in aerospace: a review, *Mater. Des.*, 209, pp./ID 110008, doi:10.1016/j.matdes.2021.110008

Clarke, J.-P., and Tomlin, C. J. (2020). Some steps toward autonomy in aeronautics. Accessed https://www.nae.edu/234438/Some-Steps-toward-Autonomy-in-Aeronautics.

Cohen, K. (2023). Grand challenges in intelligent aerospace systems. *Front. Aerosp. Eng.* 2. doi:10.3389/fpace.2023.1281522

Collis, S. S., Joslin, R. D., Seifert, A., and Theofilis, V. (2004). Issues in active flow control: theory, control, simulation, and experiment. *Prog. Aerosp. Sci.* 40, 237–289. doi:10.1016/j.paerosci.2004.06.001

Cummings, R., Mason, W. H., and Morton, S. A. (2015). *Applied computational aerodynamics: a modern engineering approach*. 1st edition. Cambridge University Press. -13: 978-1107053748.

Dale, E., Jorns, B., and Gallimore, A. (2020). Future directions for electric propulsion research. *Aerospace* 7 (9), 120. doi:10.3390/aerospace7090120

Durbin, P. (2021). *Advanced approaches in turbulence: theory, modeling, simulation, and data analysis for turbulent flows.* 1st Edition. Elsevier. 13: 978-0128207741.

Fleck, T. J., Manship, T. D., Son, S. F., and Rhoads, J. F. (2020). The effect of process parameters on the structural energetic properties of additively manufactured reactive structures. *J. Eng. Mater. Technol.* 142 (4), 041004. doi:10.1115/1.4047037

Gad-el-Hak, M. (2000). *Flow control: passive, active, and reactive flow management*. 1st Edition. Cambridge University Press. -13:978-0521770064.

Gu, S., and Olivier, H. (2020). Capabilities and limitations of existing hypersonic facilities. *Prog. Aerosp. Sci.* 113, 100607. doi:10.1016/j.paerosci.2020.100607

Huang, W., Du, Z. B., Yan, L., and Xia, Z. X. (2019). Supersonic mixing in airbreathing propulsion systems for hypersonic flights. *Prog. Aerosp. Sci.* 109, 100545. doi:10.1016/j.paerosci.2019.05.005

Jiang, X., and Lai, C.-H. (2017). *Numerical techniques for Direct and large-eddy simulations.* 1st edition. Boca Raton, FL: CRC Press. -13þ: 978-1420075786.

Kaur, D., Uslu, S., Rittichier, K. J., and Durresi, A. (2022). Trustworthy artificial intelligence: a review. *ACM Comput. Surv.* 55 (2), 1–38. doi:10.1145/3491209

Kundu, A. K., Price, M. A., and Riordan, D. (2019). *Conceptual aircraft design: an industrial approach*. 1st Edition. Wiley. -13þ: 978-1119500285.

Li, T., Liang, H., Xiao, B., Pan, Q., and He, Y. (2023). Finite mixture modeling in time series: a survey of Bayesian filters and fusion approaches. *Inf. Fusion* 98, 101827. doi:10.1016/j.inffus.2023.101827

Li, Y., Xiao, Y., Yu, L., Ji, K., and Li, D. (2022). A review on the tooling technologies for composites manufacturing of aerospace structures: materials, structures and processes. *Compos. Part A Appl. Sci. Manuf.* 154, 106762./ID 106762. doi:10.1016/j.compositesa.2021.106762

Liu, Q., Baccarella, D., and Lee, T. (2020). Review of combustion stabilization for hypersonic airbreathing propulsion. *Prog. Aerosp. Sci.* 119, 100636. doi:10.1016/j.paerosci.2020.100636

Nelson, E. S., and Reddy, D. R. (2018). *Green aviation: reduction of environmental impact through aircraft technology and alternative fuels* (Boca Raton, FL: CRC Press).

Ni, D., Cheng, Y., Zhang, J., Liu, J.-X., Zou, J., Chen, B., et al. (2022) Advances in ultra-high temperature ceramics, composites, and coatings, *J. Adv. Ceram.*, 11 (1), 1–56. doi:10.1007/s40145-021-0550-6

Nosseir, A. E., Cervone, A., and Pasini, A. (2021). Review of state-of-the-art green monopropellants: for propulsion systems analysts and designers. *Aerospace* 8 (1), 20. doi:10.3390/aerospace8010020

Oehlschlaeger, M. A. (2022). Grand challenges in aerospace propulsion. *Front. Aerosp. Eng.* 1. doi:10.3389/fpace.2022.1027943

O'Reilly, D., Herdrich, G., and Kavanagh, D. F. (2021). Electric propulsion methods for small satellites: a review. *Aerospace* 8 (1), 22. doi:10.3390/aerospace8010022

Pang, W., Li, Y., DeLuca, L. T., Liang, D., Qin, Z., Liu, X., et al. (2021). Effect of metal nano-powders on the performance of solid rocket propellants - a review. *Nanomaterials* 11 (10), 2749. doi:10.3390/nano11102749

Pelz, P. F., Leise, P., and Meck, M. (2021). Sustainable aircraft design—a review on optimization methods for electric propulsion with derived optimal number of propulsors. *Prog. Aerosp. Sci.* 123, 100714. doi:10.1016/j.paerosci.2021.100714

Qu, Q., Liu, C., Liu, P., Guo, B., and Agarwal, R. K. (2016). Numerical simulation of water-landing performance of a regional aircraft. *J. Aircr.* 53 (6), 1680–1689. doi:10.2514/1.C033686

Qu, Q., Lu, Z., Guo, H., Liu, P., and Agarwal, R. K. (2014). Numerical investigation of the aerodynamics of a delta wing in ground effect. *J. Aircr.* 52, 329–340. doi:10.2514/1.C032735

Raj, P. (1998). *Aircraft design in the 21st century: implications for design methods*. American Institute of Aeronautics and Astronautics. AIAA Paper 98-2895.

Raymer, D. (2006). *Aircraft design: a conceptual approach*. 4th Edition. American Institute of Aeronautics and Education Series. -13: 978-1563478291.

Stengel, R. (2022). *Flight dynamics*. Second Edition. Princeton University Press. ISBN 13 :978-0691220253.

Torenbeek, E. (2013). *Advanced aircraft design: conceptual design, analysis and optimization of subsonic civil airplanes*. 1st Edition. Wiley. ISBN-13 þ: 978-1118568118.

Van der Heijden, A. E. D. M. (2018). Developments and challenges in the manufacturing, characterization and scale-up of energetic nanomaterials–a review. *Chem. Eng. J.* 350, 939–948. doi:10.1016/j.cej.2018.06.051

Vinuesa, R., and Brunton, S. L. (2022). Enhancing computational fluid dynamics with machine learning. *Nat. Comput. Sci.* 2, 358–366. doi:10.1038/s43588-022-00264-7

Wilcox, D. C. (2006). *Turbulence modeling for CFD*. 3rd edition. CA: D C W Industries. ISBN-13:978-1928729082.

Wild, J. (2022). *High-lift aerodynamics*. 1st edition. Boca Raton, FL: CRC Press. ISBN13: 978-1032115467.

Wu, X., Xiao, B., Li, L., and Wu, C. (2021). Factor graph based navigation and positioning for control system design: a review. *Chin. J. Aeronautics* 35 (5), 25–39. doi:10.1016/j.cja.2021.09.001

L. Yan, H. Duan, and Y. Deng (2023). in *Advances in Guidance, Navigation and Control: Proceedings of the 2022 International Conference on Guidance, Navigation and Control (Lecture Notes in Electrical Engineering)*. Editors. 1st edition. (Springer), 845.

Ye, X., Song, F., Zhang, Z., and Zeng, Q. (2023). A review of small UAV navigation system based on multisource sensor fusion. *IEEE Sensors J.* 23 (17), 18926–18948. doi:10.1109/jsen.2023.3292427

Yin, S., Xiao, B., Ding, S. X., and Zhou, D. (2016). A review on recent development of spacecraft attitude fault tolerant control system. *IEEE Trans. Industrial Electron.* 63 (5), 3311–3320. doi:10.1109/tie.2016.2530789

Zhang, X., Chen, Y., and Hu, J. (2018) Recent advances in the development of aerospace materials, *Prog. Aerosp. Sci.*, 97, 22–34. doi:10.1016/j.paerosci.2018.01.001