Journal of Aerospace & Security Studies
2024 | Volume III | pp. 35-67

Quantum Takeoff: Applications in the Aviation Sector

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Abstract

At the intersection of advanced computer science and quantum physics, Quantum Computing has emerged as one of the most compelling technological frontiers of the 21st Century. Among the industries poised to benefit significantly, the aviation sector stands out as a key area where this transformative technology can drive substantial advancements. The findings of this research reveal several noteworthy applications of quantum computing in the aviation industry, including aircraft design, flight trajectory optimisation, navigation, schedule maintenance, and secure network management. Integrating this technology could bring numerous benefits to the aviation sector, enhancing operational efficiency, resource utilisation, and overall productivity. However, these advantages are contingent on overcoming existing challenges. As a developing country, Pakistan must also begin investing in efforts and resources to adopt quantum computing in its aviation sector, ensuring its readiness to leverage this transformative technology in the future.

Keywords: Emerging Technologies, Quantum computing, Qubits, Aviation Sector.

Introduction

Quantum computing has rapidly emerged as a transformative technology, earning its place among the most significant 'emerging' and 'disruptive technologies.'[1] In today's data-driven age, it enables unprecedented computational capabilities, solving complex problems at an accelerated pace and driving breakthroughs across various fields.[2] Its expanding applications have heightened expectations about its societal impact.[3] Among sectors such as finance, healthcare, and education, aviation is particularly poised to benefit from the profound potential of quantum computing.[4]

The aviation sector symbolises technological innovation, global connectivity, and the expansion of networks. It is currently undergoing significant transformations driven by factors such as increased connectivity, airline expansion, technological advancements, growing freight operations, emerging markets, and infrastructure development.[5] Quantum technology can further revolutionise this sector by enabling complex simulations and offering insights beyond traditional analytical methods. It has the

1 *Quantum Computing: A Sectoral Composition Approach,* report (Maryland: Center for International and Security Studies, 2020), 4, https://strategictraderesearch.org/wp-content/uploads/2020/10/Quantum.pdf.

2 Sarada Rajalaxmi and Suchita Reddy, "Quantum Computing: Applications and Future Importance," *International Research Journal on Advanced Science Hub* 3, no. 6 (2021): 157-160, https://rspsciencehub.com/article_12156_fdba83ed2793d8948d083f0238f60cf0.pdf.

3 Hiral Patel, Sejal Mishra, Rahul Jain and Nirali Kansara, "The Future of Quantum Computing and its Potential Applications," *Journal for Basic Sciences* 23, no.11 (2023): 513-518.

4 Rajalaxmi and Reddy, "Quantum Computing: Applications and Future Importance," 158.

5 Ibid.

potential to strengthen and expedite modernisation in aviation operations, making it crucial to analyse its impact on the industry.

This research paper explores the intersection of quantum computing and aviation, focusing on its applications within the sector. It begins with an overview of quantum computing, followed by an examination of its potential applications in aviation. The analysis culminates in actionable policy recommendations for leveraging this technology effectively. By highlighting the transformative role of quantum computing, this study aims to provide a foundation for understanding its implications and fostering future advancements in the aviation industry. It employs a qualitative approach, relying on secondary data sources such as books, book chapters, journal articles, reports, news articles, opinion pieces, and relevant websites. Thematic analysis is used to analyse the collected data. The research underscores the importance of quantum computing in the aviation sector and highlights its potential to transform the industry. It also opens new avenues for further in-depth exploration of quantum technology applications in various domains of aviation, paving the way for future research.

Quantum Computing

Before exploring the applications of quantum computing, it is important to understand the foundational concepts behind this technology. Quantum computing marks a major shift from traditional computing models, using principles of quantum mechanics to address complex problems with remarkable speed and efficiency. This emerging technology is often described as the 'next tech trend' due to its potential to transform computational methods.[6] The phenomena is considerably different from how

[6] Michael Chui, Mena Issler, Roger Roberts and Lareina Yee, *McKinsey Technology Trends Outlook 2023,* report (New York: McKinsey Digital, 2023), 8, https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech#tech-trends-2023.

digital computers have been performing calculations and processing information for decades.[7] Unlike traditional digital computers, which rely on bits as the fundamental unit of information (representing either 0 or 1), quantum computing operates on quantum bits, or qubits.[8] Qubits are subatomic particles such as photons, neutrons, or electrons, which possess the unique ability to exist in multiple states simultaneously—a phenomenon known as superposition. This capability allows quantum computers to perform multiple calculations at once, dramatically enhancing their computational power.[9]

The operational principles of quantum computing are further distinguished by quantum gates, which manipulate the state of qubits. These gates serve as the fundamental building blocks of quantum circuits, enabling the execution of complex algorithms that go beyond the capabilities of classical computing.[10] In classical computing, bits operate independently without interacting with one another. In contrast, quantum computing enables qubits to share information once data is provided, facilitating multiple

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7 Surya Teja Marella and Hemanth Sai Kumar Parisa, "Introduction to Quantum Computing" in *Quantum Computing and Communications* ed. Yongli Zhao (London: Intechopen, 2022), 2.

8 McKinsey and Company, "What is Quantum Computing?" April 5, 2024, https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-quantum-computing; K.S. Balamurugan, Sivakami A., Mathankumar Mounagurusamy, Yalla Jnan Devi Satya Prasad et al., "Quantum Computing Basics, Applications and Future Perspectives," *Journal of Molecular Structure* 1308, (2024): 137917, https://www.sciencedirect.com/science/article/abs/pii/S0022286024004 40X#:~:text=Unlike%20classical%20computers%2C%20the%20quantum,provided%20by%20the%20quantum%20computers.

9 Brett Landon Long, "Quantum Processing Speed: Unveiling the 'Why' Behind Quantum Computers' Lightning-Fast Calculations," *Medium*, July 19, 2023, https://medium.com/@brettlandonlong/title-quantum-processing-speed-unveiling-the-why-behind-quantum-computers-lightning-fast-7a11b2cbf1aa.

10 McKinsey and Company, "What is Quantum Computing?"

complex calculations simultaneously with greater speed and efficiency.[11]

Several phenomena associated with quantum computing contribute to its ability to perform faster calculations compared to classical computers. These include, but are not limited to, Superposition, Entanglement, and Quantum Interference. 'Superposition' enables qubits to exist in multiple states simultaneously, enhancing computational power. 'Entanglement', on the other hand, refers to the phenomenon where the quantum states of particles become interconnected, such that the state of one particle cannot be described independently of the other, regardless of the distance between them.[12] In 'Quantum Interference', particles exhibit wave-like behaviour. When two waves are in-phase, they interfere constructively, while out-of-phase waves interfere destructively. This principle is closely associated with Grover's Algorithm, which is designed to identify specific items that meet a given criterion. Grover's Algorithm consists of components such as state preparation, an oracle, measurement, and the diffusion operator, which plays a key role in quantum interference. By leveraging constructive interference to amplify correct solutions and destructive interference to suppress incorrect ones, the algorithm enhances efficiency and accuracy in solving search problems.[13]

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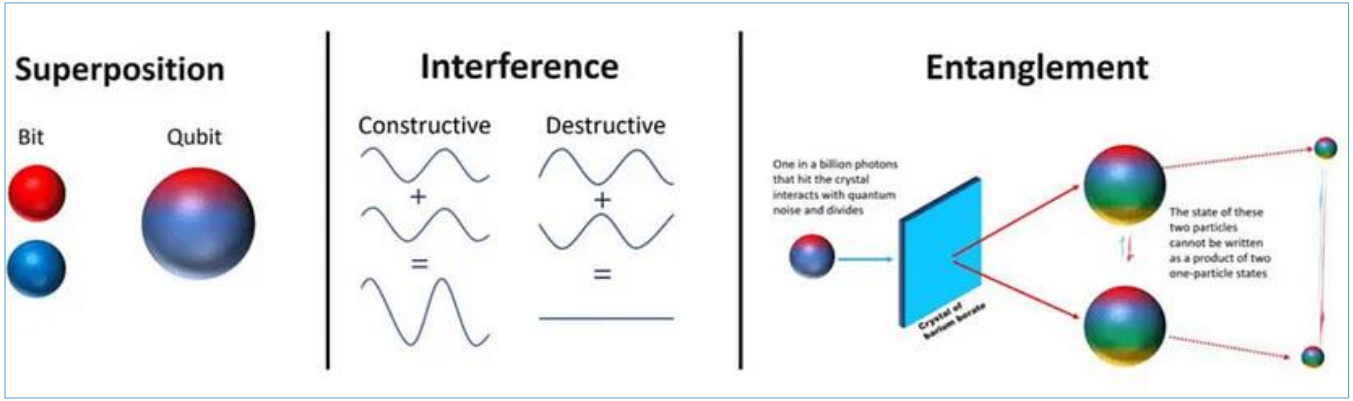
11 Ciaran Hughes, Joshua Isaacson, Anastasia Perry, Ranbel Sun and Jessica Turner, *Quantum Computing for the Quantum Curious* (Geneva: SpringerLink, 2021), 68.

12 Quantum Inspire, "Superposition and Entanglement," https://www.quantum-inspire.com/kbase/superposition-and-entanglement/ [Accessed September 12, 2024].

13 Classiq, "Interference in Quantum Computing," https://www.classiq.io/insights/interference-in- quantum-computing.

Figure I: Important Concepts of Quantum Computing



Source: Louis Chen, "A Brief History of Quantum Computing," *Medium*, April 2, 2023, https://quantumpedia.uk/a-brief-history-of-quantum-computing-e0bbd05893d0.

Another important characteristic of quantum computing is 'Quantum Annealing' which leverages quantum principles to identify low-energy states of a problem, providing the optimal or near-optimal combination of elements.[14] This approach is particularly effective in scenarios with numerous potential solutions, enabling faster and more efficient problem-solving.[15] On a case-to-case basis, each of these offer a substantial advantage in faster and more efficient calculations.

Ultimately, calculations using quantum computing can occur much more quickly and efficiently than classical computing. For instance, a 30-qubit quantum computer can surpass 10 trillion floating-point operations per second (TFLOPS).[16] In 2019, Google announced the development of a quantum machine capable of solving a problem in 200 seconds that would have taken a classical computer 10,000 years to complete.[17] More recently, in December 2024, Google unveiled a new quantum chip, Willow, which it claims can solve complex problems in just five minutes - problems that would

14 DWave, "What is Quantum Annealing?" https://docs.dwavesys.com/docs/latest/c_gs_2.html [Accessed September 12, 2024].

15 Cem Dilmegani, "Quantum Annealing in 2024: Practical Quantum Computing," *AI Multiple Research*, January 12, 2024, https://research.aimultiple.com/quantum-annealing/.

16 Filippo Di Giovanni, "Physical Principles Underpinning Quantum Computing," *Electronic Engineering Times,* January 5, 2024, https://www.eetimes.eu/physical-principles-underpinning-quantum-computing/.

17 Charles Riyle, "Google Claims its Quantum Computer Can Do the Impossible in 200 Seconds," *CNN*, October 23, 2019, https://edition.cnn.com/2019/10/23/tech/google-quantum-supremacy-scn/index.html.

otherwise take the world's fastest supercomputers ten septillion years.[18]

It is pertinent to mention that quantum computing is not a standalone replacement for digital computing, but a complementary technology designed to enhance computing power, precision, measurement capabilities, sensing, and the efficiency of existing and emerging computational methods. As a dual-use technology, it has applications in both civil and military domains. [19] While quantum computing has numerous civilian applications, it is also expected to influence warfare and battlefield outcomes.[20] However, this paper focuses exclusively on its commercial applications, specifically in the aviation sector.

Applications of Quantum Computing in the Aviation Sector

There is great optimism about the potential of quantum computing to deliver substantial benefits to the aviation industry. The sector has shown remarkable resilience, recovering rapidly from the losses incurred during the pandemic.[21]

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18 Chris Vallance, "Google Unveils 'Mind-boggling' Quantum Computing Chip," *BBC*, December 9, 2024, https://www.bbc.com/news/articles/c791ng0zvl3o.

19 Michal Krelina, "Quantum Technology for Military Applications," *European Physical Journey Quantum Technology* 8, no.24, (2021): 1-53, https://link,".springer.com/content/pdf/10.1140/epjqt/s40507-021-00113-y.

20 Herald Andas, *Emerging Technology Trends for Defence and Security* (Kjeller: Norwegian Defence Research Establishment, 2020), 8.

21 Kaitano Dube, "Emerging from the COVID-19 Pandemic: Aviation Recovery, Challenges and Opportunities," *Aerospace* 10, no.1 (2023): 1-13.

In 2023, the global aviation market size reached approximately USD 841.5 billion, reflecting a 7% increase from 2022.[22] Similarly, passenger traffic has rebounded to 94.1% of pre-pandemic levels, highlighting the industry's steady recovery.[23] These developments indicate a positive trend for the aviation industry's recovery and growth. However, airlines continue to face intense competition in managing operational costs, particularly fuel and crew expenses,[24] along with challenges such as weather uncertainties and disruptions to flight operations.[25]

Meanwhile, the quantum computing market is projected to grow significantly, reaching an estimated USD 12,620 million by 2032.[26] This expansion presents considerable opportunities for the aviation sector. Exploring the intersection of these domains could unlock sizable benefits. The next section will examine potential applications of quantum technologies in the aviation industry.

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22 "How Much Money Does the National and Global Airline Industry Make?" *Rosen Aviation,* February 21, 2024, https://www.rosenaviation.com/blog/how-much-money-does-the-national-and-global-airline-industry-make/#:~:text=In%202023%2C%20the%20national%20airline,revenue%20due%20to%20COVID%2D19.

23 Elias Al Helou, "Global Air Travel Reaches 94.1 Percent of Pre-Pandemic Levels: IATA," *Middle East Economy*, February 1, 2024, https://economymiddleeast.com/news/global-air-travel-iata/.

24 Brian Beers, "Which Major Expenses Affect Airline Companies?" *Investopedia,* July 20, 2023, https://www.investopedia.com/ask/answers/040715/what-are-major-expenses-affect-companies-airline-industry.asp.

25 Marika Svensson, "Quantum Computing for Airline Planning and Operations," (Licentiate diss., Chalmers University of Technology, Gothenburg, 2023).

26 Fortune Business Insights, "Quantum Computing Market Size," May 13, 2024, https://www.fortunebusinessinsights.com/quantum-computing-market-104855.

Aircraft Design

Quantum computing can have a profound impact on aircraft design in the future.[27] While the technology has not yet advanced to the point of designing complete aircraft components, initial efforts in this direction are already underway. Notably, private companies such as Boeing, in collaboration with IBM Computing, are making strides in leveraging quantum computing for aerospace engineering.[28] Boeing employs ply composite materials in its 787 Dreamliner, valued for their safety, lightweight properties, and strength, which enable reduced fuel consumption and extended flight distances.[29] However, designing aircraft with ply composites presents challenges due to the complexity of the required calculations, often involving up to 100,000 variables to determine the optimal placement and angles of ply strands. Classical computers struggle with such computational demands, leading engineers to simplify problems by dividing them into smaller units and later recombining them. While effective, this method is time-consuming and resource intensive.[30]

Quantum computing offers a transformative solution by expediting simulations and calculations, thereby reducing costs and resource

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27 Nahla Davies, "Here's What Quantum Computing is—and How it's Going to Impact the Future of Work, According to a Software Engineer," *Fast Company*, July 19, 2024, https://www.fastcompany.com/91015535/housing-market-home-price-prediction-2024-zillow.

28 International Business Machines, "Boeing Seeks New Ways to Engineer Strong, Lightweight Materials," https://www.ibm.com/case-studies/boeing [Accessed April 20, 2024].

29 Rafi Letzter, "How Quantum Computers Could Help Design Airplanes," *International Business Machines*, June 27, 2023, https://www.ibm.com/quantum/blog/boeing-case-study.

30 International Business Machines, "Boeing Seeks New Ways to Engineer Strong, Lightweight Materials."

requirements.[31] This capability could accelerate adoption of innovative aircraft designs and enable the industry to explore novel approaches more efficiently. For instance, Boeing has collaborated with IBM to tackle binary optimisation problems.[32] Similarly, Airbus has partnered with various European agencies to explore the use of quantum computing to overcome computational fluid dynamics (CFD) bottlenecks in aircraft design.[33] Further efforts are being undertaken by companies such as Rolls Royce, NVIDIA, and Classiq, which are investing in quantum computing for jet engine design.[34] The King Abdullah University of Science and Technology (KAUST) is also working with the US-based Zapata Computing to apply quantum computing in CFD research, aiming to enhance aerodynamic design.[35] These advancements suggest that quantum computing will likely be adopted more widely by other companies seeking to optimise aircraft design processes.

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31 Hunter Gaylor, "Quantum Computing in Aviation: Shaping the Future of Aerospace," *Quantum Minute*, August 31, 2023.

32 El Dawton, "How Quantum Computing Is Helping the Aviation Industry," *Medium*, July 12, 2023, https://medium.com/@eldawton/how-quantum-computing-is-helping-the-aviation-industry-cea8295e6db7.

33 Berenice Baker, "Airbus Looks to Quantum Computing for Decarbonization," *IoT World Today*, April 29, 2024, https://www.iotworldtoday.com/quantum/airbus-looks-to-quantum-computing-for-decarbonization.

34 Rivka Coleman, "Rolls-Royce, Nvidia and Classiq Apply Quantum to Jet Engines," *Our Crowd*, June 12, 2023, https://www.ourcrowd.com/startup-news/rolls-royce-nvidia-and-classiq-apply-quantum-to-jet-engines.

35 Matt Swayne, "KAUST and Zapata Explore How Quantum Computers Could Save Billions in Improved Aerodynamic Design of Airplanes and Cars," *Quantum Insider*, April 25, 2021, https://thequantuminsider.com/2021/04/25/kaust-and-zapata-explore-how-quantum-computers-could-save-billions-in-improved-aerodynamic-design-of-airplanes-and-cars/.

Flight Trajectory Optimisation

Flight trajectory optimisation is critically important for the aviation industry due to its potential to enhance aircraft efficiency while minimizing costs.[36] However, it remains a major challenge, as it involves navigating a complex interplay of factors such as fuel efficiency, collision avoidance, and environmental impact.[37] Furthermore, the dynamic environments in which flights operate, particularly during the climb phase, involve numerous changing variables, making speed and accuracy of calculations critical.[38] In this context, quantum computing, through the application of quantum algorithms, is anticipated to play a pivotal role in assisting the aviation industry with flight trajectory optimisation.[39] By employing quantum algorithms, real-time data comprising air traffic situation, weather patterns/condition, and other important factors can be analysed to reduce associated costs and time.[40] Moreover, quantum computing can address complex optimisation challenges arising from evolving circumstances. For instance, in scenarios requiring rerouting due to unforeseen events, quantum algorithms can simultaneously evaluate multiple variables to

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36 Yibo Lia, Shuaitao Qin and Lei Jing, "Research on Flight Trajectory Optimization Based on Quantum Genetic Algorithm," *Journal of Physics* 1549 (2020): 1-7.

37 "The Role of Quantum Computing in Aviation: Advancements and Benefits," *Quantum AI*, December 9, 2023, https://quantumai.co/the-role-of-quantum-computing-in-aviation-advancements-and-benefits/.

38 Airbus, "Is Quantum Computing an Enabler for the Decarbonisation of Aviation?" April 25, 2024, https://www.airbus.com/en/newsroom/stories/2024-04-is-quantum-computing-an-enabler-for-the-decarbonisation-of-aviation.

39 Henry Makhanov, Kanav Setia, Junyu Liu and Vanesa Gomez-Gonzalez, "Quantum Computing Applications for Flight Trajectory Optimization," (paper, arXiv, 2023), https://arxiv.org/pdf/2304.14445.

40 Lia, Qin and Jing, "Research on Flight Trajectory Optimization Based on Quantum Genetic Algorithm," 1.

minimise disruption while ensuring operational efficiency.[41] In addition, advanced technologies such as quantum genetic algorithms have the potential to overcome technical issues and mitigate climb trajectory optimisation challenges for civil aircraft.[42] In this context, Airbus has collaborated with the BMW Group to launch the Quantum Mobility Quest, , an initiative aimed at addressing critical challenges faced by the aviation industry.

Quantum computing can also be utilised to optimise flight paths for Unmanned Aerial Vehicles (UAVs). In this regard, the Virginia Innovation Partnership Corporation has partnered with Quantum Computing Inc. to develop optimal flight trajectory solutions for UAVs. This initiative focuses on determining the most efficient speed, route, and timing for UAVs to reach their destinations. It also aims to address airspace challenges and minimise risks associated with weather conditions, obstacles, and interactions with other aircraft.[43] This optimisation is achieved through the use of entropy quantum computing systems, which enable efficient processing of complex variables to determine optimal flight paths and address associated challenges.[44] Airbus' Silicon Valley innovation centre, Acubed, is actively exploring quantum trajectory

41 "The Role of Quantum Computing in Aviation: Advancements and Benefits."

42 Lia, Qin and Jing, "Research on Flight Trajectory Optimization Based on Quantum Genetic Algorithm," 6.

43 "Quantum Computing Inc. Announces Full Year 2022 Financial Results," *PR Newswire,* March 29, 2023, https://www.prnewswire.com/news-releases/quantum-computing-inc-announces-full-year-2022-financial-results-301785169.html.

44 "VIPC Selects Quantum Computing Inc. as a Partner for Risk-Based Flight Trajectories, *Global News Wire*, October 5, 2022, ttps://www.globenewswire.com/en/news-release/2022/10/05/2529095/0/en/VIPC-Selects-Quantum-Computing-Inc-as-a-Partner-for-Risk-Based-Flight-Trajectories.html.

optimisation to enhance efficiency and innovation in flight operations.[45]

The aviation industry is a substantial contributor to greenhouse gas emissions, driving climate change. Quantum computing offers promising potential for reducing carbon emissions through optimal flight path optimisation. By identifying the most fuel-efficient routes between a source and destination, quantum computing could play a pivotal role in enhancing environmental sustainability within the aviation sector.[46]

Moreover, apart from minimizing greenhouse gases, optimal flight paths could help tackle the environmental aspect vis-à-vis increasing air traffic - something that is expected to rise in the coming decades. Similarly, improved flight optimisation can reduce contrail formation, another contributor to climate change.[47] In addition, quantum speedup across various operational areas could indirectly enhance revenue management for the aviation sector.[48]

Navigation

Quantum computing holds considerable potential for enhancing navigation, a critical aspect of aviation that ensures safe and efficient air travel. Quantum sensing can enable development of

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45 Airbus, "Is Quantum Computing an Enabler for the Decarbonisation of Aviation?"

46 Makhanov, Setia, Liu and Gomez-Gonzalez, "Quantum Computing Applications for Flight Trajectory Optimization."

47 James Temple, "How Rerouting Planes to Produce Fewer Contrails Could Help Cool the Planet," *Technology Review,* March 12, 2024, https://www.technologyreview.com/2024/03/12/1089620/how-rerouting-planes-to-produce-fewer-contrails-could-help-cool-the-planet/.

48 Thomas Fiig, "Application of Quantum Computing in Airline Revenue Management," *Amadeus*, September 28, 2023, https://amadeus.com/en/blog/articles/application-quantum-computing-airline-revenue-management.

highly precise sensors capable of measuring physical quantities such as magnetic fields, acceleration, and rotation rates with unprecedented accuracy.[49] Consequently, navigation systems could greatly benefit from quantum sensors, improving positional accuracy and contributing to enhanced flight safety and more effective air traffic management.[50] Quantum technologies are anticipated to enhance positioning, navigation, and timing (PNT) systems, particularly in the context of inertial navigation. Emerging technologies and approaches are expected to lead to the development of highly sensitive precision instruments for PNT applications.[51] This is especially relevant in GPS-denied environments, operationally challenging terrains, or areas where GPS signals are degraded.[52] In such scenarios, quantum-enhanced PNT systems could offer reliable and effective navigation solutions. Airbus' Acubed, has already announced plans to leverage quantum sensing for navigation advancements.[53]

Boeing recently conducted a four-hour flight test to evaluate the quantum inertial measurement unit (IMU) for navigation in GPS-denied environments. Developed through a collaboration between Boeing and AOSense, the quantum IMU utilises interferometry, a technique that measures rotation and acceleration using atoms. This approach provides unparalleled precision and accuracy

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49 AirBus, "Quantum Technologies: A Potential Game Changer in Aerospace," https://www.airbus.com/en/innovation/disruptive-concepts/quantum-technologies [Accessed March 20, 2024].

50 Gaylor, "Quantum Computing in Aviation: Shaping the Future of Aerospace."

51 Krelina, "Quantum Technology for Military Applications."

52 Jay Lowell, interview by Konstantinos Karagiannis, *Quantum Navigation and other Aviation Use Cases with Boeing*, March 8, 2023, https://www.youtube.com/watch?v=y_R-W_gWXm4.

53 Acubed, "Acubed Announces Exploration of Quantum Sensing as an Autonomy Enabler," December 5, 2025, https://acubed.airbus.com/blog/quantum/acubed-announces-exploration-of-quantum-sensing-as-an-autonomy-enabler/.

without relying on GPS.[54] The quantum inertial sensors within the IMU measure single-axis rotation and acceleration, enabling precise detection of an aircraft's position relative to its initial coordinates.[55] The development serves as a milestone in demonstrating reliability of quantum sensors for navigation, paving the way for advanced navigation systems in aviation.

Schedule Maintenance

Airlines continue to face numerous challenges related to scheduled maintenance and flight disruptions. These disruptions, which include factors such as adverse weather, airport closures, unexpected maintenance, and delays, often trigger a cascade of subsequent delays, [56] referred to as reactionary delays. The factors can lead to a chain reaction causing further delays, termed as Reactionary Delays. According to 2023 data, reactionary delays accounted for 43 percent of total delay minutes in Europe, highlighting the widespread impact of such challenges on airline operations.[57] The Aircraft Recovery Problem (ARP) encompasses the task of restoring disrupted flight schedules, recalculating departure times, revising routes, and addressing potential flight cancellations. A critical challenge within ARP is the need to generate efficient solutions under time constraints while simultaneously minimising operational costs associated with

54 Matt Swayne, "Boeing's Quantum-based Navigation System Takes Flight in Historic Test," *Quantum Insider,* August 9, 2024, https://thequantuminsider.com/2024/08/09/boeings-quantum-based-navigation-system-takes-flight-in-historic-test/.

55 Swayne, "Boeing's Quantum-based Navigation System."

56 Yi Su, Kexin Xie, Hongjian Wang, Zhe Liang and Wanpracha Art Chaovalitwongse, "Airline Disruption Management: A Review of Models and Solution Methods," *Engineering* 7, no.4, (2021): 435 - 447,https://www.sciencedirect.com/science/article/pii/S2095809921000175.

57 EuroControl, "All-Causes Delays to Air Transport in Europe," July 7, 2023, https://www.eurocontrol.int/publication/all-causes-delays-air-transport-europe-quarter-1-2023.

delays and disruptions. The complexity of ARP underscores its importance as a focus area for optimisation in aviation management.[58] Quantum computing has potential in addressing schedule maintenance challenges faced by airlines. An experiment conducted by TAP Air Portugal demonstrated valuable insights in this regard. In the study, the ARP was modelled using Quadratic Unconstrained Binary Optimisation (QUBO), a prominent framework for tackling optimisation challenges with quantum computing. The ARP model was solved using both classical and hybrid solvers to compare relative costs and flight schedules. The findings revealed that applying quantum computing to ARP facilitated faster, more cost-effective, and practical solutions for managing flight schedules and disruptions.[59] Similarly, a team at Q-CTRL investigated the potential of quantum computing to expedite redeployment of airline assets following disruptions, further illustrating its utility in optimising operational efficiency in the aviation sector.[60]

Secure Networks

Flight security carries immense significance for the aviation industry. One of the potential applications of quantum computing in the aviation sector comprises enhancing the digital security of

58 J. Vink, B.F. Santos, W.J.C. Verhagen, I. Medeiros, and R. Filho, "Dynamic Aircraft Recovery Problem - An Operational Decision Support Framework," *Computers & Operations Research* 117, (2020): 104892.

59 Andre Mamprin Mori, "Replanning Flight Schedules Using Quantum Computing," (M.Sc. diss., Faculdade De Engenharia Da Universidade Do Porto, Portugal, 2022).

60 Dan O'Shea, "Beyond Scheduling, Quantum Can Deliver in Other Ways for Airlines," *Inside Quantum Technology News*, January 2, 2023, https://www.insidequantumtechnology.com/news-archive/beyond-scheduling-quantum-can-deliver-in-other-ways-for-airlines/.

aviation networks.[61] Existing encryption methods used to secure data within aviation networks require sizable enhancements to address future threats. As advancements in technologies, particularly in cyber domains, continue to evolve, they are accompanied by increased vulnerabilities to sophisticated hacking techniques. In this context, the adoption of quantum computing offers a promising avenue to augment data security, providing robust solutions capable of mitigating emerging cyber threats in the aviation sector.[62] Quantum communication, which relies on quantum principles for secure data transfer, could improve encryption, making cyberattacks more difficult to execute. This technology can safeguard critical aviation systems, flight operations, confidential communications, and passenger data.[63] Acknowledging the strategic value of quantum technologies, the U.S. Air Force Research Laboratory has identified their potential to enhance C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) systems.[64] This recognition highlights the importance of integrating quantum advancements into defence and aviation networks to address the growing complexity of cybersecurity challenges and improve the resilience of critical systems.

Additional Applications

Quantum computing can also be employed for the smooth scheduling of cargo and passenger traffic vis-à-vis aircraft, gates, personnel, and managing the air traffic flow at

61 El Dawton, "How Quantum Computing Is Helping the Aviation Industry."
62 Gaylor, "Quantum Computing in Aviation: Shaping the Future of Aerospace."
63 "The Role of Quantum Computing in Aviation: Advancements and Benefits," *Quantum AI*.
64 El Dawton, "How Quantum Computing Is Helping the Aviation Industry."

arrivals/departures.[65] For instance, Cargo South has developed a software that is able to optimise cargo placement inside an aircraft using quantum algorithms.[66]

The complex dynamics of propulsion systems, aerodynamics, and structural integrity, etc. can be better explained by quantum simulations, paving the way for further improvements in the aviation sector.[67]

As previously discussed, quantum computing has the potential to deliver unparalleled accuracy in measurements. This heightened precision could enable detection of irregularities during flight operations, facilitating timely identification of potential risks, thereby enhancing overall flight safety.[68]

Early adopters of quantum computing in the aviation industry stand to gain a competitive edge through innovation and enhanced operational efficiency. Notably, several airlines have begun exploring quantum computing to optimise various aspects of their operations. Delta Airlines, for instance, became the first airline to enter into a comprehensive agreement with IBM to leverage quantum computing.[69] IBM-Q, a network comprising approximately

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65 Hamed Mohammad Bagherpoor, Patrick Dreher, Mohannad Ibrahim, Young-Hyun Oh et al., "Exploring Airline Gate-Scheduling Optimization Using Quantum Computers," (paper, ArXiv, 2021), https://arxiv.org/pdf/2111.09472.

66 Jet Man Pay, "How Quantum Computing Software Enhances Air Cargo Industry," https://jetmanpay.com/how-quantum-computing-software-enhances-air-cargo-industry/ [Accessed September 19, 2024].

67 "The Role of Quantum Computing in Aviation: Advancements and Benefits," *Quantum AI*.

68 Ibid.

69 Chris Andrews, "Delta Airlines Taps IBM for Cloud Expertise and Red Hat Hybrid Cloud Platform," *International Business Machines Newsroom*, February 18, 2021, https://newsroom.ibm.com/2021-02-

500 organisations, including companies, research laboratories, academic institutions, and startups, focuses on practical applications of quantum computing across diverse sectors.[70] Through this partnership, Delta aims to enhance both customer and employee experiences by integrating quantum computing into its operations. The agreement grants Delta access to IBM-Q's advanced universal hardware quantum computers for research and commercial use, including the recently launched 53-qubit quantum computer.[71]

Discussion and Analysis

Existing literature indicates that, while still an emerging concept, quantum computing has the potential to profoundly influence various facets of the aviation sector. Its applications point to a future where operational efficiency is enhanced, costs are reduced, and environmentally sustainable practices are prioritised. Furthermore, the integration of quantum technologies could yield considerable economic benefits for airlines by optimising resource allocation and minimising operational disruptions.

Beyond operational improvements, quantum computing may elevate passenger experiences by enhancing service quality and reliability, thereby raising the overall standards of the aviation industry. These advancements also contribute to fortifying the

18-Delta-Air-Lines-Taps-IBM-for-Cloud-Expertise-and-Red-Hat-Hybrid-Cloud-Platform/.

70 Jan Lillelund, "50 Qs with IBM Q," *International Business Machines,* January 14, 2021, https://www.ibm.com/blogs/nordic-msp/50-qs-with-ibm-q/.

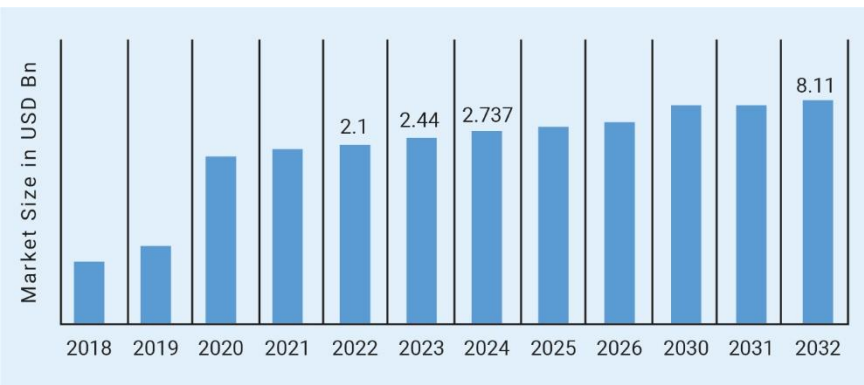
71 International Business Machines, "Delta Partners with IBM to Explore Quantum Computing - An Airline Industry First," January 8, 2020, https://newsroom.ibm.com/2020-01-08-Delta-Partners-with-IBM-to-Explore-Quantum-Computing-an-Airline-Industry-First.

sector's resilience by addressing critical logistical and operational challenges more effectively.

The exploratory applications of quantum computing are expected to drive further research and innovation, fostering advancements not only in aviation but across other industries. This ripple effect underscores the broader implications of quantum computing as a catalyst for breakthroughs and interdisciplinary solutions, reinforcing its importance as a foundational technology for the future.

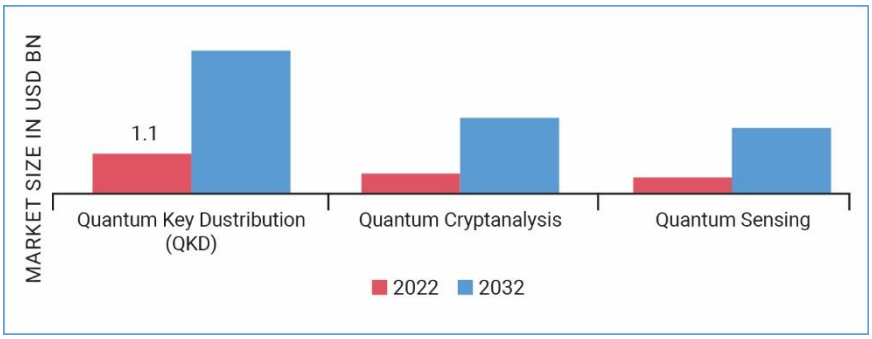
The quantum computing market within the aerospace and defence sectors is projected to grow, rising from USD 2.73 billion in 2024 to USD 8.11 billion by 2032, as shown in Figure II. This projection underscores the increasing adoption of quantum technologies across civil and military aviation domains:

Figure II : Quantum Computing in Aerospace & Defence Market



Source: Market Research Forecast, "Quantum Computing in Aerospace and Defence Market Overview," https://www.marketresearchfuture.com/reports/quantum-computing-aerospace-defense-market-7788 [Accessed September 20, 2024].

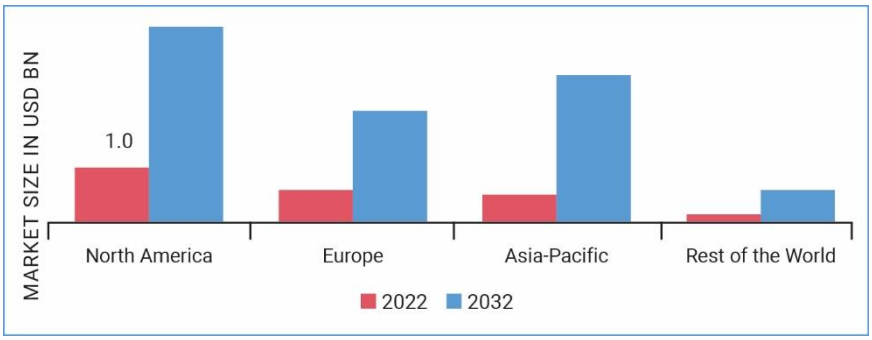
Figure III: Quantum Computing in Aerospace & Defence Market, by Application, 2022 & 2032 (USD Billion)



Source: Market Research Forecast, "Quantum Computing in Aerospace and Defence Market Overview," https://www.marketresearchfuture.com/reports/quantum-computing-aerospace-defense-market-7788 [Accessed September 20, 2024].

Figure III illustrates the expanding market size of quantum computing within the aerospace and defence sectors, highlighting its anticipated growth trajectory. These trends suggest that similar advancements are expected across related areas, including Quantum Key Distribution, Quantum Cryptanalysis, and Quantum Sensing, over the next decade. Such developments indicate a growing integration of quantum technologies in the aviation industry, as these advancements offer several advantages, including enhanced security, improved operational efficiency, and advanced sensing capabilities. The projected growth underscores the potential of quantum computing to address critical challenges and drive innovation within the sector.

Figure IV: Quantum Computing in Aerospace and Defence Market by Region



Source: Market Research Forecast, "Quantum Computing in Aerospace and Defence Market Overview," https://www.marketresearchfuture.com/reports/quantum-computing-aerospace-defense-market-7788 [Accessed September 20, 2024].

Figure IV highlights that North America, Asia-Pacific, and Europe are projected to experience the highest growth in quantum computing market size. These regions are expected to lead advancements in the aerospace and defence sectors through adoption of quantum technologies. The disparity in growth compared to other regions underscores the concentrated focus and investment in quantum computing within these leading markets, positioning them at the forefront of innovation and technological development.

The United States (US) is actively pursuing initiatives to maximise the potential of quantum computing, driving innovation across various sectors, including aerospace. Leading private companies such as Lockheed Martin, Google, IBM, Amazon, Intel, Honeywell, Microsoft, Northrop Grumman, D-Wave, and Rigetti Computing are at the forefront of advancements in quantum technology,

spearheading research and development efforts.[72] Furthermore, the US will be investing approximately USD 968 million for quantum research, doubling the figure of USD 449 as compared to 2019.[73]

China is also making substantial investments in quantum technology, accounting for nearly half of the global public funding in this domain, according to a report by the Centre for Strategic and International Studies (CSIS). Despite current legislative efforts to restrict China's access to quantum technology, the US risks falling behind Beijing in the development and implementation of quantum advancements. [74] China's advancements in quantum technology are evident through initiatives such as the partnership between the China Academy of Aerospace Aerodynamics and Origin Quantum Computing Technology Co. Ltd., aimed at enhancing aircraft design and manufacturing using quantum computing,[75] as well development of quantum radars for its aircraft.[76]

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72 Dustin Carmack, *Beating China in the Race for Quantum Supremacy*, report (Washington, D.C.: Heritage Foundation, 2023), 6, https://www.heritage.org/sites/default/files/2023-04/SR268.pdf.

73 John Kelvey, "4 Reasons to Root for Quantum Computing," *Aerospace America*, August 2024, https://aerospaceamerica.aiaa.org/features/4-reasons-to-root-for-quantum-computing/.

74 William A Reinsch, *Optimizing Export Controls for Critical and Emerging Technologies*, report (Washington, D.C.: Centre for Strategic and International Studies), 3.

75 "Aerospace Sector Uses Quantum Technology to Beat Bottlenecks," *China Services Info*, October 9, 2023, https://govt.chinadaily.com.cn/s/202310/09/WS653390c9498ed2d7b7e9e1d2/aerospace-sector-uses-quantum-technology-to-beat-bottlenecks.html.

76 Brian Hart, Bonny Lin, Samantha Lu, Hannah Price et al., "Is China a Leader in Quantum Technologies," *China Power*, August 14, 2023, https://chinapower.csis.org/china-quantum-technology/.

Germany is also actively fostering industry-academia collaboration to leverage quantum computing for enhancing airport operations. A notable example is the partnership between the University of Hamburg and Lufthansa Industry Solutions, aimed at optimising various aspects of airport management.[77]

However, it is pertinent to mention that there are number of challenges associated with the integration of quantum computing in the aviation sector.

One of the key challenges in the adoption of quantum technologies is the volatile nature of qubits, which requires further exploration to achieve practical reliability. Additionally, quantum technologies are at varying Technology Readiness Levels (TRL), introducing further complexity in their development and deployment.[78] The differing time horizons and technological variations add to these challenges, complicating the realisation of their potential applications. For example, a quantum gravimeter for underground scanning may initially emerge as a static sensor mounted on a truck with limited resolution. Subsequent generations could feature improved sensitivity and resolution, enabling broader applications, such as deployment on aircraft or drones. However, there is also the possibility that despite advancements, the sensitivity and resolution may not reach the levels required for such use. Over time, technological limitations could hinder the integration of quantum systems into aviation platforms like aircraft and drones, delaying their widespread deployment.

Many potential applications of quantum computing remain theoretical and may not materialise as anticipated. The practical deployment of quantum technologies depends on several critical

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77 "Quantum Computers to Optimize Airport Operations Worldwide," *Quantum Zeitgeis,* July 5, 2024, https://quantumzeitgeist.com/quantum-computers-to-optimize-airport-operations-worldwide/.

78 Krelina, "Quantum Technology for Military Applications," 22.

factors, including size, portability, speed, robustness, cost, and SWaP (Size, Weight, and Power) considerations. However, the current stage of quantum computing, known as the Noisy Intermediate Scale Quantum (NISQ) era, presents major challenges.[79] Susceptibility to errors and noise within quantum systems increases the risk of inaccuracies, complicating the transition of theoretical applications to practical use.

Expert opinions on the future of these challenges, often referred to as the 'Quantum Winter,' are divided.[80] While some argue that the engineering hurdles associated with quantum technologies could persist for several decades, others remain optimistic, anticipating that these issues may be resolved within a few years, paving the way for broader adoption and innovation. However, there is a consensus that the risk of error is a major challenge at the moment.

The integration of quantum technology with classical computing systems is also an issue. Compatibility issues may arise, potentially requiring the development of new infrastructure and frameworks to address these obstacles effectively.

Plus, the high cost associated with quantum technology further complicates its widespread adoption, underscoring the need for cost-effective solutions and innovations to enhance accessibility.[81] It is likely that numerous airlines might not be able to employ the technology due to economic constraints. The practicality and cost

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79 James Dargan, "What Is NISQ Quantum Computing?" *Quantum Insider*, March 13, 2023, https://thequantuminsider.com/2023/03/13/what-is-nisq-quantum-computing/.

80 Ibid.

81 Beth Stackpole, "Quantum Computing: What Leaders Need to Know Now," MIT Management Sloan School, January 11, 2024.

of the technology, will influence its employment across different sectors.[82]

The aviation industry is among the most heavily regulated sectors, and the introduction of new technologies, such as quantum computing, is likely to necessitate development of new regulatory frameworks. Establishing these frameworks will be a complex undertaking, requiring collaboration among industry stakeholders, regulatory bodies, and policymakers to ensure compliance, safety, and standardisation while fostering innovation.

Chris Coleman, a condensed matter physicist, describes the current Noisy Intermediate Scale Quantum (NISQ) era as akin to the early stages of Artificial Intelligence. He notes, 'Although still needing to overcome limitations, in many instances we're seeing the foundation being laid for bigger things to come, and there is no doubt that the field is making steady progress. This can be seen across the ecosystem.'[83] Realising the potential benefits of quantum computing will require considerable time, investment in research and development, infrastructure expansion, and financial resources.

Recommendations

Given the potential role of quantum computing in the aviation sector, it is imperative to draft certain recommendations in general and relevant / specific to Pakistan.

Pakistan's aviation industry is yet to take off, compounded by the country's limited advancements in quantum computing compared to other nations. This disparity can be attributed to resource constraints and the absence of a directed focus on developing

82 Krelina, "Quantum Technology for Military Applications," 22.
83 Dargan, "What Is NISQ Quantum Computing?"

quantum technologies.[84] The following section outlines policy recommendations aimed at addressing these challenges and fostering the integration of quantum computing in Pakistan's aviation sector for future advancements.

Quantum Ecosystem

Developing a robust national quantum ecosystem that integrates government, industry, academia, and the private sector is essential for strategically determining the scope, timing, and scale of investments in quantum computing. While the immediate applications of quantum computing may not be directly applicable to Pakistan's aviation sector, its broader adoption across other industries could create pathways for subsequent integration into aviation.

Establishing dedicated quantum research facilities focused exclusively on aviation would be a critical step in this direction. Furthermore, the creation of innovation hubs centred on quantum computing, bringing together startups, private sector stakeholders, and the research community, could foster collaboration and drive the development of tailored solutions for challenges in the aviation industry. Such initiatives would position Pakistan to gradually bridge the gap in quantum advancements while aligning with global trends.

Research & Development

There is a critical need to promote sector-specific research and development in quantum computing, particularly in areas relevant to the aviation sector such as aircraft design, traffic management, flight route optimisation, navigation, and secure networks. In

84 Abdul Hannan, "The Future of Quantum Computing in Pakistan," *Medium,* December 28, 2021, https://kelpersoft.medium.com/the-future-of-quantum-computing-in-pakistan-4e8c39ff4fed.

Pakistan's context, universities must be incentivised to undertake projects and research focused on quantum computing. Establishing collaborations with international universities leading in this technology could serve as a strategic step, fostering knowledge transfer and capacity building through joint research initiatives and student exchange programmes on quantum computing platforms.

To facilitate the practical application of quantum technology in the aviation sector, consistent and extensive collaboration between the aviation industry and academic, governmental, and private sectors is imperative. Pilot testing of quantum solutions should also be prioritised to assess their feasibility and scalability within relevant institutions. Quantum research institutes should focus on creating frameworks for the commercialisation of quantum technologies, aligning them with the specific demands of the aviation sector.

Government Support

Given the expansive scope of the aviation sector, it is essential for the government to actively support the adoption of quantum computing through funding, incentives, and the establishment of regulatory frameworks. In Pakistan, targetted grants and funding should be allocated to projects and initiatives that advance the integration of quantum computing in the aviation industry. This could include providing tax breaks or other incentives to airlines that adopt the technology, encouraging its widespread use.

Equally important is the development of regulatory frameworks that establish clear standards for the application of quantum computing in aviation, ensuring safety, compliance, and operational efficiency. These efforts should also prioritise improving the performance of Pakistan International Airlines (PIA), the state-owned carrier, by leveraging quantum computing to enhance flight operations, reduce inefficiencies, and position it competitively within the global aviation landscape.

Collaborative Model

Expensive technologies in their nascent stages often require collaborative models to drive advancements. One viable approach involves establishing one or two major facilities where multiple entities pool resources and capital to procure the technology and share its benefits.

In the context of Pakistan, a similar model could be adopted, with key stakeholders such as the flag carrier PIA, relevant universities, and private sector entities collaborating to develop a national quantum computing facility. This facility, potentially managed by the government, could operate on a time-sharing basis, ensuring equitable access for all stakeholders.

Initial Employment

In the initial employment, the aviation industry should prioritise certain areas that could benefit from quantum computing in Pakistan. These may include using quantum computing for accurate weather forecasting which is likely to mitigate issues associated with turbulence. Likewise, traffic management in aerodrome control comprises an important aspect, which is also prone to human error. Hence, a centralised system using quantum computing could be used for aerodrome control. The operating airlines could also use predictive maintenance for efficient operations.

Increased Automation

While employing quantum computing offers numerous advantages across different areas in the aviation sector, prior actions could enhance the effectiveness and integration of technology. With respect to Pakistan, there is a need to have directed focus on automation. Enhanced automation can enable better integration of quantum technology. This could provide added benefits as well. For instance, combination of enhanced automation, facial recognition

and controlled access to national databases can improve airport security.

Engaging Overseas Quantum Experts

Quantum computing is a highly intricate and specialised field that requires subject-matter experts for its effective implementation. In the context of Pakistan, engaging with the expatriate community settled abroad presents a valuable opportunity to access technical expertise in this domain. Offering targetted incentives and opportunities to attract these experts could increase the country's capacity to advance quantum technologies. Leveraging the diaspora for such initiatives offers a distinct advantage, as these individuals bring with them a wealth of knowledge and expertise acquired from leading global institutions and industries. This approach could accelerate timelines for various projects and initiatives, bridging the expertise gap and fostering rapid progress in quantum computing applications across key sectors, including aviation.

Improving Human Capital

Adoption of quantum computing in the aviation sector necessitates development of a skilled workforce equipped with technical expertise in this advanced technology. Simultaneously, it is crucial to familiarise the existing workforce in the aviation industry with the fundamentals and applications of quantum computing to facilitate seamless integration. In the context of Pakistan, targetted training programmes must be designed to bridge the knowledge gap. These programmes should focus on equipping engineers and technical professionals in the aviation industry with the requisite knowledge and skills to effectively utilise quantum computing. Such initiatives would play a pivotal role in ensuring the successful adoption of the technology and fostering its long-term integration within the sector.

Curriculum Development

While cross-cutting technologies are evolving with every passing day, there is a need to update and revamp curriculum in higher educational institutes accordingly. With respect to Pakistan, there is a need to chalk out new courses for universities whose students would later be joining relevant organisations. Subjects related to aviation and quantum computing need to be part of the curriculum. These may include Quantum Computing in Aviation, Quantum Algorithms, Classical and Hybrid Systems, and Quantum Optimisation etc.

Developing Quantum-Safe Infrastructure

With the anticipated growth of quantum computing across various sectors, it is imperative to develop comprehensive countermeasures to address emerging security challenges. Specifically, encryption methods must be advanced to safeguard aviation data against quantum-enabled threats, which could compromise critical systems and operations. In this regard, a lot of investment is required in complementary technologies such as cybersecurity and AI. Cybersecurity innovations will be essential to mitigate vulnerabilities introduced by quantum computing, while AI can enhance threat detection and response mechanisms, creating a multi-layered defense system. Proactively addressing these challenges will be key to ensuring the resilience and integrity of aviation systems in a quantum-enabled future.

Conclusion

The findings of this paper indicate that quantum computing has the potential to usher in a new era of innovation within the aviation industry. Its unparalleled capabilities in handling complexity, speed, and multiplicity are poised to transform global aviation, driving advancements across various operational and strategic dimensions. Although the technology is still in nascent stages, multiple applications of the technology are already on the horizon.

These include but are not limited to Aircraft Design, Flight Trajectory Optimisation, Navigation, Schedule Maintenance and Secure Networks.

While quantum computing holds immense promise for the aviation sector, its adoption is not without challenges. The technology's nascent and uncertain nature poses barriers that may delay the realisation of its full potential. Time and continued advancements will play a crucial role in determining its practical applications within the aviation industry. For Pakistan, it is imperative to take proactive measures to harness the potential of this technology and align with global advancements. This includes establishing a robust quantum ecosystem, fostering R&D, enhancing government support, and engaging Pakistani experts from the diaspora. Furthermore, investing in workforce development, updating educational curricula to include quantum computing, and building quantum-safe infrastructure are essential steps toward maximising the benefits of quantum technology in the aviation industry.

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