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ADVANCEMENTS IN VDL AND CPDLC: REVOLUTIONIZING EUROPEAN AVIATION COMMUNICATION

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Abstract

The paper is focused on the transformative impact of VDL and CPDLC on aviation safety, efficiency, and reliability. Tracing the historical evolution from radio systems to the adoption of VDL and its integration within Europe's unified airspace initiatives, this paper deals with key theories including VDL Mode 2, ACARS, Aeronautical Telecommunication Network, ADS-B, and CPDLC. Emphasizing interdisciplinary collaboration to tackle communication challenges, the paper spotlights CPDLC's evolution integrating AI, Machine Learning, cybersecurity protocols, and technological integrations like 5G and satellites. Human-Computer Interaction research underscores user-friendly CPDLC interface designs. Methodologies encompass operational analyses, communication protocols, avionics technologies, and usability testing. Aligning with the Single European Sky initiative, the integration of VDL and CPDLC anticipates emerging trends while addressing challenges like interoperability, training complexities, and cybersecurity vulnerabilities through proposed solutions. The paper offers a comprehensive understanding of advancements shaping the modern aviation communication landscape.

Keywords

VDL, CODLC, Aviation Technology

1. Úvod

The rapidly evolving landscape of aviation technology, innovations in communication systems have played a pivotal role in enhancing the safety, efficiency, and reliability of air travel. One of the significant advancements in this realm is the adoption of Very High Frequency Data Link Communications (VDL) and Controller Pilot Data Link Communications (CPDLC) (Pereira, 2002). The VDL, which is a method of transmitting information between aircraft and ground stations using the Very High Frequency (VHF) band, and the CPDLC, which is a subset of VDL specifically designed for text-based communication between pilots and air traffic controllers. Both have revolutionized the way information is exchanged in the aviation industry. The European aviation sector is famous for its robust regulatory framework and commitment to improve air traffic management and has been at the forefront of implementing these technologies (Novák et al., 2018).

In the early days of flight, communication between pilots and ground control was limited to rudimentary radio systems, often characterized by static interference, and limited range. With the increase of air traffic, it appeared a need for more sophisticated communication systems (Cizrelioğullari & Imanov, 2023). The introduction of VHF, radio frequencies revolutionized aviation communication. Before using VHF, HF systems where the ones used in aviation. Unlike the earlier HF systems, VHF offered superior clarity and shorter wavelengths, leading to more precise communication between aircraft and ground stations.

With the introduction of VDL, based in VHF systems, it became possible to transmit critical data, such as aircraft position information, weather reports, or any other important data in a digital way, along with voice communications. VDL represents a big change in aviation communication. By taking the advantage of the capabilities of the VHF band, VDL allows aircraft to exchange vital information with ground stations in an efficient way (Novák et al., 2018). One of the main aspects of VDL is its ability to handle a significantly higher number of aircraft simultaneously compared to traditional voice communication channels. The increase in capacity has alleviated congestion, particularly in densely trafficked European airspace, resulting in more efficient air traffic management. Facilitating the transmission of essential VDL data by means of an analogue-to-digital data exchange has streamlined the communication process, reduced the probability of misinterpretation and improved overall safety standards (Cizrelioğullari & Imanov, 2023). However, the implementation of VDL comes with its own set of challenges, such as the need for major infrastructure improvements, training programs for air traffic controllers and pilots, and the perfect integration of VDL with existing air traffic control systems (Galotti, 2019).

In the field of VDL, CPDLC stands out as a specialized communication protocol designed explicitly for interaction between pilots and air traffic controllers. Unlike traditional voice communication, which can sometimes be prone to misunderstandings due to language barriers or radio interference, CPDLC offers a clear, text-based channel for communication (Novák et al., 2018). This textual interaction reduces the workload on both pilots and controllers, allowing them to focus on critical tasks without the limitations of voice-based exchanges. In addition, CPDLC improves safety standards by ensuring standardized communication protocols. Accurate and standardized messages reduce the margin of error and improve situational awareness for both pilots and controllers (Orye et al., 2023).

The European Union, through initiatives like the Single European Sky (SES), has actively promoted the implementation of modern communication technologies. Eurocontrol has played a central role in coordinating these efforts, ensuring a harmonized approach across European nations. The SES initiative aims to create a single, unified European airspace, to improve air traffic. The integration of VDL and CPDLC within this framework aligns with the goal of enhancing air traffic management efficiency. European countries have collaborated closely to establish standardized protocols, ensuring seamless communication between diverse air traffic control centres and aircraft flying across national boundaries. With VDL and CPDLC in Europe, it becomes evident that these technologies represent more than communication upgrades. They symbolize a transformative shift in how aviation professionals interact, collaborate, and ensure the safety of millions of passengers traversing the European skies (Novák et al., 2018).

VDL, especially within the context of aviation, involve various theories and models developed by researchers and organizations to ensure efficient and reliable communication. In the realm of VDL systems, VDL Mode 2 stands out as a crucial communication mode. Specifically designed to facilitate a fluid communication between aircraft and ground stations, it establishes a robust protocol enabling the exchange of various data, including text messages. This mode addresses a critical challenge faced in densely populated airspace regions: communication congestion. By optimizing communication efficiency, VDL Mode 2 effectively alleviates congestion, ensuring reliable data exchange. The specifications of VDL Mode 2 are meticulously developed and upheld by esteemed international standards organizations such as the International Civil Aviation Organization (ICAO) and the European Organization for Civil Aviation Equipment (EUROCAE), reflecting its significance in enhancing the efficiency and safety of air traffic management (Studenberg, 2005).

The Aircraft Communications Addressing and Reporting System (ACARS) plays a pivotal role as a crucial digital data link connecting aircraft and ground stations. ACARS acts as a conduit for the transmission of vital messages, including but not limited to weather updates, mechanical diagnostics, and operational information. This sophisticated system efficiently addresses the ever-growing demand for seamless and timely communication between aircraft and ground facilities, thereby significantly enhancing operational efficiency and safety within the aviation industry. Developed through collaborative efforts involving various avionics manufacturers and airlines, ACARS stands as a testament to the successful integration of technology and collaborative research (Lehto et al., 2021). Standardization initiatives led by organizations such as Aeronautical Radio, Incorporated (ARINC) have played a central role in shaping ACARS into an industry-standard communication system. The cooperative endeavours of these entities underscore the commitment to meeting the intricate communication needs of modern aviation through innovation and standardized practices, ultimately contributing to the industry's continued advancement in safety and efficiency (Cizrelioğullari & Imanov, 2023).

In conjunction with the ACARS, the Aeronautical Telecommunication Network (ATN) emerges as a comprehensive solution to integration challenges within the realm of data link communication systems. This innovative concept goes beyond individual technologies, encompassing a variety of data link technologies used in aviation communications and harmoniously integrating different communication protocols. The ATN is a key player in the European datalink system, applying its technology to address the challenges of interoperability and facilitate a perfect data exchange between aircraft and ground systems. This capability is particularly crucial in overcoming a significant hurdle in the aviation industry and enhancing overall operational efficiency and safety (Gomez & Ortiz, 2013). To ensure the success of the ATN and promote its widespread adoption, standards and specifications are meticulously developed by international organizations. These include the International Civil Aviation Organization (ICAO), EUROCONTROL, and the Radio Technical Commission for Aeronautics (RTCA) of the United States of America. The collaborative efforts of experts in the field of aviation communication systems, spanning across different international organizations, highlight the importance of interdisciplinary cooperation in advancing the efficiency and effectiveness of aviation communication technologies. As the ATN continues to evolve and gain prominence, its role in facilitating standardized and interoperable data link communication systems becomes increasingly significant, contributing to the ongoing improvement of communication capabilities in modern aviation (Galotti, 2019).

Automatic Dependent Surveillance-Broadcast (ADS-B) serves as a linchpin in addressing the critical need for accurate and real-time aircraft surveillance within the dynamic landscape of aviation. Through the utilization of satellite navigation, ADS-B empowers aircraft to precisely determine their positions and, in turn, broadcast this information periodically to both fellow aircraft and ground stations. This technological innovation not only revolutionizes the way aircraft are tracked but also significantly enhances situational awareness for pilots and air traffic controllers alike, thereby reducing the risk of mid-air collisions and elevating overall airspace safety to unprecedented levels. As a fundamental component of modern air traffic control systems, ADS-B plays a pivotal role in facilitating the seamless flow of information throughout the aviation industry. This technology is integral to the realization of concepts such as NextGen in the United States and SESAR in Europe, aligning with broader efforts to modernize and optimize air traffic management systems on a global scale. The collaborative genesis of ADS-B involves esteemed organizations, such as the Federal Aviation Administration (FAA) in the United States and Eurocontrol in Europe. The development process brought together professionals with diverse expertise in avionics, telecommunications, and navigation systems, emphasizing the significance of interdisciplinary collaboration in shaping the trajectory of aviation surveillance technologies (Galotti, 2019). This concerted effort reflects the commitment of the industry to advancing not only technological capabilities but also the safety and efficiency of aviation operations worldwide. ADS-B stands as a testament to the successful intersection of technological innovation and collaborative expertise in meeting the evolving needs of modern aviation surveillance (Lehto et al., 2021).

CPDLC represents a significant milestone in the realm of aviation communication, revolutionizing the way pilots and air traffic controllers interact digitally. By enabling precise exchanges of instructions, clearances, and vital messages, CPDLC has effectively mitigated longstanding challenges in aviation communication. One of the notable achievements in this domain is the development of the Crew Resource Management (CRM) Theory. This model underscores the vital role of effective communication and coordination among flight crews and air traffic controllers. Visionaries such as David Woods have delved into the intricacies of human factors and automation in CPDLC interactions, aiming to optimize communication protocols and minimize errors (Sestorp & Lehto, 2019).

Certainly, in the continuous evolution of CPDLC, interdisciplinary research has illuminated various dimensions crucial to its seamless integration and optimization (Studenberg, 2005). One vital area of focus has been the development of innovative algorithms and predictive models within the realm of Artificial Intelligence (AI) and Machine Learning (ML). Researchers have delved into predictive analytics to anticipate communication patterns between pilots and controllers, enabling proactive adjustments in CPDLC interfaces. By leveraging AI-driven insights, CPDLC systems can adapt to dynamic communication scenarios, enhancing response times and further reducing the risk of misunderstandings. Additionally, significant strides have been made in cybersecurity protocols within CPDLC frameworks. Ensuring the integrity and confidentiality of transmitted data is paramount in aviation communication. Robust encryption methods, real-time threat detection, and secure authentication mechanisms have been integrated to safeguard CPDLC channels, guaranteeing the privacy of critical information exchanged during digital interactions (Orye et al., 2023).

Furthermore, the synergy between CPDLC and emerging technologies, such as 5G networks and satellite communication systems, has paved the way for unparalleled connectivity and coverage. Pilots and controllers can now engage in CPDLC interactions seamlessly, irrespective of geographical constraints. This enhanced connectivity is instrumental, especially in remote or densely populated airspace regions, where traditional communication methods might face limitations (Sestorp & Lehto, 2019).

2. Methodology

The methodology of this paper involves a exploration of VDL and CPDLC within the aviation domain. This investigation spans various methodologies, comprising comprehensive analyses of operational principles, communication protocols, avionic technologies, and usability testing. Furthermore, the paper delves into CPDLC's specialized text-based protocol, employing usability testing, technical analyses of data transmission protocols, and functionality studies. The integration of VDL and CPDLC in Europe, aligning with initiatives like the Single European Sky, is analysed through standardized protocols, interoperability challenges, and the anticipation of emerging trends, including AI integration and satellite-based communication, shaping the future of air traffic management.

3. Results

In the scientific exploration of VDL, the methodology encompasses a comprehensive analysis of the system's operational principles, communication protocols, and the integration of advanced avionic technologies. Researchers engage in rigorous data collection and analysis, focusing on various aspects of VDL to understand its functionality and effectiveness in real-world aviation scenarios. One crucial aspect of the methodology involves the evaluation of VDL transceivers and their performance characteristics. Researchers conduct extensive tests to assess the transceivers' transmission and reception capabilities, examining parameters such as data packet delivery rate, signal strength, and error rates. These assessments provide valuable insights into the reliability and efficiency of data transmission between aircraft and ground stations. Furthermore, the study delves into the avionic interfaces used by pilots to engage with VDL systems. Researchers evaluate the user experience, considering factors such as interface intuitiveness, response time, and the effectiveness of predefined message templates (Orye et al., 2023). Usability testing and human factors analysis are integral components of the methodology, ensuring that the interfaces are designed to optimize pilot communication and decision-making processes. Additionally, the methodology involves the simulation and modelling of VDL communication scenarios. Advanced simulation tools are used to recreate diverse in-flight situations, enabling researchers to observe the system's behaviors under varying conditions. By analyzing simulated interactions between aircraft and ground stations, researchers gain insights into the system's performance during critical events, such as rapid altitude changes or adverse weather conditions (Cizrelioğullari & Imanov, 2023).

Field studies are another essential component of the research methodology. Researchers collaborate with airlines, aviation authorities, and air traffic control centers to observe real-time VDL operations. These observational studies provide valuable data on system reliability, response times, and the effectiveness of communication protocols in actual flight operations. Comparative analyses between simulated scenarios and real-world observations enrich the research findings, offering a comprehensive perspective on VDL's practical applicability and limitations (Gomez & Ortiz, 2013).

VDL operates within the VHF frequency band, typically around 136-174 MHz, enabling digital data exchange between aircraft and ground stations. Unlike traditional voice communication, VDL uses a series of protocols and data formats to facilitate the exchange of information. Aircraft are equipped with VDL transceivers, which allow for the transmission and reception of data packets. These packets contain essential information, such as altitude reports, route clearances, weather updates, and maintenance requests. Pilots communicate through VDL using dedicated avionic interfaces in the cockpit. These interfaces, often integrated into the aircraft's communication and navigation systems, display text- based messages received from ground stations. Pilots can then respond using predefined templates or manually inputting messages. Similarly, air traffic controllers use ground based VDL systems to send instructions and information to aircraft in their designated airspace (Novák et al., 2018).

The advantages of VDL lie in its ability to handle a large volume of data simultaneously from multiple aircraft, reducing congestion in communication channels. It ensures accurate, reliable, and secure data exchange, crucial for ensuring safe and efficient air traffic management. CPDLC, that is a remarkable component of VDL, revolutionizes aviation communication through its specialized text-based interface between pilots and air traffic controllers. This advanced system provides a standardized, secure, and efficient means of communication, significantly reducing the workload on both parties. CPDLC messages, encompassing crucial aspects such as altitude adjustments, route modifications, weather updates, and clearance requests, are meticulously predefined and structured, ensuring clarity and precision. To delve deeper into the complexities of CPDLC, comprehensive research methodologies are employed. Usability testing, a cornerstone of CPDLC studies, involves collaboration between human factors specialists, pilots, and air traffic controllers within simulated environments (Sestorp & Lehto, 2019). These rigorous tests assess message processing efficiency, response times, and user satisfaction. Innovative techniques, including eye-tracking experiments, reveal pilots' visual attention patterns during CPDLC interactions, providing invaluable insights for interface enhancements (Orye et al., 2023).

Technical analyses scrutinize data transmission protocols and error handling mechanisms, ensuring the accuracy and integrity of transmitted messages. Researchers meticulously examine data packets' integrity, focusing on accurate transmission and reception without corruption. Robust redundancy mechanisms and error recovery protocols are studied extensively, bolstering the system's reliability, even under adverse conditions or network disturbances. Functionally, CPDLC operates on a client-server model, connecting pilots and air traffic controllers to a central server for seamless communication. When a controller initiates communication, CPDLC messages are transmitted to the aircraft's onboard system. These messages are displayed on multifunction control display units or similar interfaces in the cockpit. Pilots respond using predefined options, ensuring standardized and clear communication. In scenarios of communication breakdown or system failure, CPDLC protocols outline fallback procedures, intensively researched to ensure uninterrupted communication during critical situations (Sestorp & Lehto, 2019).

In the context of European airspace, the integration of VDL and CPDLC has been a strategic initiative. Regulatory bodies such as the European Union Aviation Safety Agency (EASA) have defined standards and protocols for the implementation of these technologies. Aircraft operating in European airspace are required to be equipped with VDL and CPDLC interfaces, ensuring a perfect communication and compliance with regional regulations. Standardization efforts have been critical in ensuring interoperability across different European countries. Harmonized protocols enable pilots to communicate effectively as they traverse various airspace regions, regardless of national boundaries. This standardized approach is fundamental for the success of CPDLC, particularly in international flights where aircraft cross multiple countries and encounter diverse air traffic control centers. Additionally, the integration of VDL and CPDLC aligns with the broader goals of the Single European Sky initiative (Galotti, 2019).

Upon analyzing VDL and CPDLC in European aviation, several critical challenges have emerged. Among them is the imperative need for seamless integration across diverse national airspace regulations. The existence of varied standards and protocols among European countries has given rise to interoperability challenges, substantially limiting the potential of these sophisticated communication systems (Lehto et al., 2021). Additionally, the transition from conventional voice-based communication to digital text-based methods has introduced complexities in terms of training and adaptation for pilots and air traffic controllers, intensifying the hurdles faced during this technological shift. Another profound challenge centers around cybersecurity vulnerabilities. Given the heavy reliance of VDL and CPDLC on digital data exchange, it becomes paramount to fortify these communication channels against an array of evolving cyber threats (Gomez & Ortiz, 2013). Ensuring the integrity of data, especially considering the increasing sophistication of cyberattacks, necessitates continuous monitoring and the implementation of resilient encryption strategies (Orye et al., 2023).

To tackle these challenges comprehensively, a multifaceted approach is indispensable. Foremost, there is an urgent need to harmonize communication standards and protocols across European countries. In anticipation of the future, several trends are reshaping the landscape of VDL and CPDLC in Europe. Chief among these is the integration of AI and machine learning algorithms. The predictive analytics afforded by these technologies empower proactive maintenance initiatives and facilitate the optimization of communication routes based on historical data. AI- driven decision-making enhances operational efficiency significantly, heralding a paradigm shift in minimizing delays and revolutionizing airspace management practices. Another conspicuous trend is the rapid proliferation of satellite-based communication systems. Satellite-enabled VDL and CPDLC dramatically extend coverage, especially in remote or oceanic airspace where traditional ground-based communication infrastructure is inherently limited. This trend, in alignment with the global thrust toward a more interconnected and accessible aviation network, augments connectivity and fortifies safety protocols (Cizrelioğullari & Imanov, 2023).

4. Conclusion

The integration of VDL and CPDLC marks a important moment in the evolution of aviation communication within Europe. These advancements have not only enhanced safety, efficiency, and reliability in air travel but also reshaped the way information is exchanged between aircraft and ground stations. The transition from antiquated radio systems to the sophistication of VDL and CPDLC demonstrates the pivotal role of innovation in overcoming communication challenges. This evolution aligns seamlessly with Europe's Single European Sky initiative, embodying a commitment to standardized communication protocols and harmonized airspace management.

Throughout this exploration, pivotal theories and models have emerged, highlighting the importance of interdisciplinary collaboration. VDL Mode 2, ACARS, ATN, ADS-B, and CPDLC represent cornerstones in technological advancements, showcasing the dedication of international organizations and regulatory bodies to establish robust standards and protocols. The evolution of CPDLC, coupled with the integration of AI, Machine Learning, cybersecurity protocols, and technological integrations like 5G and satellite systems, underscores a relentless pursuit of enhancing safety, efficiency, and user experience in aviation communication.

However, challenges persist, such as interoperability issues, training complexities, and cybersecurity vulnerabilities, necessitating comprehensive solutions. Harmonizing communication standards, leveraging emerging technologies, and embracing satellite-based communication systems are pivotal in addressing these challenges. By proactively embracing anticipated trends Europe can fortify its position at the forefront of aviation technology. This ongoing commitment to innovation and collaboration will undoubtedly shape a future where aviation communication systems set new global standards for safety, efficiency, and reliability, ensuring safer skies and more efficient air travel for millions of passengers.

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References

Bae, J. W., Kim, H. K., Kim, I. K., Kim, T. S., 2008. Design and development of VDL Mode 2 System. Aerospace Engineering and Technology, 7(1), 30-39.

Cizrelioğullari, M. N., Imanov, T., 2023. Transforming to NextGen air transportation system: a case study for Turkey's national aerospace development. International Journal of Sustainable Aviation, 9(3), 262-278.

Galotti, V. P., 2019. The Future Air Navigation System (FANS): Communications, Navigation, Surveillance–Air Traffic Management (CNS/ATM). Routledge.

Gomez, L., Ortiz, J., 2013. Modelling and simulation of VDL mode 2 subnets for CPDLC in El Dorado airport. In 2013 IEEE/AIAA 32nd Digital Avionics Systems Conference (DASC), pp. 3B4-1.

Lehto, A., Sestorp, I., Khan, S., Gurtov, A., 2021. Controller pilot data link communication security: A practical study. In 2021 Integrated Communications Navigation and Surveillance Conference (ICNS), pp. 1-11.

Novák, A., Havel, K., Bugaj, M., 2018. Measurement of GNSS signal interference by a flight laboratory. Transportation research procedia, 35, 271-278.

Orye, E., Visky, G., Maennel, O., 2023. Analysing the Actual Use of Controller–Pilot Data Link Communications. Engineering Proceedings, 28(1), 18.

Pereira, M. S., 2002. Choosing the right VHF data link technology for commercial aviation air traffic services. Doctoral dissertation, University of Colorado.

Sestorp, I., Lehto, A., 2019. CPDLC in practice: a dissection of the controller pilot data link communication security.

Studenberg, F., 2005. The capacity and performance of a CPDLC system using VDL mode E. In 24th Digital Avionics Systems Conference Vol. 1, pp. 1-B, IEEE.

Žvinys, J., Rudinskas, D., 2023. Investigation of the application of CPDLC to aerodrome air traffic control procedures. Aviation, 27(2), 95-103.

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TRADITIONAL AIR CARRIERS FARE AND BOOKING CLASS NAMES AS A PART OF THEIR MARKETING STRATEGY

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Abstract

This paper focuses on the issue of fare and booking class names of traditional air carriers. Paper discusses the issues of traditional air carriers, history, development and current status, fleets, airline networks, services offered as well as mutual alliances. The article also focuses on the market analysis of the offered class names of the traditional air carriers divided by region. Paper includes an analysis of the data obtained in clear tables regarding preferred names of classes.

Keywords

traditional carriers, marketing, booking, fare class

1. Introduction

Traditional air carriers, also known as full service carriers (FSCs), are airlines that offer a range of services and amenities included in the price of a ticket. These services include in-flight meals, baggage, in-flight entertainment, seat assignments, and other amenities such as blankets and travel kits. FSCs also typically offer multi-class service, loyalty program membership, access to premium airport lounges, connecting flights and other benefits. FSCs predominantly use major airports instead of secondary airports and have a more diversified distribution through a network of resellers. Unlike FSCs, low-cost carriers (LCCs) offer lower prices with surcharges for all ancillary services. LCCs focus on route profitability rather than network profitability. LCCs rely heavily on ancillary revenues to make money. Ancillary revenues include checked baggage, stale cheese sandwiches, pre-sold seats and other ancillary services not included in the ticket price. In contrast to the lower LCC fares with surcharges for additional services, FSCs charge a flat ticket price that includes most of the necessary services (Tomová et al., 2017).

FSCs provide more comfort and convenience to passengers than LCCs. Passengers flying with FSCs do not have to worry about meals as they are served hot meals on board depending on the length of the flight. On long-haul FSC flights, at least two meals and snacks are served to passengers. In addition to the catering services, FSC passengers can enjoy in-flight entertainment systems that include movies or television programmes. Criteria for evaluating FSC products include passenger comfort, such as seat configuration and quality of business class beds on long-haul flights. The evaluation criteria also take into account the quality of the catering services provided by the airline. A higher rating is given if the airline provides high quality catering services, such as gourmet meals or local cuisine options (Bína et al., 2014).

In conclusion, traditional or full-service carriers offer a range of services included in the ticket price, such as on-board catering, baggage, in-flight entertainment systems, among others. They also provide greater comfort and convenience compared to low-cost carriers. Whereas low-cost carriers focus on route profitability through additional revenue streams such as checked baggage or seats sold separately from the ticket price; (Prúša et al., 2015).

2. Analysis of selected traditional air carriers with regard to the fare classes offered

2.1. Gulf carriers

2.1.1. Emirates

Emirates, the world's fourth largest airline by kilometres flown, is known for its luxury travel. Emirates offers a range of classes to cater to the different needs of passengers, including economy class, business class and first class.

Emirates First Class is the epitome of luxury travel. Passengers can enjoy their own private suite with a closing door, comfortable bed, massive desk, wardrobe, large entertainment screen, two lamps and a dressing table that can be raised or lowered. There is also a drawer in each suite containing writing utensils with a diary and pen.

Emirates' First Class Suites are not only comfortable, but also offer a whole other level of luxury. The nine Boeing 777-300ERs in the cabin feature completely different first-class suites that are arguably the best in the world. These aircraft, referred to as "gamechangers", offer just six first class suites in a 1-1-1 layout. Unlike any other first-class suites on any other airline in the world, these suites feature floor-to-ceiling sliding doors that provide complete privacy. Each suite has its own minibar with soft drinks and snacks.

Emirates offers courses to teach passengers how to make the most of their flight experience. For example, Emirates offers wine appreciation courses for passengers who want to learn more about wine and champagne during their flight. The course covers topics such as how to taste wine properly and how to pair wine with food. Emirates also offers cooking classes for passengers who want to learn how to cook dishes from around the world during their flight (Expert, 2022).

2.1.2. Qatar

Qatar Airways, the national carrier of the State of Qatar, offers passengers a range of classes to suit a variety of travel needs and budgets. Qatar Airways is known for its award-winning service and state-of-the-art aircraft.

First class is the most luxurious class offered by Qatar Airways. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. First Class passengers also have access to on-board bars on selected aircraft.

Business class is another popular class offered by Qatar Airways. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. Business class passengers also have access to on-board bars on selected aircraft.

Economy Class is the most affordable class offered by Qatar Airways. It includes comfortable seats with personal entertainment systems and catering services. Although economy class does not offer the same level of luxury as first or business class, it still provides a comfortable flying experience at an affordable price.

Qatar Airways also offers Premium Economy Class on selected aircraft. This class provides more legroom than Economy Class and additional amenities such as larger screen personal entertainment systems and enhanced food services (Hayward, 2022).

2.1.3. Etihad

Etihad Airways offers a range of travel classes to suit a variety of needs and budgets. The airline's first class is designed to provide passengers with a luxurious and private experience. Passengers can step into their own private suite, relax with a drink or have the crew prepare their bed for them to sleep. Etihad's Business Class offers passengers a comfortable and spacious seat that converts into a fully flat bed, as well as access to lounges and other premium airline services.

Etihad's economy class provides passengers who like to keep costs down with an affordable way to travel, while still enjoying a degree of comfort. The seats on most of Etihad's Boeing 777 and 787 aircraft are 17 to 17.5 inches wide and have a pitch of 31 to 33 inches. On Airbus A330 aircraft, the seats are slightly wider, 17.5 inches, with the same pitch. Passengers can also book a seat in economy class, which gives them more legroom. Although economy class passengers board last, unless they have elite status or have paid for Priority Access, they can still enjoy in-flight entertainment, food and beverages.

Etihad Airways has received positive reviews from customers regarding in-flight amenities, baggage, customer service and the overall experience. The airline has won several awards for its premium services such as first-class suites and business studios. However, even budget-conscious travellers can make the most of their flight if they know the ins and outs of Etihad's economy class (Expert, 2023).

2.1.4. Saudia

Saudia offers several travel classes on most of its aircraft. The airline has three travel classes: first suite, first class and business class. First Suite passengers can relax in a private suite with a full-size bed, 23-inch HD screen and dine on gourmet meals. First Class passengers can relax or catch up on work with uniquely designed seating and enjoy gourmet meals. Business Class passengers can stretch out on their seats, which transform into flat beds, and enjoy gourmet meals.

Saudia also offers an economy class called Guest Class or Premium Economy. Passengers in this class receive additional services such as welcome packages, hot towels, welcome drinks, upgraded meals, priority boarding, lounge access (on some airlines), and increased loyalty points. Comfort in the cabin is determined by the distance between seats, which is 38 to 39 inches on Saudia Airlines flights. The level of amenities varies from electrical outlets to wifi to individual television screens, depending on the length of the flight and the general level of service offered by the airline. Some airlines, such as Saudia, offer an on-screen ordering service where passengers can select the products of their choice using their credit card details and a hostess will deliver them directly to their seat.

2.2. European airlines

2.2.1. Air France

Air France offers a range of travel classes on its flights to suit different travel needs and budgets.

La Première is the most luxurious class offered by Air France. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. La Première Class passengers also have access to on-board bars on selected aircraft.

Business class is another popular class offered by Air France. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. Business Class passengers also have access to on-board bars on select aircraft.

Premium Economy Class is a class offered by Air France that provides more legroom than Economy Class and additional amenities such as larger screen personal entertainment systems and enhanced dining services.

Economy class is the most affordable class offered by Air France. It includes comfortable seats with personal entertainment systems and catering services. Although Economy Class does not offer the same level of luxury as La Première or Business Class, it still provides a comfortable flying experience (Stephen, 2019a).

2.2.2. *Lufthansa*

Lufthansa Allegris is a new travel experience offered by Lufthansa on long-haul routes that aims to provide a more personal and comfortable flight experience in all classes. It includes several new features such as fully enclosed single and double suites in first class, 14 different seat options in business class and enhanced amenities in economy and premium economy.

Lufthansa Allegris is part of Lufthansa's cabin refreshment program, which aims to improve the overall passenger travel experience. The program includes enhancements to seats, entertainment systems, dining options and other amenities in all travel classes.

Overall, the Lufthansa Allegris programme represents a significant investment by Lufthansa to improve the flight experience for its passengers. Whether you are travelling in economy, premium, business or first class, Lufthansa Allegris aims to provide a more personalised and comfortable flight experience that meets your individual needs (Pande, 2022).

2.2.3. *British Airways*

British Airways offers a range of travel classes on its flights to suit different travel needs and budgets.

Economy class is the most affordable class offered by British Airways. It includes comfortable seats with personal entertainment systems and catering services. Although economy class does not offer the same level of luxury as premium economy, business class or first class, it still provides a comfortable flying experience at an affordable price.

Premium Economy is a class offered by British Airways that provides more legroom than economy class and additional amenities such as larger screen personal entertainment systems and enhanced food service.

Business class is another popular class offered by British Airways. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Business Class passengers also have access to on-board bars on select aircraft.

First Class is the most luxurious class offered by British Airways. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. First Class passengers also have access to on-board bars on selected aircraft (Kramer, n.d.).

2.2.4. *Turkish airlines*

Turkish Airlines does not offer first class on its flights. Instead, they focus on providing a high-quality business class experience that includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges.

The decision not to offer first class may be driven by a variety of factors, such as cost savings or a focus on providing a more efficient and streamlined travel experience for passengers. However, Turkish Airlines' business class is highly regarded and has won numerous awards for its quality and service.

Overall, although Turkish Airlines does not offer first class, they still provide a high-quality business class travel experience that suits the needs of their passengers.

2.3. *Asian carries*

2.3.1. *ANA*

ANA (All Nippon Airways) offers a range of travel classes on its flights to suit a variety of travel needs and budgets, including The Room Business Class.

The Room is ANA's newest Business Class product, offering huge seats with closing doors for privacy, excellent in-flight entertainment systems, gourmet dining options and access to exclusive airport lounges. The Room provides a luxurious in-flight experience that rivals many first-class products offered by other airlines.

First Class is another premium class offered by ANA. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges.

Economy Class is the most affordable class offered by ANA. It includes comfortable seats with personal entertainment systems and dining services. Although economy class does not offer the same level of luxury as first or business class, it still provides a comfortable flight experience at an affordable price (Stephen, 2019b).

2.3.2. *Japan Airlines*

Economy class is the cheapest class offered by Japan Airlines. It includes comfortable seats with personal entertainment systems, excellent cuisine, wider legroom than competitors, and amenities. Japan Airlines' Economy Class has won numerous awards for quality and service.

Premium Economy Class is another class offered by Japan Airlines that provides more legroom than Economy Class and additional amenities such as enhanced food service, priority boarding, and access to exclusive airport lounges.

Business class is another popular class offered by Japan Airlines. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Business class passengers also have access to on-board bars on selected aircraft.

First Class is the most luxurious class offered by Japan Airlines. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. First Class passengers also have access to onboard bars on select aircraft.

2.3.3. *China Southern*

China Southern Airlines offers First Class, Business Class, Premium Economy Class and Economy Class seats on its flights. The First Class cabin is equipped with four exclusive cocoon-design seats that provide in-plane comfort. The seats are arranged in a 1-2-1 configuration with a seat pitch of 84" and a seat width of 27" when the side bolsters are folded down.

Passengers are provided with a 17" or 15" personal television, in-flight power outlet and USB port.

China Southern Airlines' international flights offer the above classes. However, on domestic flights, they usually only offer Business Class cabins, a few rows of Premium Economy seats and an Economy Class cabin. China Southern Airlines also has a separate Premium Lounge for international First and Business Class customers.

Passengers can book China Southern Airlines First Class using miles. Purchases between the Asia 2 region (which includes Guangzhou) and the mainland US cost 110,000 miles in first class.

Overall, China Southern Airlines' first class has met with mixed reviews. Some passengers praised the service and convenience provided by the airline, while others criticized it.

2.3.4. China Eastern

China Eastern Airlines offers different classes of service including First Class, Business Class and Economy Class. China Eastern Airlines' first class seats are oversized and can be converted into fully flat beds. The comfortable seats can be reclined to different positions to optimise personal comfort. The airline's business class king bed is the largest business class seat available. Retractable privacy screens give passengers additional shoulder room, and on-demand entertainment systems offer more than 150 songs, movies and games.

China Eastern Airlines flies to more than 1,000 destinations in 177 countries around the world. However, it is not clear from the search results what specific classes of service are offered on each flight. For more information on the classes of service offered on a particular flight, we recommend checking the airline's website or contacting its customer service.

2.4. North American carriers

2.4.1. Delta

Delta Air Lines offers a variety of travel classes on its flights to suit different travel needs and budgets. Whether you're looking for an affordable economy class option or a luxurious flight experience in First Class or Delta One, Delta has something for everyone.

Economy Class is the most affordable class Delta Air Lines offers. It includes comfortable seats with personal entertainment systems and food service. While economy class doesn't offer the same level of luxury as premium economy, business class, or first class, it still provides a comfortable flying experience at an affordable price.

Delta Comfort+ is another class offered by Delta Air Lines that provides more legroom than economy class and additional amenities such as enhanced dining services, priority boarding, and access to exclusive airport lounges.

Business class is another popular class offered by Delta Air Lines. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Business class passengers also have access to on-board bars on selected aircraft.

Delta One is the most luxurious class offered by Delta Air Lines. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges.

2.4.2. United

Economy Class is the most affordable class offered by United Airlines. It includes comfortable seats with personal entertainment systems and meal services. Although economy class does not offer the same level of luxury as premium economy, business class or first class, it still provides a comfortable flying experience at an affordable price.

Premium Economy is a class offered by United Airlines that provides more legroom than economy class and additional amenities such as larger screen personal entertainment systems and enhanced food service.

Business class is another popular class offered by United Airlines. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Business class passengers also have access to on-board bars on select aircraft.

Polaris Business Class is the most luxurious class offered by United Airlines. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Polaris Business Class passengers also have access to onboard bars on select aircraft.

2.4.3. American Airlines

American Airlines offers Flagship First and Flagship Business classes, which provide a luxury flying experience on select international and transcontinental routes.

Flagship First is the most luxurious class offered by American Airlines. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. Flagship First Class passengers also have access to onboard bars on select aircraft.

Flagship Business is another premium class offered by American Airlines. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options, and access to exclusive airport lounges. Flagship Business Class passengers also have access to onboard bars on select aircraft.

Both classes offer premium amenities such as chef-inspired meals, amenity kits, priority boarding and more. However, Flagship First is generally more expensive than Flagship Business when both are available (Miller, 2018).

2.4.4. Air Canada

Economy Class is the most affordable class offered by Air Canada. It includes comfortable seats with personal entertainment systems and meal services. Although Economy Class does not offer the same level of luxury as Premium Economy, Business or Signature Class, it still provides a comfortable flying experience at an affordable price.

Premium Economy is a class offered by Air Canada that provides more legroom than economy class and additional benefits such as enhanced meal service, priority boarding, and access to exclusive airport lounges.

Business class is another popular class offered by Air Canada. It includes reclining seats with direct aisle access, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. Business Class passengers also have access to on-board bars on select aircraft.

Signature Class is the most luxurious class offered by Air Canada. It includes private suites with full flat beds, personal entertainment systems, gourmet dining options and access to exclusive airport lounges. Signature Class passengers also have access to on-board bars on select aircraft (Loh, 2022).

3. Results

Table 1: Gulf carries. Source: Authors.

	First class	**Business class**	**Economy**	**Others**
Emirates	*First class*	*Business class*	*Economy*	*Premium economy class*
Qatar	*First class*	*Qsuite*	*Economy*	-
Etihad	*First class/ The Residence*	*Business class*	*Economy*	*The Apartment*
Saudia	*First class*	*Business class*	*Economy*	*Guest class*

Table 2: European carriers. Source: Authors.

	First class	**Business class**	**Economy**	**Others**
Air France	*La Premiere*	*Business class*	*Economy*	*Premium economy class*
Turkish	-	*Business class*	*Economy*	*Comfort class (začiatkom 2023 postupne zrušená)*
Lufthansa	*First class*	*Business class*	*Economy*	*Premium economy, Allegris, Suite*
British Airways	*First class*	*Business class*	*Economy*	*Premium economy*

Table 3: Asian carriers. Source: Authors.

	First class	**Business**	**Economy**	**Others**
ANA	*First class*	*Business class/The Room*	*Economy*	*Premium economy*
Japan	*First class*	*Business class*	*Economy*	*Premium economy*
China Southern	*First class*	*Business class*	*Economy*	*Premium economy*
China Eastern	*First class*	*Business class*	*Economy*	*King Bed*

Table 4: American carries. Source: Authors.

	First	**Business**	**Economy**	**Others**
AA	First class/ Flagship	Business c./ Flagship	Basic Economy	Premium Economy, Main Cabin (Extra)
Delta	First class/ Delta One	Premium select	Basic Economy	Comfort Plus, Main Cabin
United	-	Polaris	Basic Economy	Economy plus/ Premium economy
Air Canada	-	Signature/Business	Economy	Premium economy

4. Conclusion

The aim was to collect up-to-date information that in the current era of progressive and dynamic development of traditional air carriers is very often changing and companies are often coming to the market with new products. Subsequently, by synthesizing the collected data we were able to determine the trend of changes in travel classes according to geographic presence in relation to the global presence of traditional air carriers. The trend of changes is already given and it is only a matter of time before other airlines start to gradually introduce new products to their portfolio and this work shows the importance of this trend and can serve as a tool for the marketing departments of the selected but also other traditional airlines around the world to determine the marketing strategy and their travel class names in the future, taking into account the collected and processed data of the most famous airlines in their given geographical territory.

Airlines are changing the names of their traditional classes to more interesting ones to differentiate themselves from competitors and attract more customers. By using catchy and memorable names for their classes, airlines can create a unique brand identity that differentiates them from other airlines. In addition, renaming classes can help airlines simplify their fare structure and make it easier for passengers to understand what they are paying for. For example, some airlines have renamed their economy classes as basic economy or standard economy to distinguish them from premium economy classes. However, it is important to note that not all airlines change the names of their traditional classes. Some airlines continue to use the same class names they have used for years, such as First Class, Business Class, Premium Economy and Economy Class.

Overall, when it comes to naming travel classes, many airlines are opting for flashier and more interesting names in an attempt to stand out in a crowded marketplace. A perfect example is the market in North America, where change and trend adaptation and marketing strategies are very much needed to keep the traditional airlines in the market.

References

Bína, L. et al. 2014. Provozování letecké dopravy a logistika. 1. vydanie. Brno 2014. ISBN 978-80-7402-855-7

EXPERT, 2023. The Flight, 2023. Guide to Etihad Economy Fare Types and Booking Classes. The Flight Expert [online] [cit. 21.3.2023]. Dostupné na: https://www.theflightexpert.com/etihad-airways-how-to-find-fare-class-and-frequent-flyer-mileage-accrual/

EXPERT. 2022. The Flight, 2022. Emirates fare types, booking classes, and seat types explained. The Flight Expert [online] [cit. 21.3.2023]. Dostupné na: https://www.theflightexpert.com/emirates-fare-classes-explained-booking-classes-fare-type-guide/

Hayward, J., 2022. What Classes Of Travel Does Qatar Airways Offer? Simple Flying [online] [cit. 21.3.2023]. Dostupné na: https://simpleflying.com/qatar-airways-classes-of-travel/

Kramer, Ch., n.d. Everything you need to know about British Airways' fare classes [online]. [cit. 21.3.2023]. Dostupné na: https://thepointsguy.co.uk/guide/ba-fare-classes-explained/

Loh, Ch. 2022. What Classes Of Travel Does Air Canada Offer? Simple Flying[online] [cit. 21.3.2023]. Dostupné na: https://simpleflying.com/air-canada-classes-of-travel/

Miller, E. 2018. American Airlines Review - Seats, Amenities, Customer Service, Baggage Fees, & More. UpgradedPoints.com [online]. [cit. 21.3.2023]. Dostupné na: https://upgradedpoints.com/travel/airlines/american-airlines-review/

Pande, P., 2022. What Classes Of Travel Does Lufthansa Offer? Simple Flying[online] [cit. 21.3.2023]. Dostupné na: https://simpleflying.com/lufthansa-classes-of-travel/

Pruša, J. et al. 2015. Svet leteckej dopravy. 2.vydanie. Praha 2015. ISBN 978-80- 260-8309-2

Stephen, A. U. 2019a. The Definitive Guide to Air France's Direct Routes From the U.S. [Plane Types & Seat Options]. UpgradedPoints.com [online]. [cit. 21.3.2023]. Dostupné na: https://upgradedpoints.com/travel/airlines/air-france-us-routes-plane-types/

Stephen, A. U. 2019b. The Definitive Guide to ANA U.S. Routes [Plane Types & Seat Options]. UpgradedPoints.com [online]. [cit. 21.3.2023]. Dostupné na: https://upgradedpoints.com/travel/airlines/ana-us-routes-plane-types/

Tomová, A. et al., 2017. Ekonomika leteckých spoločností. 1. vydanie. 2017. ISBN 978-80-5541-359-4

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CREATION OF A Z 43 AEROPLANE MODEL FOR A FLIGHT SIMULATOR

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Abstract

This paper describes the process of developing a Zlin Z 43 aircraft for a flight simulator. Work on an aircraft simulation consists of multiple parts. The development of the flight model is the first and core part of the simulation. Work on this part consisted of an analysis of the X-Plane blade element theory-based flight model, sourcing of the data this model requires, flight testing and further editing of the data to match the known performance of the Zlín Z43. The aircraft systems are another core part of the simulation. A Mix of the simulator's default, customised and fully custom systems are used. The theory and process of creating, animating, and texturing a 3D model are described, too. Visual quality can also be important, especially for its use in virtual reality. The last part is about the user interface, user experience and how the various use cases shape their design for an aircraft simulation.

Keywords

simulator, flight model, airfoil analysis

1. Introduction

The aim is to create a simulation of the Zlín Z 43 aircraft, including a flight model, aircraft systems, visual model, and user interface for interaction with the simulation. X-Plane 11 has been chosen as the platform, as it was deemed the best fit for the project in its initial phase. The primary reason was the fact, that it was the only commercial flight simulator that allowed both professional and entertainment use in active development. During the development of the aircraft, the next major version of the simulator, X-Plane 12, has been released. Most of the work was fully compatible with the new version. However, some changes still had to be made to the flight model, systems, and visual model for both compatibility reasons, as well as to utilise some of its new features. The model of aircraft has been chosen in part because there was no existing, high-quality simulation of the type available. Neither the more modern Z 242L or Viper SD4 operated by LVVC were considered, as both are equipped with glass cockpit avionics of which no simulation exists for the X-Plane flight simulator. Creating a custom simulation of such modern avionics is beyond the scope of this project.

2. Flight model

2.1. X-Plane 12 flight model

The flight model of the X-Plane flight simulator is based on blade element theory. At the core of this flight model is a basic 3D model that is used for its calculations. This model consists of fuselage, wings, propellers/rotors, cowlings, gears, and other miscellaneous objects, all of which affect the flight model. Wings are defined by their length along the 25% chord, tip and root chords, sweep, dihedral and can be split along the chord into ten equally spaced sections – elements. Incidence can then be set for each individual element, as well as which flight controls are present for this element. Specifications for these flight controls, such as their deflections and chord ratio as well as coefficients for flaps and slats are then defined separately. Propeller is defined by its position, cant, type, turn direction, radius and pitch range. Like a wing, a propeller blade is split into ten elements, each defined by chord lengths and its angle of incidence. This defines the geometry of wings and propeller blades, next we need the coefficients of lift, drag and moment. These are stored in airfoil files, which contain coefficients of lift, drag and moment for the whole -180 to 180 degree angle of attack range. Each airfoil can contain data for up to ten Reynolds numbers. Every wing or blade can be assigned three airfoil files which are then blended along their chord. The last two things needed for the lift, drag and moment equations is the air density, which comes from the simulator's atmosphere simulation, and the velocity. For velocity, it's not enough to simply consider the speed at which the air moves relative to the aircraft. Additional calculations are done to get the local air velocity affected by things like propwash, upwash, downwash and other interactions between the wings and bodies.

2.2. Creating the airfoils

X-Plane comes with its own program for creating the airfoil files called airfoilmaker. This program can, however only create curves for each coefficient based on entered parameters. For this project, data from airfoil analysis was directly imported into an airfoil file. For this analysis, XFOIL has been used. The biggest limitation of XFOIL for this use is its inaccuracy at higher angles of attack. It can generally predict results well within the linear range of the lift coefficient, however, it begins to overpredict the lift and underpredict drag at higher angles of attack approaching the stall (Kallstrom, 2022).

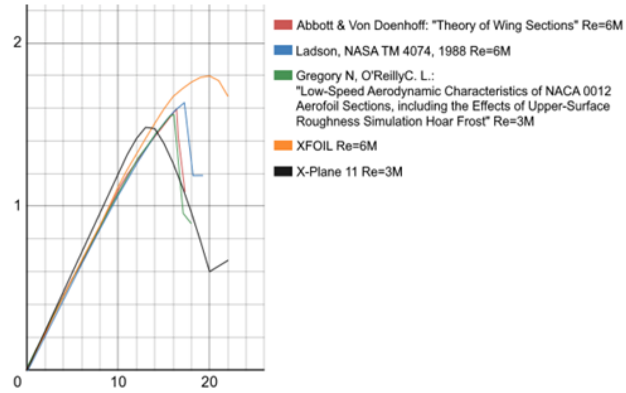

Figure. 1: Comparison of the lift coefficient for NACA 0012 airfoil from experiments, XFOIL analysis and an airfoil file included with X-Plane. Source: Authors.

Figure 1. shows the overprediction of lift coefficient by XFOIL analysis in comparison to experimental data (Langley Research Center, 2023). It also shows the need to create new airfoil file, even though one for the NACA 0012 airfoil, which is used on the empennage of the Z 43, is included with the simulator. On the main wing, NACA 63-416.5 is used. Unlike for the NACA 0012, there is no experimental data available for verifying and adjusting the results of the analysis. Therefore, a different approach has been taken where the data for angles of attack approaching the stall have been gradually corrected with estimations based on known errors of XFOIL analysis and then validated and corrected further with flight tests. These corrections are shown in figure 2. where the original analysis results are shown in blue, and the correction is overlayed in red. Results are shown for ten evenly spaced Reynolds numbers between 1 and 10 million.

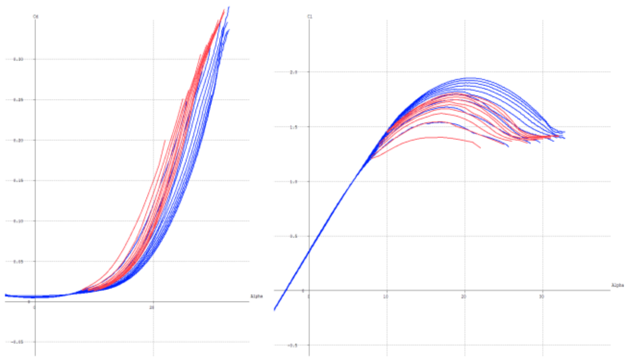

Figure. 2: Visualisation of the modified drag and lift coefficients. Source: Authors.

For the stall speed flight tests a procedure described in the "Certification Specifications and Acceptable Means of Compliance for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes CS-23" document was used. According to paragraph 23.201 b, the wings level stall characteristics must be demonstrated starting from a speed at least 10 knots above the stall speed, the elevator control must be pulled back so that the rate of speed reduction will not exceed 1 knot per second until a stall is produced, as shown by either:

- An uncontrollable downward pitching motion of the aeroplane; or
- A downward pitching motion of the aeroplane, which results from the activation of a device (e.g. stick pusher); or
- The control reaching the stop.

For the Z 43, wing level stall is shown by an uncontrollable downward pitching motion, as shown in figure 3. by a vertical grey line.

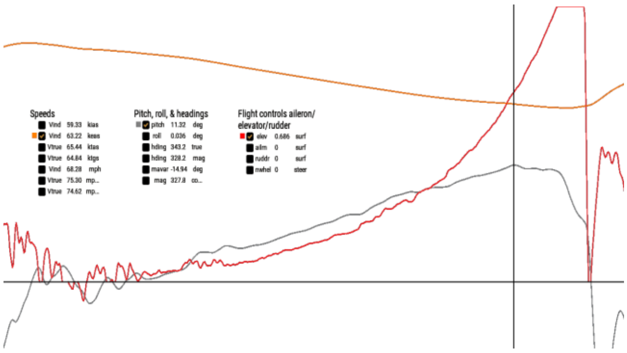

Figure 3: Wing level stall flight test data output. Source: Authors.

The graph shows a downward pitching motion which could not be stopped by increasing elevator deflection without increasing the deceleration to a value greater than 1 knot per second. When this happens the equivalent airspeed, which is practically equal to calibrated airspeed under these conditions, is 63.22 knots, while indicated airspeed is 59.33 knots. These speeds closely match the values from the flight manual as shown in figure 4.

Power setting	**Configuration**	**CAS [km/h]**	**IAS [km/h]**	**CAS [kts]**	**IAS [kts]**
Idle	Clean	117	110	63.17	59.39
	Take-off	110	102	59.39	55.07
	Landing	103	94	55.61	50.75
90% max. continuous	Clean	112	104	60.47	56.15
	Take-off	105	96	56.69	51.83
	Landing	95	85	51.29	45.89

Figure 4. Stall speed table. Source: EASA (2015).

With the clean configuration performance matching the real world performance, flaps can be tuned. The same procedure as before has been used. X-Plane doesn't have separate polars for airfoils with the high lift devices deployed. Instead, for flaps the increase in the coefficient of lift, drag and moment is set inside the planemaker. Planemaker estimates these values based on the flap type and the geometry of both the flap and the wing. Flight tests have shown this estimation to be accurate for the take-off configuration of 14 degrees. However, for the landing configuration of 37 degrees, the stall speed has been significantly lower in comparison to the values in the flight manual. This means, that there is no single value that can be used. Instead, these coefficients have to be driven with a plugin which can change them dynamically. After getting accurate coefficients for both take-off and landing flap settings, a linear function has been added to smoothly interpolate between the two values. Since there is no data available to validate performance for other deflection angles and the time spent in between the 0, 14 and 37 degrees, linear interpolation has been deemed as satisfactorily accurate.

2.3. Mass and balance

The dry operating mass, DOM, as well as the dry operating index, DOI, can vary significantly between different airframes. This is due to various factory options, but more importantly, various modifications to specific aircraft that have been made. For this reason, it was decided to let the user enter these values and change the DOM and DOI of the simulated aircraft automatically to match the desired values. Initially this was done by changing the mass of the payload and moving the longitudinal centre of gravity. User could then enter the payload masses through a menu separately for front and rear seats as well as for the top and bottom baggage compartment. Payload and longitudinal centre of gravity would again be adjusted in accordance with the arms as defined in the flight manual.

However, with the release of X-Plane 12, this had to be changed to work with the new payload station system. This new system allows to creation nine payload stations, each with defined arm for all three axes. This has allowed for the vertical and lateral centre of gravity to be changed based on payload, as well as the moment of inertia. However, this change also made changing the empty centre of gravity location in a way it was done before impossible. To solve this issue and continue allowing the users to specify DOI, an extra payload station has been added. This station cannot be loaded by the user, but instead is controlled by code that adjusts the mass of the loading station in a way that results in DOI that the user has requested.

Fuel tanks have always worked in a similar way as the new payload stations do, affecting both the centre of gravity and the moments of inertia based on their location and the mass of the fuel inside them. Their arm can be changed depending on the amount of fuel in tank. However, this relationship can only be linear.

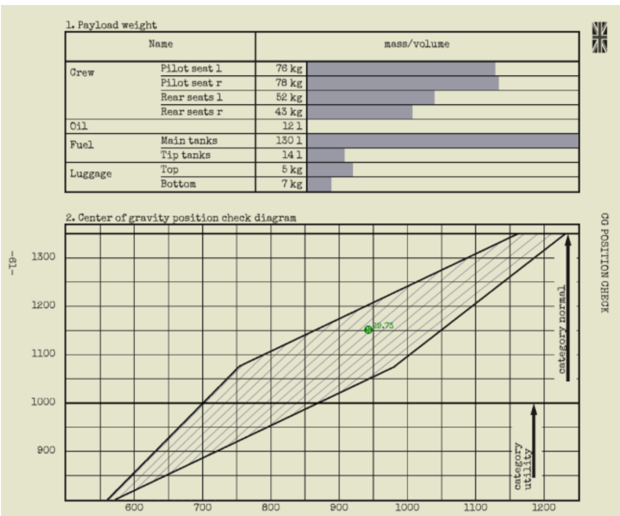

Figure 5: Mass and balance menu user interface, adapded from flight manual.

After adding payload and fuel the user is presented with centre of gravity position check diagram as shown in figure 5. This diagram shows whether the aircraft is within its centre of gravity and mass limitations as well as whether the payload is suitable for carrying out a utility category flight.

3. Aircraft systems

3.1. Simulator extensions

The X-Plane Plugin software development kit, SDK, allows developers to write additions that work inside X-Plane without modifying its code. For easier access to SDK's features for less experienced programmers, different frameworks were created. XLua has been developed internally and is used by the art team of Laminar Research. However, it only has basic functionality (Moravan, 1999). For aircraft plugins, there are two other popular Lua frameworks, SASL and Gizmo. Both are more complex than XLua and allow the developer to use almost all features of the X-Plane SDK and also offer their own digital rights management. For this project SASL has been chosen as it supports all three operating systems as the base simulator, while Gizmo lacks Linux support. SASL also doesn't require the global plugin to be installed in the simulator and is not tied to one publisher.

3.2. Electrical system

The Z 43 electrical system uses primarily direct current, with alternating current only being used to power the factory-installed attitude indicator and directional gyro. These were powered using the PAG-1FP inverter. Aircraft which had the factory gyroscopic instruments replaced with ones powered by DC have had this inverter removed. All the components are, with the exemption of the pitot heating system during its system check, connected in parallel. This has allowed for multiple simplifications in the simulation. The custom simulation can be split into two parts. The first part is the logical state of the system. This state is not calculated every frame, instead this is only done in situations where a change to its state could happen and only for the affected busses. Based on this state, the voltage, current and power is calculated for its components. These calculations must be done every frame. Even though it's not a very complex simulation, it offers multiple benefits over default electrical system implementation, such as more accurate behaviour under many different conditions. This way of simulating the system automatically results in correct behaviour of different failures, checks and of circuit breakers, fuses and even disconnected electrical connectors. The system was connected in accordance with the schematic in the Czech language version of the technical manual and has uncovered a few errors (EASA, 2015).

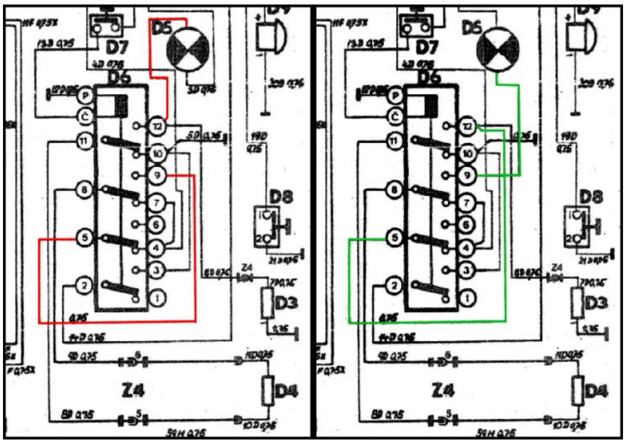

Figure 6: Erroneous schematic (left) copared with the corrected one (right).

The biggest error was wrong connection of the RP-6 relay in the pitot heat system check circuit, marked as "D6" in the schematic. After initial configuration the system was not working as intended in the simulator. After closer inspection it was clear that a circuit wired as shown in the schematic cannot result in the desired functionality. A schematic from the Z 142 technical manual was used for this system instead, as the pitot heat system is identical between these two aircraft (Moravan, 1980; 1988). Using this schematic has resulted in correct behaviour of the pitot heat check system.

3.3. Avionics

One of the primary uses the Zlin Z 43 was designed for was air navigation training. For this purpose, it could have been optionally equipped with RKL-41 automatic direction finder as well as with either LUN 3524.21, or in later models, the KY-96A VHF radio stations. Over time many aircraft were upgraded with more modern navigation and communication equipment. This means, that currently the equipment installed on these aircraft can vary from airframe to airframe quite significantly. For this reason, it was decided that instead of focusing on recreating a single, specific airframe, a way for the user to customise the panel will be added. This meant adding UI for selecting the configuration as well as creating a way to store and load saved configurations automatically, so users do not need to configure the aircraft for every flight. The simulation of the electrical circuits that power avionics also had to be made modular, to support many different configurations.

The configuration menu offers five basic presets. One based on the factory configuration and one with Bendix King avionics for radio navigation including VHF NAV, DME and ADF equipment. Other three configurations include a GPS. First of includes KLN-90B GPS. An open source simulation of this unit is used. Last two configurations offer a more modern Garmin GPS. For both, it can be either GNS430 or GTN650. First one is a basic VFR configuration with a GPS, transponder, and an audio panel, second is based on a specific airframe, currently registered as OM-LOW.

Figure 6: 3D reconstruction of a modernised Z 43 panel of OM-LOW. Source: Authors.

A basic simulation of GNS430 is included in the X-Plane flight simulator by default. It can be replaced by the Garmin trainer software with the use of third party commercial software. Third party software is also required for the GTN650, as the simulator doesn't include any simulation of this unit by default. There is no high-quality default simulation of communication and navigation radios or transponder, so a custom simulation of those devices has been developed. All features of these avionics, except for maintenance and configuration pages, have been accurately replicated. Special attention was given to the code input functions of the GTX330 transponder. This is commonly incorrectly implemented, which diminishes it's use for cockpit familiarisation and in some cases can result in the user entering a wrong squawk code. Other functions including pressure altitude display, flight timer, altitude monitor, count up/down timer, temperature and density altitude display as well as options related to these functions were also modelled.

Each of these five presets can be further customised. This includes the aforementioned GPS options, as well as options for different attitude indicators, altimeter in feet or meter and more.

3.4. Configuration and system state saving

The ability to save the current state of the aircraft systems as well as its position and velocity can be very useful for both entertainment as well as professional training use cases. Therefore, a system that allows to save and load this data was created. This system works in a very similar way as the system required to save aircraft configuration. Aircraft state and position is being saved to a file in the output directory of the flight simulator. Each livery has its own state and configuration file. State files are saved every ten seconds when the simulator is running, i.e. it is not paused or in replay mode, while the configuration file is saved every time there is a change made to the aircraft configuration. If state file is not found or if its corrupted, default values are used instead. The system should be backwards compatible, so if new features are added in the future, old state files will work, with default values used for the newly added features. Configuration files have another layer, where user configurations are saved in the output folder, if this file is missing or corrupted, a livery specific file stored in the livery folder is checked. If this file is not usable either, default configuration is used. This system allows for livery specific defaults which the user can revert to at any time.

4. Visuals

As mentioned in the flight model section, every aircraft n X-Plane has a basic 3D model used for the calculation of the forces acting on the aircraft. This model can be, and in the past versions of the simulator had to be, used for the visual representation of the aircraft as well. As the capabilities of computer hardware increased, so did the expectations and requirements for visual quality. Therefore, an option to hide this basic model was added as well as the option to add more detailed 3D models. These 3D models have no effect on the flight model and the hidden model is still needed and used for its calculation. This also allows for creation of a detailed and interactive 3D model of the cockpit, which is especially important with the introduction of virtual and mixed reality based simulators. X-Plane uses its own file format for 3D models called OBJ8, not to be confused with another commonly used format for 3D models called obj. There are multiple options for 3D modelling software which can export in this format. In the past Laminar Research have used AC3D, which is a commercial, but relatively affordable option as well as easy to use. However currently Blender is being used by Laminar Research as well as by many third party developers. It is a more powerful 3D modelling software which is at the same time free and open source. Since it's used by the developers of the simulator itself, high quality export plugin for OBJ8 that is being updated with the latest features is available. These are the biggest reasons why it was chosen for this project. However, an older version of Blender, 2.79, is still being used as it was the latest version when the work on the project started and switching a major version of the modelling software for an ongoing project is not advised. For textures Adobe Substance 3D Painter was used. It is an industry standard software which allows for creation of PBR textures and export in the PBR format used by X-Plane.

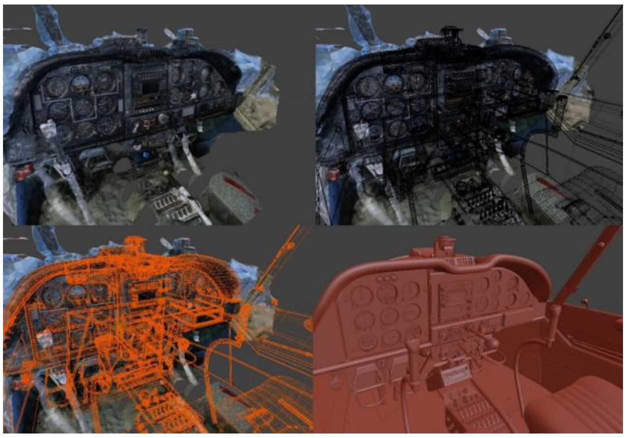

Figure 8: Process of turning a photogrammetry reconstruction into a usable 3D mesh. Source: Authors.

When creating the 3D model, technical drawings of various components were used. However, for the aircraft itself, no accurate technical drawings are publicly available. Drawing from the flight manual or one intended for scale model builders could have been used. However, usage of these kinds of references can lead to inaccuracies. To help with creation of more accurate model, aside from regular reference photos, photogrammetry was used as well. Due to limited resources the quality of the results was limited as well. Despite this it has been a great resource, especially for areas with more detail which result in better quality reconstruction which allowed for accurate determination of panel lines, doors, rivets etc. Photogrammetry has also been used in the cockpit, although the simple shapes and the large number of components with known dimensions and accurate blueprints available made it less crucial for an accurate result. Every single gauge and piece of avionics has been exported as a separate object. Reason for this is the large amount of customisation available. If the whole gauge object is not needed in the current configuration, "object kill" feature can be used. Unlike a simple hide animation, this means the object and its assigned textures are completely unloaded form memory. However, since all manipulators and displays have to be in one object, ones associated with unused gauges and avionics have to be hidden using hide animation.

5. Conclusion

As a result of this work, a partially complete simulation of an aircraft has been created. It is possible to complete an entire flight, including startup and shutdown. Basic flight behaviour including basic aerobatic manoeuvres like spins, have been tested by pilots and instructors of the type with satisfactory results. Aircraft has also been tested in virtual reality, where all the basic interactions with manipulators were working as expected and the accuracy of the visual model, thanks to the use of photogrammetry and textures created with modern PBR workflow, was apparent. However, more work is needed to complete the textures for the exterior of the aircraft. More work is also needed for the user interface elements to be fully supported in virtual reality without the need to revert back to a 2D screen. Framework for aircraft configuration is completed along with some basic configuration options, including one of the OM-LOW aircraft operated by LVVC Žilina. However, all planned options have not been completed yet. Lastly, an update to replace the default sounds with real recordings utilising FMOD 2.02 sound engine of X-Plane 12 would bring the sound to a quality level in line with the rest of the simulation.

Acknowledgement

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References

European Aviation Safety Agency (EASA). 2015. Certification Specifications and Acceptable Means of Compliance for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes CS-23. 15 7 2015. č. Amendment 4.

Kallstrom, K. 2022 Exploring Airfoil Table Generation using XFOIL and OVERFLOW. San Jose: NASA Ames Research Center, 2022.

Langley Research Center. 2023 2D NACA 0012 Airfoil Validation Case. Turbulence Modeling Resource. [online] 8 9 2022. [cit. 12 3 2023] Avaliable at: https://turbmodels.larc.nasa.gov/naca0012_val.html.

Moravan, N. P. 1980. Technický Popis a Návod k Obsluze Z43. Otrokovice, 10 1980.

Moravan, N. P. 1988. Technický popis a návod k obsluze Z 142. 4. Rev 05 2007 Otrokovice, 1988.

Moravan, N. P. 1999. Letová příručka Z43. Otrokovice, 1972, Rev. 1999.

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LONG-RANGE UAV HYBRID PETROL-ELECTRIC POWERTRAIN

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Abstract

Along with increasing UAV both weight load and endurance requirements, there is a need to use alternative propulsion solutions, to satisfy the market as well as various customer applications. Although lithium polymer cells are yet well developed, they are still too heavy for long-endurance UAV missions. Hybrid petrol-electric powertrains are outstanding imitations of hybrid hydrogen-electric propulsion systems, which are currently under intensive development. Not only for their onboard power production and improved overall efficiency but also for simulating a weight load of a future hydrogen-electric system. Therefore, such a system is being tested and aimed to be used in fixed-wing UAVs for long-endurance missions. This paper describes the design and operation of a hybrid petrol-electric propulsion system and further operational optimization based on comprehensive ground testing.

Keywords

hybrid, petrol, electric, powertrain, UAV

1. Introduction

Hybrid powertrain, in its basics, utilizes at least two energy sources or energy conversion agents. By energy conversion is meant chemically stored energy in a fuel or an electrical accumulator to be transformed into mechanical work or kinetic energy of a driven object (Ehsani et al., 2018)

Well-developed hybrid petrol-electric drivetrains, nowadays widely used in the car industry, manifest their capabilities and usability in general.

Mainly, considering VTOL requirements in future applications, as lithium cells are still not energetically dense enough, engine-driven generators are outstanding energy conversion agents, where similarities with the car industry are vastly significant.

As there are many ways of approaching a hybrid UAV powertrain design, the most obvious one is not to use a combustion or jet engine for direct propulsion in combination with another source of energy, but as an onboard powerplant (Bayindir et al., 2010).

The accurate ratio of onboard power production and storage delivers a smart, reliable, and efficient solutions for both fixed-wing and VTOL UAV propulsion, altered respectively (Bongermino et al., 2017).

2. Theoretical approach

As of now, hybrid powertrains are yet applied in UAV usage. Different types of combinations of petrol engines and electric propulsion are designed and built for commercial employment. Divided into two categories, both are considered hybrid powertrains.

2.1. Primarily combustion engine propulsion

The conception of primarily combustion engine propulsion in a UAV utilization fits best for fixed-wing UAVs. Combustion engine mounted with a propeller is being used during forward flight ascend, cruise and descent. Electric propulsion though, typically consisting of three or four smaller electric engines, provides just enough thrust for vertical takeoff and landing, with no other purpose during the flight (Mull & Nix, 2022).

Number of possible vertical takeoffs and landings strictly depends on battery pack size, which is usually limited by maximum takeoff mass restrictions.

Individual propelling systems of such UAV powertrain are mostly not interconnected which could be very beneficial in terms of structural integration and overall simplicity, although instability or failure of one of the systems can cause emergency or an accident.

Such propulsion design is not applicable on multicopter UAVs, which significantly limits general usability and therefore fewer commercially available technologies are offered worldwide.

Operator actions are also required during startup procedure since there is mostly no electric starter present for combustion engine start sequence. Not even starter guarantee successful engine startup since cold starts require choke to be engaged. Multiple attempts are often executed for combustion engine to start. Since these facts are deviating user friendly experience idea, higher level system interoperability is desired.

2.2. Primarily electric propulsion

Primarily electric propulsion provides significantly more satisfying user experience trough well developed electric motors and remote control systems. Generally considered, multicopters are most suitable to be propelled by such propulsion.

Since considering this a hybrid powertrain, electric generator is driven by petrol engine providing enough power to produce required amount of electric energy onboard the UAV. System is always equipped with a small battery pack to store some energy reserve for peak demands and help dampen power fluctuations (Brown, 2017).

These powertrains offer longer endurance compared to pure electric systems however not a much of a range extension which is obvious regarding the design and usage of multicopter type UAVs.

The difference of not using combustion engine for direct propulsion results in mandatory higher-level system interconnection and as a benefit of that, powertrain is adequately integrated as well as redundant.

Although primarily electric hybrid propulsion was previously mentioned to be used mainly in multicopter applications, there is also a great potential in fixed wing UAV utilization.

Not even system interconnection improves operators work load during the startup procedure, unless system control optimizations are made. Similar handling procedures are mandatory as for primarily combustion engine propulsion in terms of operator participation. Complex digital powertrain control and effective involvement of all systems components are crucial for achieving satisfactory results.

3. Hardware and operation design

In this paper, the focus is being kept on designing compact and reliable physical petrol electric hybrid powertrain as well as developing sufficiently intelligent control actions executed by programmable micro computer unit.

Not only energy conversion or multiple energy sources make hybrid, but also the ability of such system to run independently and solely on one of the energy sources at a time.

The idea is closer to primarily combustion engine hybrid powertrain type, however only little improvement possibilities occur. On the other hand, primarily electric hybrid propulsion shown in Figure 1 could possibly be improved in terms of onboard energy conversion and production and general operational autonomy.

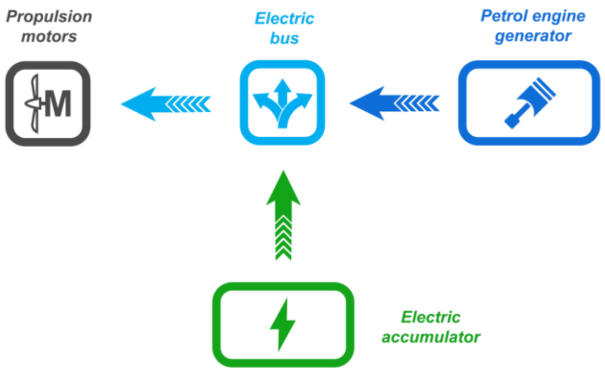

Figure 1: Primarily electric propulsion system scheme.

Various computer executed procedures could reduce operator's startup work load, save fuel and thus increase endurance and range and help manage energy flow within the system.

Powertrain autonomy is a critical factor for efficient operation. Ideally, including self-startup, which is only primarily electric hybrid powertrain type with combustion engine generator eligible for.

Combustion engine is being mechanically solidly linked with the generator, considering RPM identical. Coupler shown in Figure 2 consist of two discs, each of which is customized for individual respective shaft mounting and four flexible shock and oscillation dumping elements.

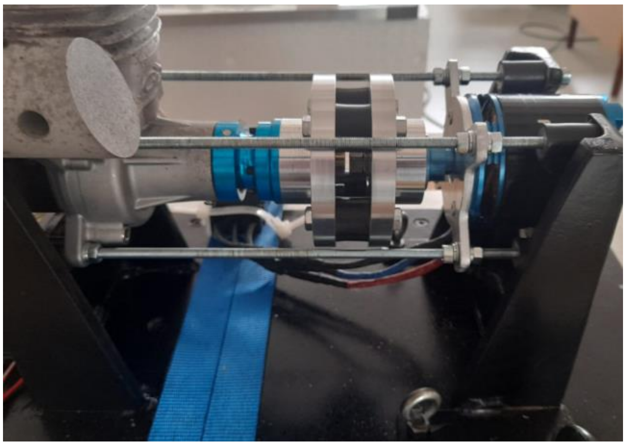

Figure 2: Mounted coupler.

Since generator could also act as a motor, there is no need for additional electric starter to be mounted, whatsoever. Electric energy stored in battery pack is used for combustion engine startup executed by control computer as shown in the Figure 3.

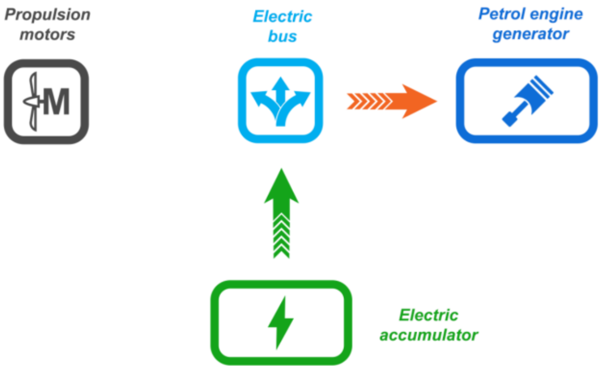

Figure 3: Combustion engine startup - energy flow.

During and after successful startup, electronic servos shown in the Figure 4 control carburetor valves of the combustion engine. Determining factor would be the output voltage as it directly disproportionally changes depending on system load.

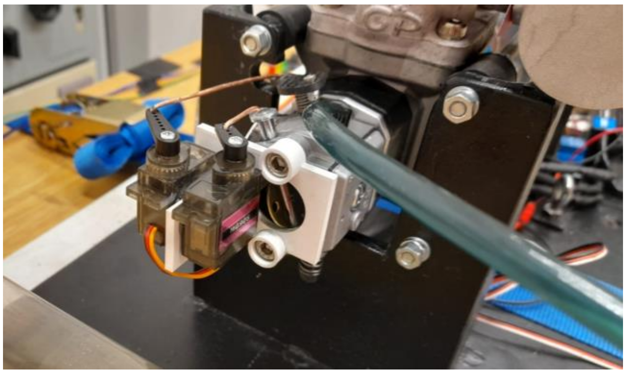

Figure 4: Carburetor control electronic servos.

Generator output voltage value directly relates to generator RPM. Generator under the load though, requires much higher RPM, in order to produce equivalent voltage in comparison with no load applied.

Load as such is reflected by voltage drop even in pure electric powertrains, which is why continuous voltage tracking is essential.

Consequently, generator RPM are controlled by regulating combustion engine power output trough carburetor valve servo.

Voltage measurement should be conducted as close to interconnection between all of the propulsion system components, such as propulsion motors, battery pack and electric generator as possible. Simple yet very efficient solution for both the system main interconnection and voltage reference measurement point is an electric bus bar.

Another key factor is to combine combustion engine and electric motor used as generator with similar nominal power outputs. Based on what, given combination is assumed energetically compatible.

Energetical compatibility could be described as a satisfactory compromise between lost energy and energy converted in a given connection, in this case of using an electric motor as a generator.

4. General operation

As stated before, the system is designed primarily electric, which comes with certain improvement possibilities. One of those, already done, is petrol engine startup performed by the generator. No operator action is needed.

Since bus voltage is main determination factor of petrol generator output control and battery is directly connected to it, battery cell amount sets limitation of operational voltage. Six cell lithium polymer battery of capacity 99 Wh is used. Such battery has nominal voltage of 22.2 volts. Maximum operating voltage is 25.2 volts, while minimum is 19.2 volts.

In the case of an emergency combustion engine shutdown, thus depriving electricity production, battery is expected to cover the demand until safe landing.

This drivetrain was designed and built to actively support maximum of 2 600 W in conditional hybrid operation mode, as shown in Figure 5, which means certain amount of energy is taken from battery pack, while majority is generated.

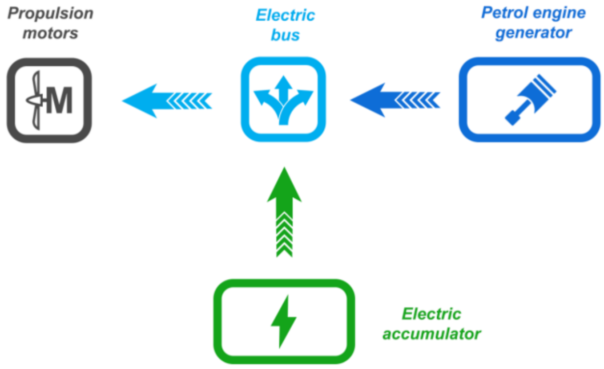

Figure 5: Conditional hybrid operation mode.

For safe operation it is mandatory to keep battery charged within suitable limits, in terms of possible cell damage. Not only after energetically demanding climb flight, but also during relatively slow petrol engine control response to overvoltage caused by 'sensor to servo' delay. Therefore, battery pack shouldn't be charged during cruise flight over 75 percent of its capacity, so it can store overproduced energy for a short time.

As the voltage would be direct indicator of unloaded battery charge level, analogically, 75 percent of its capacity represents voltage of about 23.5 volts. Such voltage provides satisfactory energy backup as well as sufficient overproduction storage.

Drained battery after climb-out acts as a load as propulsion electric motors do, which obviously cause petrol engine with the generator to stay at its maximum power output and recharge battery as shown in the Figure 6.

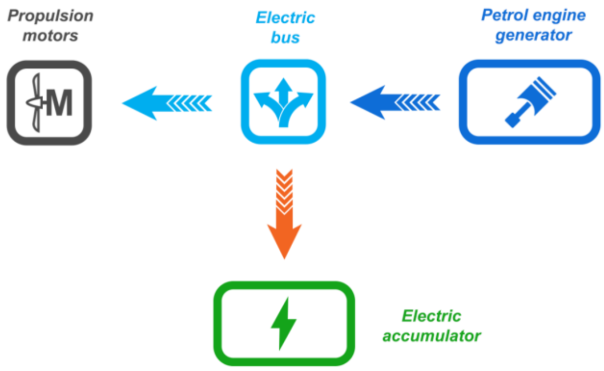

Figure 6: Inflight battery recharge.

After battery recharge to voltage of 23.5 volts is accomplished, system operates in its normal mode, observable in Figure 7, in which demand-production equilibrium is established by control microcomputer. Battery no longer drain or provide energy from and to electric bus. Two stroke, one piston combustion engine is operating near its nominal, 7000 RPM.

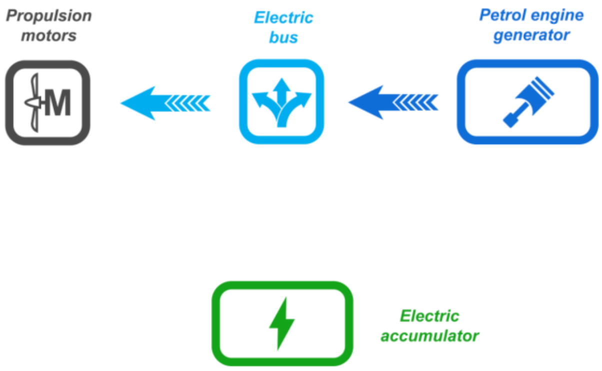

Figure 7: Normal operational mode.

During long endurance cruise flight, with battery recharged up to 23.5 volts and no plan of further climbing, certain amount of stored energy could possibly be used, whereas combustion engine power output lowered, to meet the demand. The process of this specific energy management is described as unconditional hybrid operation mode, manifested in Figure 8.

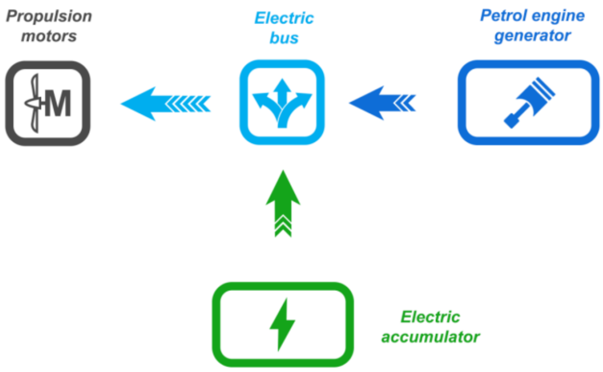

Figure 8: Unconditional hybrid operation mode.

Such operation mode is executed by control microcomputer after certain conditions had been met. Mainly, stable voltage, low absolute battery current and mid-range combustion engine output are required, for the mode to be considered engageable.

Engagement though, depends not only on actual values, but average values of monitored sensors or their time function.

5. Powertrain control

Arduino microcomputer continuously gathers real time data from voltage, current and temperature sensors, based on which subsequently controls startup procedure and combustion engine carburetor valves to adjust power output.

Safety and emergency procedures are involved within the primary code consisting of overheat protection, overvoltage and undervoltage protection.

Simple troubleshooting is available for operator to observe, which consists of three LEDs, determining voltage sufficiency for the startup, safety and emergency protocols engagement and startup pending.

Even complex diagnostics can be received with the laptop connected, shown in Figure 9.

```
-> / / / / / / / / / / / / / / / / / / / /
-> FADEC DIAGNOSTICS
->
-> BUS VOLTAGE ACT/AVG          23.04 / 23.57
->                              LOW |   |*|   | HIGH
->
-> BATTERY CURRENT ACT/AVG      23.70 / 12.06
->                              DEMAND | *|  |   | CHARGE
->
-> TEMPERATURE AIR/ENG          19.49 / 109.98
->                              LOW |   |  |* | HIGH
->
-> CARB SERVO PULSE             1390 // DEMAND //
->
-> FUSE                         OK  0
->
-> ENGINE SWITCH                ARMED / ATTEMPT DISENGAGED
->
-> PAGE # 423
->
-> / / / / / / / / / / / / / / / / / / / /
```

Figure 9: Computer based diagnostics example page.

6. Conclusion

Hybrid UAV powertrains provide not only superior results in endurance and performance, in comparison with pure electric ones, but also limitless opportunities for their improvement in their operation and efficiency.

Highly autonomous systems are often reliable and even deployable in very specific and demanding missions.

Further development and improvements were aspired and successfully conducted, resulted in capable primarily electric hybrid petrol-electric powertrain.

Powertrain control level is adequately strict about outputs as well as inputs, preventing any emergency to become serious incident.

Most importantly though, by imitating weight load and power output of similar hydrogen-electric hybrid powertrain, this research manifests the potential of hydrogen powertrain potential in UAV utilization.

References

Bayindir, K., Gozukucuk, M., Teke, A. 2010. “A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. Energy Conversion and Management.,” Çukurova University, Department of Electrical and Electronics Engineering, Balcali, Saricam, Adana, Turkey, pp. 1305-1313, 2010.

Bongermino, E., Mastrorocco, F., Tomaselli, M., Monopoli, V. G., Naso, D. 2017. “Model and Energy Management System for a Parallel Hybrid Electric Unmanned Aerial Vehicle,” Department of Electrical and Information Engineering, Politecnico di Bari, Italy, pp. 1687 – 1873, 2017.

Brown, S. 2017. “Design and Optimization of a 1 kW Hybrid Powertrain for Unmanned Aerial Vehicles,” Oregon State University, USA, pp. 8-13, 2017.

Ehsani, M., Gao, Y., Longp, S., Ebrahimi, K. 2018. “Modern electric, hybrid electric and fuel cell vehicles,” CRC Press, Taylor & Francis Group, pp. 113-132, 2018.

Mull, A., Nix, M. 2022 Perhinschi, “Powertrain Fuel Consumption Modeling and Benchmark Analysis of a Parallel P4 Hybrid Electric Vehicle Using Dynamic Programming,” Journal of Transportation Technologies, West Virginia University, Morgantown, USA, pp. 804-832, 2022.

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