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Human-machine Interaction Technology in Single Pilot Operation Mode

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Abstract:

With the intensification of the global pilot shortage, the single-pilot operation mode (SPO) has gradually become an important trend in the development of the aviation industry. This article provides a review of human-machine interaction technologies under the SPO mode, with a focus on discussing the application of key technologies such as multimodal interaction and immersive technology in enhancing the operational efficiency and safety of pilots. Through literature review and analysis of existing technologies, it reveals how these technologies play a role in reducing the cognitive load of pilots, optimizing information transmission, and enhancing pilots' situational awareness. This article also points out challenges such as technological maturity, information overload, and system security. Meanwhile, with the gradual improvement of technology and cross-domain innovation, the single-pilot driving mode will play a significant role in future aviation operations and promote efficient collaboration between pilots and intelligent systems, providing a guarantee for the enhancement of aviation safety and efficiency.

Keywords: SPO; human-machine interaction; multimodal interaction; immersive technologies

1. Introduction

The global aviation industry is under pressure from a shortage of pilots and rising operating costs. Data shows that the global shortage of civil aviation pilots will reach 340,000 by 2025. Under the background of the globalization of the aviation industry and the tight labor market, the Single Pilot Operations (SPO) model, as one of the important changes in the modern aviation industry, is gradually changing the traditional double pilot operation paradigm. With the progress of technology and the expansion of application scenarios, the central role of Human Machine Interaction (HMI) in SPO has become more and more prominent.

In the SPO mode, only one pilot is assigned to carry out the navigation mission, and the duties of a second pilot in the traditional sense are shared through a highly integrated automated system. This model will help reduce operating costs and improve flight efficiency and also effectively alleviate the growing shortage of pilots. HMI refers to the information exchange process between the pilot and the aviation system, including command input, data display and

decision support. An efficient HMI system can not only improve pilot efficiency, but also significantly enhance flight safety and task completion. However, in the practical application process, technical limitations, increased cognitive load and system reliability still restrict the further promotion and optimization of SPO mode [1].

This paper presents a systematic review of HMI technology in SPO mode. Firstly, the single pilot mode is introduced. Then some key HMI technologies in the SPO mode are introduced. Finally, it expounds the challenges of today's development and prospects for the future. This paper aims to provide theoretical support and reference for future SPO technology innovation and application.

2. Overview of the Single-pilot Operation Mode

With global urbanization and the approaching saturation of ground transportation, the number of flights will continue to increase in the coming years, and airlines and aircraft manufacturers are facing a severe shortage of pilots. One solution to the shortage of pilots is to reduce the number of pilots required for flights. The single-pilot operation mode improves economic efficiency and reduces cockpit resource allocation conflicts and pilot decision-making burdens, making it an important trend in future advanced air transportation.

Different from the other two modes, in SPO, the pilot controls the whole flight alone, which puts forward higher requirements for the safety and quality of the flight. In SPO mode, the pilot is supported by the ground operator and the automatic system in the cockpit in a tripartite cooperative operation mode to safely complete the long-range flight task. The airborne automation system is highly intelligent in SPO mode, which can monitor the pilot's driving specifications and physical states in real time, and ensure flight safety by adjusting the decision-making rights. Under normal conditions, the captain controls the aircraft with the assistance of the automatic system, and the ground operator conducts monitoring and other tasks with the help of the automatic system.However, in extreme cases (such as pilot failure, aircraft failure, extreme weather, etc.), the ground operator needs to take over from the pilot for remote driving with the assistance of the onboard automatic system to complete the flight task [1].

Therefore, HMI technology is an important support for the normal operation of the SPO mode. This article will focus on introducing some important HMI technologies in the SPO mode.

3. Human-machine Interaction Technology

3.1 Human-machine Interfaces Design

The role of HMI is particularly prominent in the SPO mode, because it is directly related to the pilot's situation awareness and operational efficiency. Despite the continuous improvement of automation, flight safety still depends on the correct understanding of information and timely decision-making of pilots, and interface design is the core to support this process. The rapid development of modern avionics has promoted the introduction of increasingly integrated and automated human-machine interfaces and interactions on aircraft boards, enabling the integration of multiple advanced systems in the cockpit. These technologies not only enhance the level of automation but also drive the transformation of the cockpit from manual operation to monitoring and management. However, increased automation does not completely eliminate risks caused by human factors; instead, it highlights the importance of HMI quality for flight safety [2].

Human-machine Interfaces (HMIs) are the medium and carrier of information interaction between Human and Machine. Its core is to transmit instructions and receive feedback through visual or physical operation, so as to improve the operation efficiency and safety of the system. Ismayilov[2] proposed a new concept of creating a virtual pilot assistant (VPA) for pilots' work on aircraft boards using a human-machine interface, and carried out the architecture of the VPA system after considering various options for realizing the HMIs and the interaction of avionics on the aircraft board shown in Fig.1. It helps relieve the stress of individual pilots in high-load environments by monitoring the flight status in real time and providing predictive prompts to the pilots. Predictably, the future of the HMIs not only is a tool for information transmission, more will become the pilot's intelligent collaboration partner, providing more solid safety guarantees for SPO mode.

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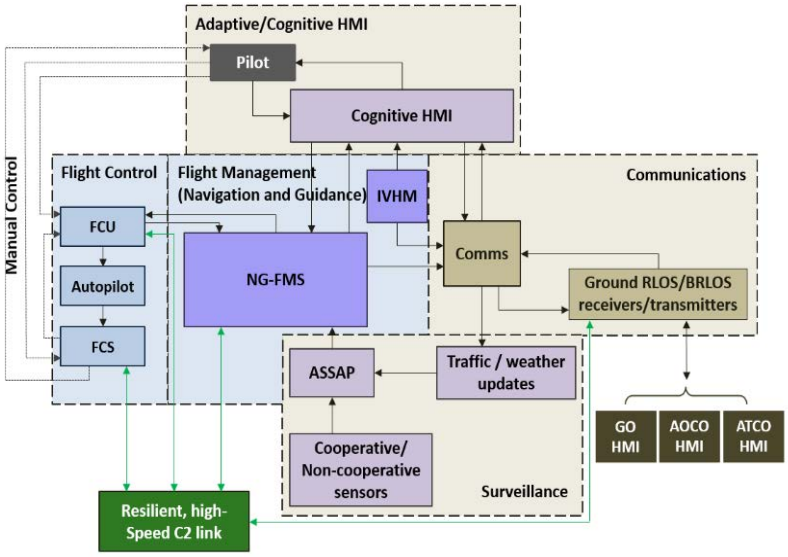

Fig. 1 VPA system architecture [2]

3.2 Multimodal Interaction Technology

Multimodal interaction technology is a form of human-machine interface, referring to a technical system that realizes natural HMI by integrating multiple sensory channels (such as vision, hearing, touch, gesture, etc.), simulating multi-dimensional human perception and expression methods, and enhancing interaction efficiency and experience.In gradually self-independence of automation and air environment, need to take various measures to improve safety, efficiency and decision-making ability. Dormoy et al. [3] emphasized the significance of multimodal collaboration assisted by cognitive computing to support human-machine intelligent collaboration within the SPO framework. Their review points out that multiple modalities can present information in the best way according to the specific requirements of the situation and task, which is crucial for effective human-machine interaction in SPO scenarios.

3.2.1 Voice interaction

In SPO mode, the voice interaction module, as an important component of multimodal interaction, provides pilots with a convenient interaction method that does not require manual operation. Speech recognition technology can realize control, input and query tasks in the cockpit by recognizing and analyzing the pilot's voice commands and converting them into control signals, and significantly improve the pilot's operation efficiency and flight safety [4-6].

Voice interaction technology can not only perform non-critical control functions with low real-time requirements, such as screen switching and mode selection, but also effectively relieve psychological pressure and enhance concentration when pilots fly alone for a long time, similar to the auxiliary role of the "virtual co-pilot" function.The progress of speech recognition technology, especially the application of deep learning algorithms, has greatly improved the recognition accuracy and stability. In the complex cockpit noise environment, the voice recognition system can effectively filter out background noise and accurately identify the pilot's instructions. For example, the control commands commonly used by pilots, such as adjusting altitude, speed, heading, etc., or calling up the aircraft system page, can be precisely performed by voice commands.With the improvement of aircraft automation, voice interaction can also assist pilots to operate various control switches, providing more auxiliary support for pilots [4-6].

In addition, the application of voice interaction systems also involves communication with air traffic controllers. By recognizing the instructions of controllers and converting them into text, voice recognition technology can help pilots reduce communication pressure and avoid misunderstandings caused by slips of the tongue. In the future, with the further development of speech recognition technology, voice assistants are expected to achieve a higher level of "human-computer dialogue", providing real-time flight data analysis, suggestions and decision support for pilots, thereby further optimizing the workflow and flight safety in SPO mode [4-6].

3.2.2 Gesture interaction

In SPO mode, gesture interaction technology, as an intuitive, flexible and highly efficient interaction method, provides pilots with more convenient control means.

Through visual recognition, data gloves or muscle electri-

cal signals, gesture recognition can accurately capture the pilot's hand movements and convert them into instructions for execution, which greatly improves the naturalness and convenience of interaction. Especially in the cockpit, the pilot's hand movements are frequent, so the gesture control is in line with the pilot's operating habits and can effectively reduce the dependence on physical keys and touch screens. At present, gesture recognition technology based on computer vision, which uses convolutional neural networks (CNNS) for feature extraction, has been able to accurately identify and track pilots' gestures, supporting various control operations during flight, such as adjusting instruments, switching views or regulating flight modes. This technology, when combined with data gloves, can further enhance the accuracy and flexibility of interaction [4-6].

Tran et al. [7] further explored innovative interaction methods, demonstrating the feasibility of gesture recognition through wrist-worn cameras. Their high precision results (98.85% precision, 97.40% recall) indicate that gesture-based HMI is highly unique and reliable, opening up new avenues for wearable interfaces and iot applications in the aviation field. Such technologies are expected to enhance pilots' situational awareness and control capabilities in SPO environments.

3.2.3 Eye movement interaction

Pilots obtain most of their information through vision. During flight, they need to continuously monitor the cockpit and the external field of vision to obtain key flight information. Eye movement interaction technology, as a non-invasive HMI method in SPO mode, can greatly enhance the operational efficiency and flight safety of pilots [4,5,8].

There is a close relationship between the pilot's eye movement and psychological state. The eye movement control system can automatically adjust the display content based on the position of the pilot's gaze and blink, such as blink trigger information display or operation confirmation, so as to improve the accuracy and response speed of the operation. Eye tracking technology can accurately identify the area or button of the pilot's gaze by capturing the real-time data of his eye movement. This technology can not only be used for the interaction between the pilot and the system, but also intelligently adjust the display interface to ensure that the pilot can always receive the key flight data, reduce the time and effort of information search, and avoid the omission or misreading of visual information. Eye movement interaction technology can also be combined with physiological monitoring to track the fatigue degree of pilots in real time. By monitoring physiological data of the eyeball, such as pupil diameter and blink frequency, fatigue warnings can be issued in time to ensure flight safety [4,5,8]. Through eye-movement interaction technology, pilots can select operation targets more quickly, reducing the complexity of traditional interaction methods. At the same time, it enhances pilots' situational awareness and operation accuracy, providing an important technical support for the future SPO mode.

3.3 Immersive Technology

Immersive technology provides a more intuitive and efficient user interface experience by superimposing virtual information onto the real world. The application of immersive technology in SPO, especially with the support of augmented reality (AR) and mixed reality (MR), has significantly enhanced the operation experience and training effect of pilots.By superposing virtual information into the real environment, AR technology provides more intuitive navigation and situation awareness support for pilots, and optimizes the interaction between pilots and the cockpit information system. For example, AR can help pilots improve environmental perception and enhance decision-making accuracy and reaction speed in critical flight links such as take-off and landing [9,10].

The integration of immersive technology has gradually been widely applied in the aviation field in recent years. Especially in the flight testing and training of advanced air mobility (AAM) and eVTOL aircraft, mixed reality (MR) technology, as a means to enhance the human-machine interface, provides a safe and risk-free training environment, simulating various flight scenarios and emergency situations. By optimizing the interaction between pilots and flight systems, these technologies not only help pilots improve their skills in the virtual environment, but also reduce training costs and carbon footprints, and improve pilots' situational awareness and responsiveness [11,12]. By applying these immersive technologies to pilot training and airspace management, not only can the skills of operators be enhanced, but also the safety and efficiency of the overall flight system can be effectively improved.

3.4 Artificial Intelligence Assistance

In the SPO mode, the introduction of artificial intelligence (AI) has greatly enhanced the decision-making ability and operational efficiency of pilots. AI helps pilots cope with complex flight environments through real-time data analysis, optimizing flight paths and managing air traffic. However, the true value of AI lies not only in its independent functions but also in its ability to collaborate with pilots. Effective human-machine collaboration requires AI to be able to understand the cognitive process of pilots and respond in real time according to their needs. This concept

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of "hybrid intelligence" provides support for the execution of complex flight missions by combining the computing power of AI with the judgment of pilots, especially when dealing with new types of aircraft such as eVTOL. As the complexity of air traffic management increases, the role of artificial intelligence in advanced air mobility (AAM) and urban airspace management has become increasingly prominent. In the future, seamless collaboration between AI and pilots will not only enhance flight safety but also improve pilots' situational awareness, enabling them to make more accurate decisions in complex environments and ensuring more efficient and safe human-machine interaction in the SPO mode [10].

The Co2Team (Cognitive Collaboration for Teaming) project proposed a Human intelligent Machine Team (HiMT), providing strong cognitive support for pilots. Especially when facing complex flight missions. The core concept of HiMT is to deeply collaborate artificial intelligence systems with pilots rather than relying solely on automation. Guided by the concept of "pilot in the loop", the AI system becomes the cognitive computing teammate of the pilot, assisting the pilot to make more effective decisions and ensure the achievement of flight objectives and flight safety. In this framework, the AI and the pilot maintain close interaction through two-way multimodal communication (MMC) shown in Fig. 2, which includes both verbal and non-verbal communication to ensure timely delivery and understanding of information. In emergency situations, pilots are no longer isolated, but are supported by intelligent systems that optimize pilot workload and improve safety margins. Studies show that a good communication and cooperation mechanism is crucial for the successful realization of SPO, especially in the cockpit environment with a high level of automation. The application of HiMT provides decision support for pilots and improves operational efficiency and flight safety [3]. Therefore, HiMT is not only the key technical support for SPO mode, but also the basis for efficient cooperation between future pilots and intelligent systems.

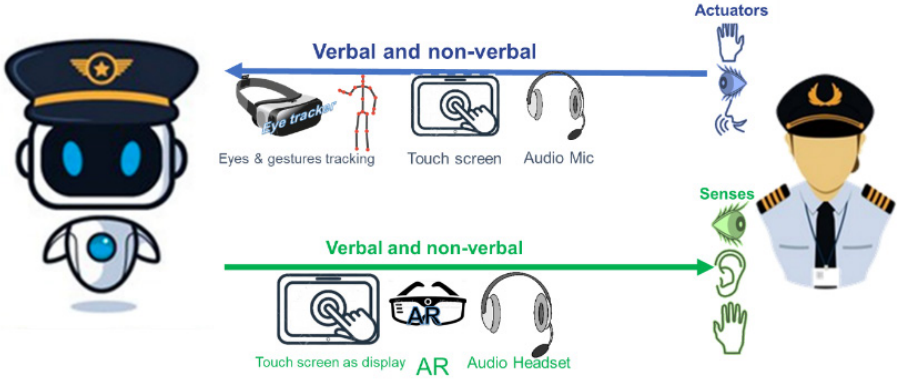

Fig. 2 Bi-directional MMC[3]

4. Challenges and the Future

In the SPO mode, although HMI technology has brought significant convenience and security improvements, it still faces many challenges.

The technologies mentioned above are related to artificial intelligence technology in different degrees, but the application of artificial intelligence in the field of civil aviation is very few, its certainty of flight is questionable, and the problem of trusted computing needs to be solved.

The development of some HMI technologies is still limited. For example, in complex flight environment, gesture recognition is still facing challenges. The diversity and complexity of gestures may lead to false recognition, which will bring operational distress to pilots. However, with the continuous advancement of technology, gesture recognition technology may be combined with AR technology in the future, providing a more intuitive and efficient interaction method. Gesture control technology based on computer vision, which captures and analyzes gestures by visual devices, can effectively generate control instructions, and combined with the stereo display window in AR, will greatly improve the interaction efficiency between pilots and aircraft [4,5].

Information overload and cognitive load optimization are the main problems in pilot operation. Pilots are prone to cognitive fatigue under the influence of high-intensity information flow. Therefore, how to reduce the cognitive burden of pilots through intelligent human-computer interface design has become the key to future development. Research on personalized and adaptive systems is becoming an important direction to alleviate this problem, which are able to adjust the presentation of information according to the pilot's operating habits and context, reducing

redundant and irrelevant information.

In addition, the reliability and security of the system also need to be guaranteed urgently. System failure in extreme environments can cause serious consequences, so more stringent safety standards and certification systems, such as ISO certification, need to be developed. With the popularization of information technology, data privacy and network security issues are increasingly prominent. To address the risk of data leakage, the application of blockchain and encryption algorithms offers new solutions.

In human-machine collaboration, the responsibility boundary between the pilot and the automated system is also a topic of concern. In particular, when the autonomous decision of AI (such as emergency avoidance operation) conflicts with the control of the pilot, how to balance the relationship between them and ensure that the pilot always has the final decision of flight control is still an unsolved ethical and legal issue. The EASA of the European Union has not yet established a unified regulatory framework, which leads to inconsistent technical standards worldwide. In the future, as these technologies are gradually perfected, the operation in SPO mode will be safer and more efficient, while providing a better flight experience.

5. Summary

This study reviews some of the key HMI technologies in SPO mode, pointing out the advantages and challenges of current technologies. These technologies are integrated to improve pilot efficiency and flight safety and promote the smooth implementation of SPO model. However, the development of these technologies still has many limitations, such as the error in gesture recognition, the cognitive burden of information overload, and the reliability and security issues of the system. This study provides important theoretical support for technological innovation and application under the SPO model, and offers references for future pilot training, flight system design and airspace management. The development of the SPO model will rely on the further integration and innovation of technologies. AI and automation systems will continue to evolve for more efficient collaboration with pilots. The application of multimodal interaction technology and immersive technology will provide pilots with a more intuitive and efficient operating environment, further enhancing flight safety. Despite challenges related to technological maturity, ethics, and law, interdisciplinary research will make SPO mode more viable, pushing the aviation industry toward greater efficiency and intelligence.

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