Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/147/2025.22591

# *Design of a Personalized Adaptive Human-Machine Interaction System for a Single Pilot*

**Aoyu Wang**

*School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China*
*waywang06@163.com*

***Abstract:*** With the rapid development of the aerospace industry, there is a trend towards transitioning from two-person to single-pilot crewing. However, to ensure safety during flight operations, it is crucial to adhere to the principle that the workload of a single pilot must not exceed safe limits while operating the aircraft. Therefore, this paper has designed a personalized adaptive adjustment system that can individually and autonomously analyze and adjust for different states and pilots, thereby reducing pilots' workload in real-time and ensuring flight safety. The system consists of three parts: the sensor endpoint, the analysis endpoint, and the adjustment endpoint. The sensor endpoint collects physiological and operational data from pilots during flight and preprocesses the data. The analysis endpoint analyzes the processed data to determine the pilot's state during flight and evaluate their operational behavior. Finally, the analyzed information is transmitted to the adjustment endpoint, which makes automated decisions based on the analysis, allowing for personalized and autonomous adjustments to the interaction mode and operational approach. This system effectively reduces pilots' workload during flight operations, thereby significantly enhancing flight safety.

***Keywords:*** Adaptive adjustment, Human-machine interaction, Personalization, Single Pilot, Multimodal

## 1. Introduction

As the aviation industry develops over recent years, the prevalence of aircraft has increased, yet the accident rate remains high. Despite continuous upgrades in equipment, the accident rate attributed to human factors has not decreased, and there is an inextricable link between excessive pilot workload and flight safety [1]. Therefore, as we transition from dual-pilot to single-pilot crewing, it is essential to ensure that the workload of pilots does not exceed safe limits.

Many methods have been developed to address this issue, including enhancing situational awareness and optimizing human-machine interaction. Techniques such as Augmented Reality (AR) [2], wearable augmented situational awareness devices [3], and the use of third-person perspectives [4] have significantly enhanced pilots' situational awareness. Additionally, Xia, Z [5] et al. proposed a multi-agent-based situational awareness analysis model to supplement situational awareness. Enhancing human-machine interaction [6, 7] remains a direction many teams are exploring. Wen-Chin [8] reduced pilot workload through enhanced visual display design in interactive displays, Prajapati [9] designed a physical human-machine interaction method for real-time adjustment, Sylvain, P [10] proposed a novel nonlinear interaction method to alleviate pilot workload, and Weiwei,

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DOI: 10.54254/2755-2721/147/2025.22591

Y [11] proposed an adaptive system to adjust interactions to reduce pilot workload. In summary, the current approach primarily focuses on enhancing situational awareness and optimizing interaction to reduce pilot workload.

This research focuses on the optimized design of an adaptive personalized interaction system, which consists of three core components: the sensor endpoint, the analysis endpoint, and the adjustment endpoint. The sensor endpoint is responsible for collecting pilots' physiological and operational data during flight and performing preliminary data processing. The analysis endpoint analyzes the processed data to assess the pilot's state during flight and evaluate their operational behavior. Finally, the analyzed results are transmitted to the adjustment endpoint, which makes automated decisions based on the analysis, enabling personalized and autonomous adjustments to the interaction mode and operational approach.

This system effectively reduces single pilot's workload, thereby reducing fatigue during operations and significantly lowering the likelihood of hazards during flight [12], which is crucial for reducing the rate of aviation accidents.

## 2. Sensor endpoint

To achieve personalized and adaptive adjustment, a triggering mechanism needs to be set up that activates the system and adjusts the interaction mode when certain conditions are met. Therefore, multimodal indicators are chosen as the triggering conditions. Due to the rapid development of sensing technology [13], a hybrid form of multiple sensors is adopted to monitor indicators during the pilot's flight. To assess the pilot's workload during flight, it is necessary to first collect physiological indicators and operational data from the pilot.

### 2.1. Physiological data collection

Multimodal data fusion is crucial for comprehensively studying the pilot's physiological state. To more effectively evaluate the pilot's workload, the following physiological data are collected: eye movement data, electrocardiogram (ECG) data, electroencephalogram (EEG) data, respiratory data, and skin conductance data, to lay the foundation for subsequent processing. These data serve as a foundation for subsequent processing and are gathered using appropriate sensors.

#### 2.1.1. Eye movement data

Electrooculography (EOG) is an eye movement tracking technology based on the potential changes between the anterior and posterior poles of the eye, utilizing the biological electrical signals of the eye. In recent years, the rapid development of EOG has significantly increased its accuracy and usage rate in eye movement tracking. By using EOG, eye movements in various directions can be detected, and the pilot's level of fatigue can be monitored, providing trigger information for subsequent interactions. The EOG during the flight process by deploying sensors on the pilot, allowing for the collection of blinking frequency.

#### 2.1.2. Electrocardiogram (ECG) data

The electrocardiogram (ECG) is an important diagnostic test for characterizing heart structure [14], and it is currently an essential method for evaluating the physiological state of the human body. By analyzing the pilot's ECG, critical parameters related to heart health are obtained [15], offering valuable insights into the pilot's heart health and physiological state. Primary indicators monitored within the collected ECG data include heart rate (HR) and heart rate variability (HRV). By assessing changes in HR and HRV, the current physiological condition of the pilot can be determined.

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#### 2.1.3. Electrocerebral (EEG) data

As an emerging technology, electroencephalography (EEG) is a technique that records electrophysiological signals within the brain by placing measurement electrodes in the brain, reflecting the electrophysiological activities of intracranial neurons [16]. By installing human-machine interfaces in pilots, electro signals in the pilot's brain are measured, capturing EEG activity. Different brain wave patterns exhibit distinct changes based on the pilot's state, allowing for the determination of the pilot's current condition through the collective analysis of wave content variations.

#### 2.1.4. Respiratory data

Monitoring the pilot's respiratory condition is of crucial importance during flight operations, as their respiratory state is directly related to the level of fatigue and current workload, and abnormal breathing during the flight can pose significant threats to flight safety. Therefore, respiratory frequency and oxygen saturation are measured using sensors to assess whether the pilot is in a normal physiological state.

#### 2.1.5. Skin conductance activity (EDA) data

Skin conductance activity (EDA) refers to a physiological signal that reflects the physiological state of the human body through changes in skin conductivity [17]. When the pilot's workload increases or fatigue accumulates, the pilot's physiological state and mood change, which can lead to changes in their skin conductance responses. Therefore, pilot status is assessed by detecting indicators such as skin conductance level and skin conductance response.

#### 2.1.6. Sensor management

Due to the increasing ease of sensor design for wearability and convenience in our layout, several wearable sensors have been selected to measure pilots' physiological data efficiently.For measuring pilots' electrooculograms (EOGs), wearable devices such as wristwatches are employed, ensuring that cardiac indicators are measured without disrupting the pilot's operations. Alternatively, wearable devices (such as watches) can be used to measure electrocardiograms (ECGs), which neither disrupt the pilot's operations nor interfere with the accurate measurement of cardiac indicators. When measuring EEGs, electrode caps are now available that integrate electrodes on a hat, allowing for long-term and accurate EEG measurements of the wearer. For respiratory measurement, wristband devices equipped with sensors can also be used. Skin conductance measurements can be conducted by attaching electrode patches to the skin. These methods of physiological measurement are convenient, comfortable, and do not impose additional workload on the pilots, making them ideal for gathering the required data.

### 2.2. Collecting operational data

Operational data collection involves the concurrent use of multiple sensors to gather data on the control stick usage and interactions with the interface panel, enabling the evaluation of the pilot's operational preferences and state. For control stick usage, displacement sensors are employed to measure the position and speed of the control stick movement, while force sensors are used to monitor changes in the force applied to the stick. Inertial measurement units are also utilized to detect the three-dimensional acceleration and angular velocity of the control stick. For interactions with the interface panel, pressure sensors are used to detect the pressure and frequency of physical button presses, while touchscreen interactions are monitored by collecting parameters such as touch gestures,

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touch force, and touch trajectory. Voice command interactions are tracked through microphone arrays, enabling directional detection of voice interactions between the pilot and the cabin system, as well as the collection of the pilot's commands. The gathered data provide a foundation for subsequent analysis.

## 3. Analysis endpoint

### 3.1. State determination based on physiological data

To accurately and precisely determine the pilot's state, it is essential to analyze the pilot's multimodal physiological data to determine the psychological state. By aligning the timestamps of the various data we collect, high-stress, fatigue, and normal states can be analyzed separately. When a pilot is in a high-stress state, we can observe frequent and irregular eye movements, accompanied by a significant increase in $\beta$ waves and the appearance of $\gamma$ waves in the EEG, an increased heart rate measured by the ECG, and a significant decrease in HRV. The skin conductance activity significantly increases, the respiratory rate accelerates, and irregular breathing patterns appear. For pilots in a fatigued state, the data show an extension of blink time and a slowing of eye movements. The EEG shows an increase in $\theta$ waves, and $\alpha$ and $\beta$ waves decrease significantly. The ECG shows a decrease in heart rate and HRV, and the skin conductance activity and respiratory rate slow down, indicating a decrease in physiological arousal. For pilots in a normal state, there is stable eye movement, higher $\beta$ waves, and moderate $\alpha$ waves, along with a stable heart rate and HRV within the normal range. Additionally, the skin conductance activity and respiratory rate are relatively stable. In summary, by detecting corresponding feature changes, multimodal signals can be used to more accurately determine the pilot's physiological state.

### 3.2. State analysis based on operational behavior

The analysis of data from the sensors enables the determination of the pilot's current state based on control stick usage and interactions with the interface panel. Force and frequency of control stick operations are analyzed, with high force and frequency typically associated with a high-stress state. Lower force and frequency, along with excessive invalid and repetitive actions, suggest fatigue. A normal state is indicated by smooth and continuous movement of the control stick. For interface panel analysis, a mixed analysis is performed, including indicators such as over-pressing physical buttons, lack of operations, rapid and irregular swiping on the touchscreen with a large contact area, and disorganized speech with a fast pace and loud volume in voice commands, which suggest a high-stress state. On the other hand, low and uneven pressure with frequent mis-operations on physical buttons, high error rates, sluggish touchscreen operations, repeated corrections, and smaller volume or ambiguous voice interactions suggest fatigue. In a normal state, accurate and decisive pressing actions, smooth touch trajectories, clear voice commands, and coordinated multimodal interactions are observed.

### 3.3. State analysis modeling

The analysis of the pilot's state employs a multimodal data integration approach, combining physiological and operational data for judgment. Physiological data, including eye movement, electroencephalogram (EEG), heart rate, skin conductance, and respiratory data, are collected using multiple sensors, while operational data, such as control stick movement and interaction behaviors, are also monitored. By analyzing both data types together, a more accurate assessment of the pilot's physiological state is achieved. The flowchart for the analysis endpoint is illustrated in Fig 1.

DOI: 10.54254/2755-2721/147/2025.22591

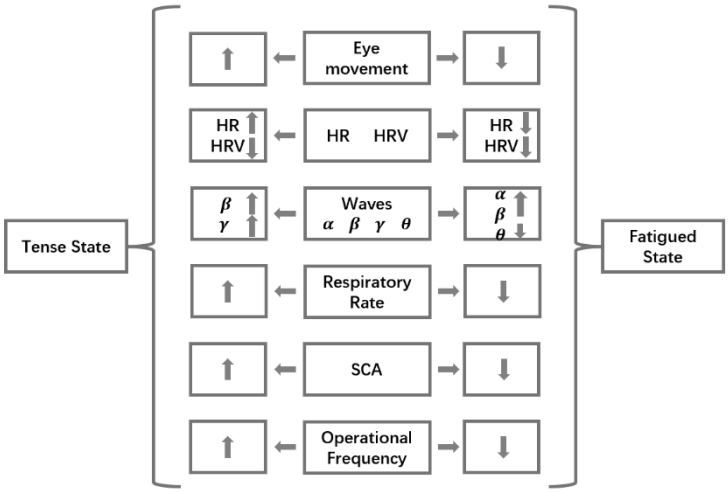



Figure 1: Modeling for pilot state assessment

## 4. Adjustment endpoint

### 4.1. Personalized adjustment for pilots

With changes in the environment, the system can make personalized adjustments to the pilot's state, based on both physiological conditions and operational behavior. In terms of physiological state, when fatigue or high stress is detected in the pilot, the interaction method can be personalized to make situational awareness more easily comprehensible, thereby reducing the current workload. Additionally, voice reminders can be used to help alleviate the psychological burden of fatigue or stress. In terms of operational behavior, adjustments to the interaction method and the trigger thresholds for physiological states can be made based on the pilot's past flying habits, reducing the pilot's adaptability to different aircraft and enabling more effective customization. In the design of personalized adjustments, the layout of the interaction interface can also be optimized based on the pilot's common interaction methods, which is beneficial for reducing the pressure caused by interaction during flight operations.

### 4.2. Adaptive adjustment of human-machine interaction

For pilots in different states, different adjustment methods are developed to enable adaptive regulation of the human-machine interaction between pilots and the cabin. Since pilots in a normal state can be considered to maintain the original interaction method, adjustments are analyzed from two perspectives: high-stress and fatigue states. When pilots are in a high-stress state, the workload needs to be reduced. The following steps are taken to adjust for pilots in high-stress and fatigue states. Through this closed-loop adjustment shown in Fig 2, the risks associated with increased workload during single-pilot operations can be effectively reduced.

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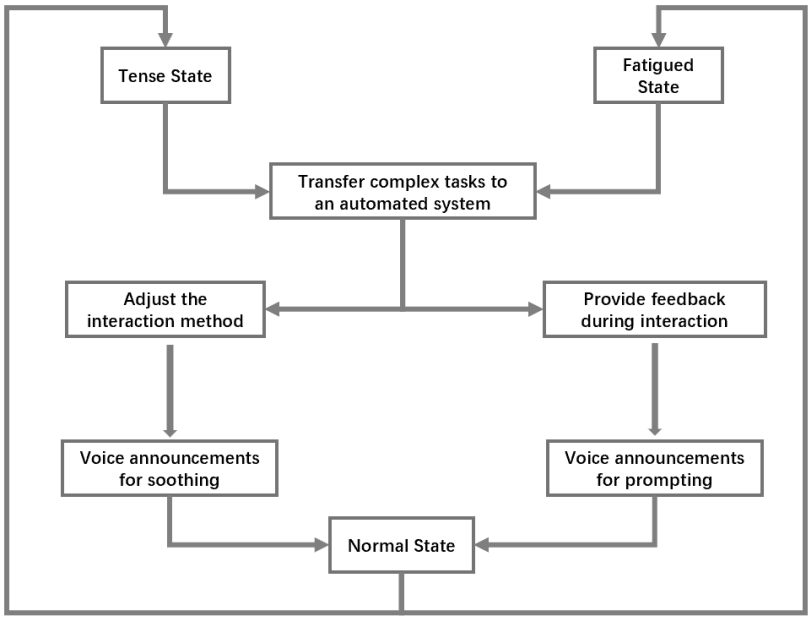



Figure 2: Adaptive human-machine interaction adjustment modeling

## 5. Conclusion

This paper presents the design of a personalized adaptive interaction system to regulate human-machine interaction during single-pilot flight operations. First, multiple sensors were combined to collect multimodal data, including physiological indicators and operational data, which were integrated as the foundation for state assessment. Second, during the analysis process, various collected signals were combined for comprehensive analysis. When multiple signals exhibit changes in the same direction, the pilot's state can be identified, ensuring that the state determined through the integration of multiple indicators is more accurate. Finally, the pilot's operational methods were personalized based on the collected operational preferences, and the determined pilot state was used to adaptively adjust the human-machine interaction, thereby reducing the single-pilot's workload and mitigating the dangers associated with flight, the specific workflow is shown in Fig 3. In the future, further research will focus on collecting pilot psychological and emotional data to assess psychological stress, enabling more precise control of the human-machine interaction form. At the same time, the system will transition from simulated to real flight operations to gather more authentic flight data, which will be beneficial for enhancing flight safety. Finally, a pilot flight database will be established, compiling operational behaviors during flight operations to enable customized design for each pilot, thereby significantly enhancing the pilot's adaptability and improving the safety of the flight process.

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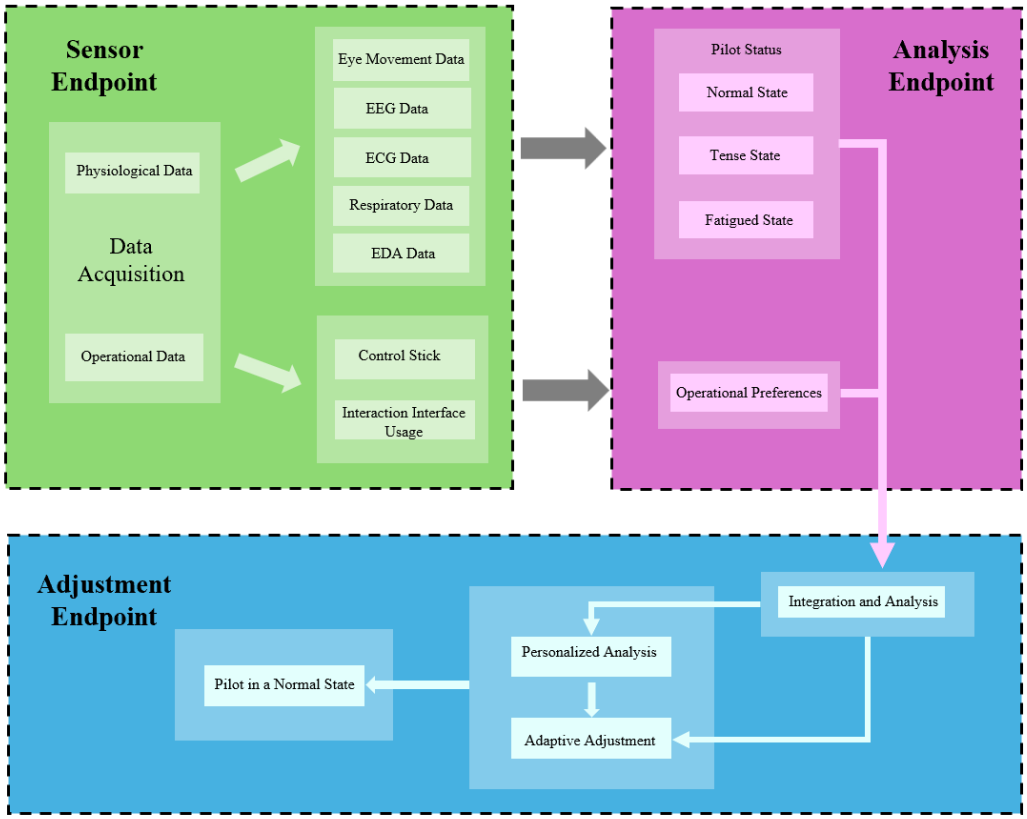



Figure 3: The workflow diagram

## References


[1] *Jordan, E., Rosemary Estevez, B., Chase, A., Xin-Qun, W., Ryan, K., Caley, K., Kyra, K., Nathan, S., & Wayne, T. (2024) 0329 Cleared for Takeoff: Sleep Leadership Training for Air Traffic Control Instructors, Sleep, 47*

[2] *Sara, B., Francesca De, C., Sergio, P., Carlo A., P., Mohamed, E., Alan R., G., & Jorge, H. (2020) Human-in-the-loop Evaluation of an Augmented Reality Based Interface for the Airport Control Tower, Computers in industry, 123*

[3] *Marlena R., F., Ahmed S., K., Mahlet, Z., Poom, P., Zahra, N., Sultan A., A., Igor, D., Bill, H., Son, T., & Phoebe O. Toups, D. (2020) Developing Future Wearable Interfaces for Human-Drone Teams Through a Virtual Drone Search Game, International Journal of Human-Computer Studies, 147: 102573-102573.*

[4] *Ryotaro, T., Kazuki, T., Kazuyuki, F., Koh, S., & Yoshifumi, K. (2019) Third-Person Piloting: Increasing Situational Awareness Using a Spatially Coupled Second Drone, ACM Symposium on User Interface Software and Technology: 507-519.*

[5] *Xia, Z., Youchao, S., Yanjun, Z., & Siyu, S. (2021) Multi-agent Modelling and Situational Awareness Analysis of Human-Computer Interaction in the Aircraft Cockpit: A Case Study., Simulation Modelling Practice and Theory, 111: 102355-102355.*

[6] *Amr, A., Mark van, H., & Antonio, F. (2022) Toward Physical Human-Robot Interaction Control with Aerial Manipulators: Compliance, Redundancy Resolution, and Input Limits, IEEE International Conference on Robotics and Automation*

[7] *Stephan, H., Johanna, G., Selina, P., Simon, M., Eliana, H., & Tobias, G. (2022) Toward User Experience in ATC: Exploring Novel Interface Concepts for Air Traffic Control, Interacting with computers, 34.2: 43-59.*

[8] *Wen-Chin, L., Andreas, H., Zhen, S., Jingyi, Z., & Graham, B. (2020) Augmented Visualization Cues on Primary Flight Display Facilitating Pilot's Monitoring Performance, International Journal of Human-Computer Studies, 135*

[9] *Prajapati, P., & Vashista, V. (2023) Aerial Physical Human Robot Interaction for Payload Transportation., IEEE Robotics and Automation Letters, 8.8: 4903-4910.*

DOI: 10.54254/2755-2721/147/2025.22591

[10] *Sylvain, P., Jean-Luc, V., Catherine, L., Alexandre, L., Claire, L., Timothée, L., Stéphanie, R., Valentin, B., & Guillaume, C. (2019) Multi-plié - A Linear Foldable and Flattenable Interactive Display to Support Efficiency, Safety and Collaboration., ACM Conference on Human Factors in Computing Systems: 154.*

[11] *Weiwei, Y., Dian, J., Feng, Z., & Xiaokun, Z. (2023) Towards Pilot's Situation Awareness Enhancement: A Framework of Adaptive Interaction System and Its Realization, ISA transactions, 132: 109-119.*

[12] *Yu-Hern, C., Hui-Hua, Y., & Wan-Jou, H. (2019) Effects of Work Shifts on Fatigue Levels of Air Traffic Controllers, Journal of Air Transport Management, 76: 1-9.*

[13] *Mohammad, J., Irvyne, A., Sara, K., Philippa, N., & Richa, P. (2022) Recent Advances, Opportunities, and Challenges in Developing Nucleic Acid Integrated Wearable Biosensors for Expanding the Capabilities of Wearable Technologies in Health Monitoring., Biosensors, 12.986*

[14] *Geoffrey H., T., Jeffrey, Z., Francesca N., D., & Rahul C., D. (2019) Automated and Interpretable Patient ECG Profiles for Disease Detection, Tracking, and Discovery., Circulation-cardiovascular Quality and Outcomes, 12.9*

[15] *Fred, S., & J P, G. (2017) An Overview of Heart Rate Variability Metrics and Norms., Frontiers in Public Health, 5.: 258.*

[16] *J. C., H. (2006) Electroencephalography: Basic Principles, Clinical Applications, and Related Fields, Fifth Edition, Neurology, 67.11: 2092-2092.*

[17] *Chao, W., Wansheng, L., Liang, W., Zhicheng, C., Zijian, H., Qingliang, L., Ziquan, G., Yuhan, S., Yuanjin, Z., Xinqin, L., & Zhong, C. (2023) Conformal Human–Machine Integration Using Highly Bending-Insensitive, Unpixelated, and Waterproof Epidermal Electronics Toward Metaverse, NANO-MICRO LETTERS, 15.1*