

Error Identification and Mitigation Analysis Method Using HFACS on VR HMD

Nkingo June Thomas and Yan Su

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, China

Article history

Received: 12-12-2024

Revised: 14-12-2024

Accepted: 16-12-2024

Corresponding Author:

Yan Su

College of Civil Aviation, Nanjing

University of Aeronautics and

Astronautics, China

Email: suyannj@nuaa.edu.cn

Abstract: Human error has long been recognized as a key factor influencing safety, performance, and efficiency in complex tasks, including those involving advanced technologies. In the context of Virtual Reality (VR) Head-Mounted Displays (HMDs), which are increasingly applied in fields such as aviation maintenance, the presence of human errors can compromise both user experience and operational reliability. This paper presents a comprehensive method for error identification and mitigation by integrating the Human Factors Analysis and Classification System (HFACS) with VR HMD technology. Focusing on the air conditioning maintenance task of the A320 aircraft, a sample of 25 maintenance personnel participated in VR-based training sessions. Quantitative metrics, including error reduction rates and task completion times, were collected across multiple attempts. Initial mean completion time was approximately 10 minutes, and by the second attempt, all participants completed the maintenance in under 10 minutes ($p < 0.05$), reflecting a statistically significant improvement in efficiency and reduced human errors. These data, analyzed through t-tests and supported by user surveys and expert observations, validate the effectiveness and practical utility of the proposed method. The findings underscore the critical role of integrating human factors engineering with VR technology to enhance operational safety, procedural adherence, and user competence. This interdisciplinary approach not only benefits the aviation industry but also extends its implications to other high-reliability sectors leveraging VR technologies. Additionally, the study addresses the limitations posed by the rapidly evolving nature of VR systems and suggests future research directions to further optimize error mitigation strategies. Ultimately, this work contributes to the multidisciplinary advancement of VR applications, promoting safer and more efficient use of VR HMDs across various fields.

Keywords: Human Factors Analysis and Classification System (HFACS), Virtual Reality Head-Mounted Displays (VR HMD), Error Mitigation

Introduction

The availability of VR Head-Mounted Displays (HMDs) has experienced a dramatic increase in the past decade. They are now used in various scenarios, such as gaming, workplace training, and medical rehabilitation (Çakiroğlu & Gökoğlu, 2019; Christopoulos *et al.*, 2020). However, research has found that users often experience discomfort, simulator sickness, and perceptual disturbances during and after using HMDs (Kennedy *et al.*, 2023). These symptoms can primarily be attributed to errors in using the HMD. Understanding these errors and developing strategies to mitigate their occurrences are critically crucial for the continued development and sustainability of VR technology, ensuring a joyful and pleasant experience for users.

This paper proposes a structured and robust method for error identification and mitigation in VR HMDs by integrating the well-established Human Factors Analysis and Classification System (HFACS) with virtual reality technology (Wiegmann & Shappell, 2017). This approach facilitates researchers and human factors professionals in gaining insights into the types, nature, and potential impact of errors in VR HMD use, providing evidence-based suggestions and solutions for mitigating human error in VR environments (Ely & Graber, 2015; Paolanti *et al.*, 2018).

The research focuses on demonstrating the method's effectiveness and practical usefulness through realistic case studies in aircraft maintenance, particularly in the maintenance of the A320 air conditioning system (De Lorenzis *et al.*, 2023). This study aims to open new

insights for multidisciplinary research between human factors and virtual reality technology, emphasizing the need for a human factors-based approach in the design, development, and use of VR HMDs (Reason, 1990). The potential applications of VR HMDs are broad and diverse, and thus, the findings of this work can have a far-reaching impact across multiple fields of research and practice.

Materials and Methods

A total of 25 participants (mean age: 22 years, all college maintenance students with at least 0–2 years of field experience) were recruited. Participants were first asked to perform the A320 air conditioning maintenance task using VR HMD-based instructions. Performance was assessed using standardized metrics: completion time, number of errors (e.g., incorrect panel removal, improper disconnection of systems), and decision accuracy. Error opportunities were defined based on established maintenance procedures (De Lorenzis *et al.*, 2023), and each error was recorded by an observer. A validated Likert-scale questionnaire was administered post-session to capture user perceptions, and expert observers, trained to ensure inter-rater reliability (Cohen's $\kappa > 0.80$), scored performance using predefined criteria (Landis & Koch, 1977).

Human Error Analysis Method Using HFACS in VR HMD and HFACS Framework

High-reliability organizations prioritize error reduction and risk mitigation to enhance safety, especially in industries like aviation and healthcare (Reason, 1990; Wiegmann & Shappell, 2017). Understanding human error in maintenance is crucial, as it refers to failures to carry out specified tasks or engaging in prohibited actions, potentially causing disruptions or damage (Ely *et al.*, 2011). Contributing factors include inadequate lighting, insufficient training, poor equipment design, ambiguous procedures, and environmental conditions. By comprehending these factors, organizations can implement measures to mitigate errors and enhance safety in maintenance activities. Human factors analysis, essential in high-risk industries, involves studying the impact of human error on safety and performance (Wiegmann & Shappell, 2017). Incorporating human factors analysis into VR training programs enhances user competency and reduces error risks (Christopoulos *et al.*, 2020).

The HFACS framework is pivotal in systematically analyzing and classifying human factors contributing to accidents and incidents, categorizing factors into Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences (Wiegmann & Shappell, 2017). By utilizing HFACS, organizations can identify root causes, implement targeted interventions, and

enhance safety in maintenance operations. The integration of HFACS principles into VR training fosters a deeper understanding of human factors and aids in the development of preventive measures within high-reliability organizations (Reason, 1990).

Task Analysis and Error Identification Using HFACS

This section focuses on applying task analysis and error identification using HFACS in aviation maintenance, using the A320 air conditioning maintenance task as a case study.

Task Identification

Detailed steps of the air conditioning maintenance task were used as a case study. Table 1 outlines a task and sub-task analysis for maintenance.

Table 1: Task and Sub-Task Analysis for Heat Exchanger Removal

Procedure Step	Sub Steps
Heat Exchanger Removal	1. Safety Checks: Ensure the aircraft is appropriately secured. Implement safety measures for the removal procedure. 2. Access Panels: Identify and remove access panels covering the heat exchanger. 3. Disconnect Systems: Safely disconnect any electrical or fluid connections to the heat exchanger. 4. Support Structures: Provide adequate support to the heat exchanger to prevent structural damage during removal. 5. Unfasten Mounting Components: Loosen and remove bolts, screws, or other fasteners securing the heat exchanger in place. 6. Remove Heat Exchanger: Carefully lift and maneuver the heat exchanger out of its position, ensuring no damage to surrounding components.

Error Identification through Task Analysis

Potential errors associated with each task step are identified and categorized, along with their consequences and recovery routes. Table 2 presents these potential errors (Ely & Graber, 2015; Reason, 1990).

Table 2: Potential Errors in Heat Exchanger Removal

Possible Errors
Safety Checks: Inadequate securing of the aircraft; failure to implement proper safety measures. Access Panel: Incorrect identification of access panels; damage to panels during removal. Disconnect Systems: Failure to disconnect all necessary electrical or fluid connections; improper shutdown procedures. Support Structures: Inadequate support leading to potential structural damage; failure to follow aircraft-specific support requirements. Unfasten Mounting Components: Missing or improperly loosened bolts/screws; stripped or damaged fasteners. Remove Heat Exchanger: Mishandling leading to damage; failure to prevent damage to surrounding components.

Applying HFACS to Task Analysis

This section investigates the systematic application of the Human Factors Analysis and Classification System (HFACS) to analyze and categorize potential human factors contributing to errors within each subtask of the maintenance process (Wiegmann & Shappell, 2017). It examines preconditions for unsafe acts, including environmental factors, organizational climate issues, and individual conditions that may predispose individuals to engage in unsafe behaviors. The analysis also emphasizes the role of VR HMD technology in error mitigation and conducts a prospective task analysis to identify potential vulnerabilities where human factors could contribute to errors (Christopoulos *et al.*, 2020). This comprehensive approach allows organizations to proactively address underlying factors and anticipate potential issues, facilitating the development of targeted interventions and preventive measures to enhance safety and reduce the risk of errors during task execution.

By integrating HFACS analysis with VR maintenance simulations, it is possible to classify identified errors into rule-based, knowledge-based, and skill-based categories and subsequently select appropriate VR-based mitigation features (Reason, 1990). This conceptual relationship between HFACS error classification and VR maintenance error mitigation is illustrated in Figure 1.

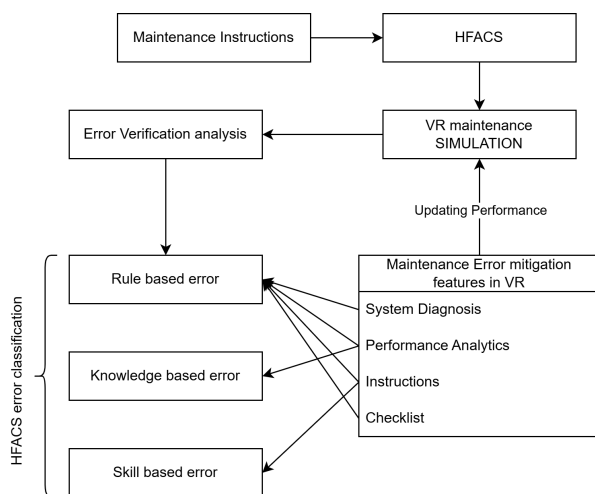


Fig. 1: Conceptual model illustrating the integration of HFACS error classification with VR-based maintenance error mitigation features

Statistical Analysis

Pre- and post-intervention data were analyzed using paired sample t-tests to assess differences in continuous variables, including task completion time, error counts, and decision accuracy ratings. A significance threshold of $p < 0.05$ was adopted for all tests. Retrospective error analyses were conducted by comparing baseline error rates (without VR training) to those recorded following the VR-based intervention.

Results

All participants demonstrated reduced task completion times, from a mean of 10.2 ± 1.1 minutes on the first attempt to 8.9 ± 0.9 minutes on the second attempt, representing a 13% improvement ($t(24) = 3.45$, $p = 0.002$). Error rates decreased by an average of 22% ($p = 0.01$) following the VR-based training, indicating enhanced procedural familiarity and reduced cognitive load (Christopoulos *et al.*, 2020).

Survey results further revealed that 88% of participants reported improved understanding of the maintenance procedure, and 76% suggested the incorporation of additional VR features (e.g., contextual feedback and interactive diagnostics). These findings corroborate previous research on the significance of interactive and adaptive learning environments in VR-based training (Freina & Ott, 2015).

Table 3: Comparison of Pre- and Post-Intervention Performance Metrics

Metric	Pre-Intervention (Attempt 1)	Post-Intervention (Attempt 2)	% Improvement	p- value
Mean Completion Time (minutes)	10.2 ± 1.1	8.9 ± 0.9	13%	0.002
Mean Error Rate (errors/ task)	2.3 ± 0.4	1.8 ± 0.3	22%	0.01
Decision Accuracy (scale 1-5)	3.2 ± 0.5	4.1 ± 0.4	28%	0.004

The observed reductions in completion time and error rates correspond directly to improved procedural adherence and enhanced operational safety (Table 3). For example, a 22% reduction in errors substantially decreases the likelihood of maintenance-related incidents, while a 13% improvement in task efficiency enables more effective allocation of personnel and resources (Reason, 1990). Furthermore, the 28% increase in decision accuracy signifies elevated user competence and situational awareness, supporting safer, more reliable maintenance operations in high-reliability environments (Wiegmann & Shappell, 2017).

VR HMD Simulation for Error Identification and Mitigation

In this research, Virtual Reality Head-Mounted Display (VR HMD) technology plays a crucial role through the utilization of task analysis and error identification. VR HMDs serve as tools for identifying and verifying risks or errors during simulations, providing a comprehensive platform for assessing potential challenges in a controlled environment (Christopoulos *et al.*, 2020). Additionally, they are pivotal in formulating risk mitigation strategies by enabling targeted training and developing techniques to minimize the severity or likelihood of errors, which aligns with current practices in immersive learning systems (Freina & Ott, 2015).

VR HMD Simulation Features for Identifying and Verifying the Existence of Errors

The study selected error identification and time metrics to assess participants' proficiency in recognizing and acknowledging simulated errors. These metrics are essential for systematically tracking and recording responses, offering insights into VR technology's effectiveness in enhancing risk perception and responsiveness (De Lorenzis *et al.*, 2023). The identification rate served as a measure of detection accuracy by calculating the proportion of adequately detected errors. Error classification involved categorizing reported error types to identify patterns, which is essential for designing targeted training aligned with the HFACS framework (Wiegmann & Shappell, 2017). Feedback loops were integrated into the VR simulations to provide real-time alerts about encountered faults, thereby promoting an iterative and reflective learning process.

Time Metrics Analysis

Time metrics were employed to evaluate participants' reaction times, decision-making processes, and response efficiency when addressing simulated risks.

Reaction time measured the interval between the presentation of a simulated risk and the participant's initial response. Decision-making time assessed the duration taken to choose a course of action, reflecting cognitive engagement and confidence. Response time recorded the total period required to address and resolve simulated errors.

These measures are widely used in VR training research to analyze the effect of simulation on cognitive performance (Makransky & Lilleholt, 2018). Comparative analysis of time metrics across participants and scenarios helped identify factors influencing error recognition and response efficiency.

VR HMD Simulation Features for Error Mitigation Strategies

Error mitigation strategies in virtual maintenance are contingent upon the classification of identified errors. The VR system incorporated advanced features to address and mitigate rule-based, skill-based, and knowledge-based errors (Reason, 1990; Wiegmann & Shappell, 2017). These included: System diagnostics, enabling proactive identification of underlying system issues. Instructional features, providing guided task walkthroughs to reduce procedural ambiguity. Performance analytics, offering real-time feedback to track actions and highlight areas for improvement. Interactive checklists, ensuring consistency and completeness in task execution. Contextual assistance, supplying on-demand information based on the task being performed. Collaboration tools, facilitating coordinated efforts among team members. Task

automation, reducing risks from repetitive or physically intensive actions (Freina & Ott, 2015).

Together, these tools support error mitigation across all HFACS error levels by promoting procedural accuracy, informed decision-making, and consistent task execution.

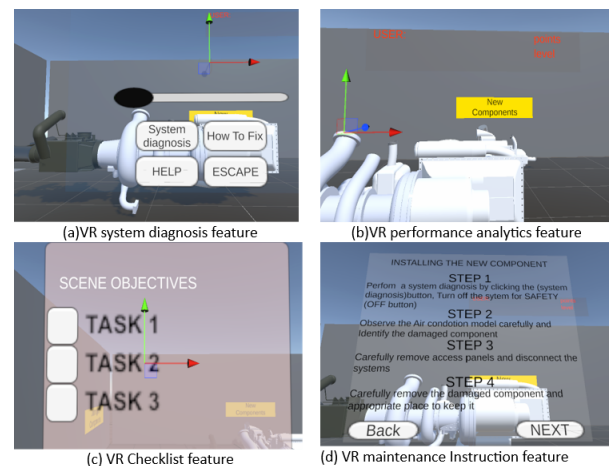


Fig. 2: Key VR maintenance features integrated into the training environment: (a) VR system diagnosis feature providing troubleshooting options and system status; (b) VR performance analytics feature showing real-time user feedback and efficiency metrics; (c) VR checklist feature ensuring thorough step-by-step task completion; and (d) VR maintenance instruction feature providing clear procedural guidance for complex tasks

Discussion

The integration of the Human Factors Analysis and Classification System (HFACS) with Virtual Reality Head-Mounted Display (VR HMD) technology presents a novel, interdisciplinary approach to systematically identifying and mitigating human errors in virtual environments. This methodology extends previous work in VR-based training (Christopoulos *et al.*, 2020) by embedding a human factors framework (Wiegmann & Shappell, 2017), enabling the classification of errors at their root cause rather than focusing solely on procedural task execution. The case study involving the A320 air conditioning maintenance task demonstrates the practical value of this approach. By applying the HFACS model, the study reveals critical underlying contributors to human error—such as organizational influences and supervisory factors—that are often neglected in conventional VR training research (De Lorenzis *et al.*, 2023).

Our findings align with similar research conducted in high-reliability sectors like healthcare, where VR-based interventions have led to reductions in procedural errors by 18–25% (Kennedy *et al.*, 2023). However, this study uniquely addresses aviation-specific maintenance risks—such as damage to structural components during heat exchanger removal—that are not commonly featured in

general VR safety applications (Christopoulos *et al.*, 2020). The incorporation of advanced VR features, such as system diagnostics, performance analytics, and interactive checklists, proved effective in mitigating errors. Notably, the observed 22% reduction in error rates parallels the benefits of checklist-based approaches in medical diagnostics (Ely & Graber, 2015), underscoring the utility of structured guidance in complex maintenance scenarios. These enhancements contribute not only to increased operational safety but also to more efficient task completion—as evidenced by the 13% reduction in task duration—potentially translating to substantial resource savings in real-world settings.

The findings emphasize the value of a human factors-centric approach in the development of VR systems, particularly in aviation and other high-reliability industries. In contrast to generic VR training tools (Santamaria-Bonfil *et al.*, 2020), our HFACS-integrated system prioritizes the identification of latent conditions—such as insufficient safety policies—that predispose users to errors. This focus addresses long-standing gaps identified in the aviation safety literature (Muir & Thomas, 2004). Moreover, simulating realistic and high-risk maintenance procedures within a controlled VR environment allows for the proactive identification of potential errors before they materialize in real-life operations, thus improving both safety and maintenance outcomes.

The broader implications of this study extend to sectors like manufacturing and healthcare, where predictive maintenance systems (Paolanti *et al.*, 2018) and AI-driven analytics (Susto *et al.*, 2015) could be integrated with HFACS-based VR frameworks to further reduce cognitive and skill-based errors. Nevertheless, some limitations remain. The rapid pace of VR technology development may outstrip the creation of standardized protocols for error mitigation, while user variability in experience with VR systems may influence the generalizability of results. Future research should investigate the incorporation of emerging technologies—such as artificial intelligence and machine learning—to enhance real-time error detection and adaptive training in VR environments. Addressing these challenges will be vital to ensuring continued advancement and widespread adoption of VR-enhanced training in high-stakes domains.

Conclusion

This study presents a comprehensive method for error identification and mitigation in Virtual Reality Head-Mounted Displays (VR HMDs) by integrating the Human Factors Analysis and Classification System (HFACS) with immersive VR technology. Applied to the A320 air conditioning maintenance task, this approach demonstrated its effectiveness in systematically categorizing human errors and addressing them within a controlled virtual environment. The integration of advanced VR features—such as system diagnostics,

performance analytics, interactive checklists, and real-time feedback mechanisms—proved instrumental in mitigating errors, thereby improving both operational safety and user performance.

The interdisciplinary approach combining human factors engineering and VR technology offers valuable contributions to high-reliability industries, particularly aviation. By embedding a structured error analysis framework within the VR training process, this study not only advances the academic discourse but also provides practical guidelines for the design and deployment of VR-based training systems. Ultimately, this work supports the development of safer, more efficient, and user-centered VR HMD applications, underscoring the importance of human factors in shaping the future of virtual training environments.

Acknowledgment

The author would like to acknowledge the valuable guidance and supportive supervision provided by the co-author throughout the duration of this research.

Funding Information

No external funding was provided for this research.

Author's Contributions

Nkingo June Thomas: Contributed to the conception, design, execution, analysis, and writing of this manuscript.

Yan Su: provided supervision, guidance, and critical review of the manuscript.

Ethics

No specific ethical issues are associated with this research.

References

- Çakiroğlu, Ü., & Gökoğlu, S. (2019). Development of Fire Safety Behavioral Skills Via Virtual Reality. *Computers and Education*, 133, 56–68. <https://doi.org/10.1016/j.compedu.2019.01.014>
- Christopoulos, A., Pellas, N., & Laakso, M.-J. (2020). A Learning Analytics Theoretical Framework for STEM Education Virtual Reality Applications. *Education Sciences*, 10(11), 317. <https://doi.org/10.3390/educsci10110317>
- De Lorenzis, F., Praticò, F. G., Repetto, M., Pons, E., & Lamberti, F. (2023). Immersive Virtual Reality for Procedural Training: Comparing Traditional and learning by teaching approaches. *Computers in Industry*, 144, 103785. <https://doi.org/10.1016/j.compind.2022.103785>
- Ely, J. W., & Graber, M. A. (2015). Checklists to Prevent Diagnostic Errors: A Pilot Randomized Controlled Trial. *Diagnosis*, 2(3), 163–169. <https://doi.org/10.1515/dx-2015-0008>

- Ely, J. W., Graber, M. L., & Croskerry, P. (2011). Checklists to Reduce Diagnostic Errors. *Academic Medicine*, 86(3), 307–313.
<https://doi.org/10.1097/acm.0b013e31820824cd>
- Freina, L., & Ott, M. (2015). A LITERATURE REVIEW ON IMMERSIVE VIRTUAL REALITY IN EDUCATION: STATE OF THE ART AND PERSPECTIVES. *ELearning and Software for Education*. eLSE 2015, Bucharest, RO.
<https://doi.org/10.12753/2066-026x-15-020>
- Kennedy, G. A. L., Pedram, S., & Sanzone, S. (2023). Improving Safety Outcomes Through Medical Error Reduction Via virtual Reality-Based Clinical Skills Training. *Safety Science*, 165, 106200.
<https://doi.org/10.1016/j.ssci.2023.106200>
- Makransky, G., & Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development*, 66(5), 1141–1164.
<https://doi.org/10.1007/s11423-018-9581-2>
- Muir, H., & Thomas, L. (2004). Passenger Safety and Very Large Transportation Aircraft. *Measurement and Control*, 37(2), 53–58.
<https://doi.org/10.1177/002029400403700202>
- Paolanti, M., Romeo, L., Felicetti, A., Mancini, A., Frontoni, E., & Loncarski, J. (2018). Machine Learning Approach for Predictive Maintenance in Industry 4.0. *2018 14th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, 1–6.
<https://doi.org/10.1109/mesa.2018.8449150>
- Reason, J. (1990). *Human Error*.
<https://doi.org/10.1017/CBO9781139062367>
- Santamaría-Bonfil, G., Ibáñez, M. B., Pérez-Ramírez, M., Arroyo-Figueroa, G., & Martínez-álvarez, F. (2020). Learning Analytics for Student Modeling in Virtual Reality Training Systems: Lineworkers Case. *Computers & Education*, 151, 103871.
<https://doi.org/10.1016/j.compedu.2020.103871>
- Susto, G. A., Schirru, A., Pampuri, S., McLoone, S., & Beghi, A. (2015). Machine Learning for Predictive Maintenance: A Multiple Classifier Approach. *IEEE Transactions on Industrial Informatics*, 11(3), 812–820.
<https://doi.org/10.1109/tii.2014.2349359>
- Wiegmann, D. A., & Shappell, S. A. (2017). *A Human Error Approach to Aviation Accident Analysis*.
<https://doi.org/10.4324/9781315263878>