

Human Factor Considerations in the Implementation of IVHM

RATIONALE

Integrated vehicle health management (IVHM) capabilities are increasingly being implemented, in whole or in part, on aerospace fixed-wing vehicles. These capabilities furnish diagnostic and prognostic information regarding the vehicle state. The information provided to the human in the loop should be unequivocal with clear instructions to avoid unexpected and potentially dangerous situations. This document provides information concerning human factors and safety considerations regarding future IVHM systems. The information in this SAE Aerospace Information Report (AIR) is also intended to be of assistance to IVHM design engineers by providing illustrative examples of real-life catastrophic events which could have been mitigated by elements of an IVHM capability.

INTRODUCTION

IVHM has evolved significantly in recent years. Initial concepts involving this system of systems approach were oriented to it being primarily a tool to aid vehicle maintenance, specifically condition based maintenance (CBM). Synthesis of data from various systems provides diagnostic information to enable the maintainer and the operator to optimise their respective tasks. Further development and refinement of algorithms has led to significant prognostic capability in recent IVHM systems. Use of the data from IVHM systems will enable vehicle level reasoning systems. Such systems may allow prioritization of cockpit warnings to the crew, thus relieving operational pressure and stress, particularly in times of high work load, such as an emergency.

The cause of many commercial aviation accidents in recent years has been related to human error. The impact of the human error has been well documented and supported through reports issued by the regulatory authorities. Therefore, in an effort to reduce the impact of human errors, lessons should be drawn from the warnings and the behavior of the crew as they have reacted to alerts in critical situations.

While the functions and performance of individual components of the monitoring system are well understood, these components are only beginning to be considered at the higher level of a complete, integrated vehicle health management (IVHM) system. With increased complexity comes greater potential for error, induced by the fact that the human mind is incapable of comprehending all the possible permutations and combinations of sensory inputs and computed outputs. Hence, misinterpretation of IVHM system outputs can lead to unexpected consequences which may be severely disruptive.

For example, loss of control has been determined to be one of the main causes of several incidents and accidents involving large transport category aircraft. Also, information overload in the cockpit of commercial aircraft during emergencies is a serious concern, which has been the cause of several aircraft accidents.

Human factors may be broken down into two main subject areas: those affecting the concept, execution, and intended usage of the monitoring system itself, and those that are caused by human interaction and communication with the system and surrounding user environment.

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Many conferences and university courses are held on these topics, but their influence on the design and operation of monitoring systems has not been of great importance in the past. As these systems become more ubiquitous, this situation will change.

This document discusses the considerations concerning the pilot and maintenance staff, both military and civil. The issue of false information and some case studies are also included.

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1. SCOPE

This SAE Aerospace Information Report (AIR) offers information on how human factors should be considered when developing and implementing IVHM capabilities for both military and civil fixed wing aircraft. These considerations will cover the perception, analysis, and action taken by the flight crew and the maintenance personnel in response to outputs from the IVHM system. These outputs would be onboard realtime for the flight crew and post flight for maintenance. This document is not intended to be a guideline; it is intended to provide information that should be considered when designing and implementing future IVHM systems.

1.1 Purpose

The purpose of this document is to provide information on human factors when developing and implementing IVHM capabilities for fixed-wing aircraft.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AS6296 Electronic Flight Instrument System (EFIS) Displays

AS8034 Minimum Performance Standard for Airborne Multipurpose Electronic Displays

R-441 No Fault Found: The Search for the Root Cause

2.1.2 Other Publications

1. Wickens, C. (1992), Engineering Psychology and Human Performance, Harper Collins Publishers, Illinois, USA.
2. Wogalter, M., DeJoy, D., and Laughery, K. (Eds.), (1999). Warnings and risk communication - Chapters 3 and 4 - Methodological considerations for research on warnings, Taylor and Francis Inc. Philadelphia.
3. Swedish Airforce journal Flygdags, No. 1, 2018.
4. Report of the C-130 Broad Area Review (January 1998), retrieved from <https://fas.org/man/dod-101/sys/ac/docs/c-130-bar.htm>, as of September 21, 2018, also available at <https://www.scribd.com/document/54327304/C-130-Broad-Area-Review> (with a user account). Compilation of information, retrieved from <http://www.usdeadlyevents.com/1996-nov-22-usaf-hercules-engine-loss-and-crash-pacific-cape-mendocino-ca-10/>, as of September 21, 2018.
5. HMSO London, Department of Transport, Aircraft Accident Investigation Report 4/90.
6. Bureau d'Enquetes et d'Analyses pour la securitie de l'aviation civile, Final Report published July 2012. F-GZCP - 1st June 2009.
7. National Transportation Safety Board NTSB/AAR-10/03, PB2010-910403.
8. National Transportation Safety Board NTSB/AAR-02/01.

9. Accident of the Boeing 757-200 Aircraft Operated by Empresa de Transporte Aereo del Peru S.A. Aeroperu, www.skybrary.aero/index.php/B757_Series. Edited 13 October 2014.
10. National Transportation Safety Board NTSB/AAR-84/04.
11. Scandura, P.A. Jr. and Garcia-Galan, C., "A Unified System to Provide Crew Alerting, Electronic Checklists and Maintenance Using IVHM," IEEE 23rd Digital Avionics System Conference, October 2004.
12. FAA 14 CFR 25.1309.
13. FAA AC 25-1309.
14. EASA CS25.1322.
15. EASA AMC 25.1322.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

R-438 Integrated Vehicle Health Management: Implementation and Lessons Learned

2.2.2 Other Publications

ASD STE-100 Simplified Technical English.

The Operators Guide to Human Factors in Aviation (OGHFA).

Brombacher, A.C., Sander, P.C., Sonnemans, P.J., and Rouvroye, J.L., "Managing Product Reliability in Business Processes 'Under Pressure,'" Reliability Engineering & System Safety, Vol. 88, Issue 2, May 2005, pp. 137-146.

FAA Human Factors Guide for Aviation Maintenance and Inspection.

Hawkins, F.H., Human Factors in Flight, 2nd edition, Aldershot, UK: Ashgate, 1987.

Hockley, C.J., Hubby, G.M., James, I.J.P., Fedrick, V.F., et al., 2016, "No-Fault Found - A Best Practice Guide," Cranfield University.

Khan, S., Phillips, P., Jennions, I., and Hockley, C., "No Fault Found Events in Maintenance Engineering Part 1: Current trends, implications and organizational practices," Reliability Engineering & System Safety, Vol. 123, March 2014, pp. 183-195.

Knotts, R.M., "Civil Aircraft Maintenance and Support Fault Diagnosis from a Business Perspective," Journal of Quality in Maintenance Engineering, Vol. 5, Issue 4, 1999, pp. 335-348.

Pickthall, N., "Contribution of Maintenance Human Factors to No Fault Finds on Aircraft Systems Engineering," Proceedings of the 3rd International Conference in Through-life Engineering Services, November 4-5, 2013, Cranfield, UK.

Sauer, J., Hockey, G.R., and Wastell, D.G., "Effects of Training on Short- and Long-Term Skill Retention in a Complex Multiple-Task Environment," Ergonomics 43(12):2043-64, 2000.

Singer, G. (2002), Methods for Validating Cockpit Design: The Best Tool for the Task, Department of Aeronautics, Royal Institute of Technology, Sweden.

Wise, J.A., Hopkin, V.D., and Garland, D.J., Handbook of Aviation Human Factors, 2nd Edition, CRC Press, 2009.

2.3 Definitions

FALSE NEGATIVE: Not indicating a fault when one does exist.

FALSE POSITIVE: Indication of a fault when one does not exist.

HUMAN FACTORS: Human factors is used in this document to mean the humans perception, analysis, and action taken from the provided IVHM information.

INTEGRATED VEHICLE HEALTH MANAGEMENT (IVHM): IVHM is used in this document to mean an onboard system of systems that should be capable of prioritizing cockpit warnings to the flight crew, and providing useful diagnostic and prognostic information to the maintainer.

NO FAULT FOUND (NFF): The outcome of a subsequent investigation which did not confirm an assignable cause for an onboard fault notification.

PROGNOSTIC HEALTH MANAGEMENT (PHM): The ability to predict impending faults and to determine remaining useful life.

3. HUMAN FACTORS CONSIDERATIONS

The effectiveness of humans in operating any machine or system is impacted by several main aspects:

- Human conditions (physical, knowledge, attitude, culture, stress, experience)
- System conditions (tools, equipment, workspace, procedures, policies, manuals)
- Environmental conditions (weather, noise, economic, teamwork, leadership)

The human-machine interface context can be defined as: the information provided to humans, how humans respond to the information, and the machine's feedback to the response of the human. A human error could result directly from an incorrect human response to the machine or could result from a chain of events that involves multiple responses and feedbacks involving both human and machine.

From the IVHM context, the human's response to the information generated by an IVHM system (e.g., realtime alerts, troubleshooting and maintenance actions), and the aircraft systems' feedback to the responses is the focus of this document. Essentially, the human-machine interface under the context of IVHM information exchange is the scope for this AIR. Figure 1 shows the scope of the human-machine interface in the context of IVHM considerations.

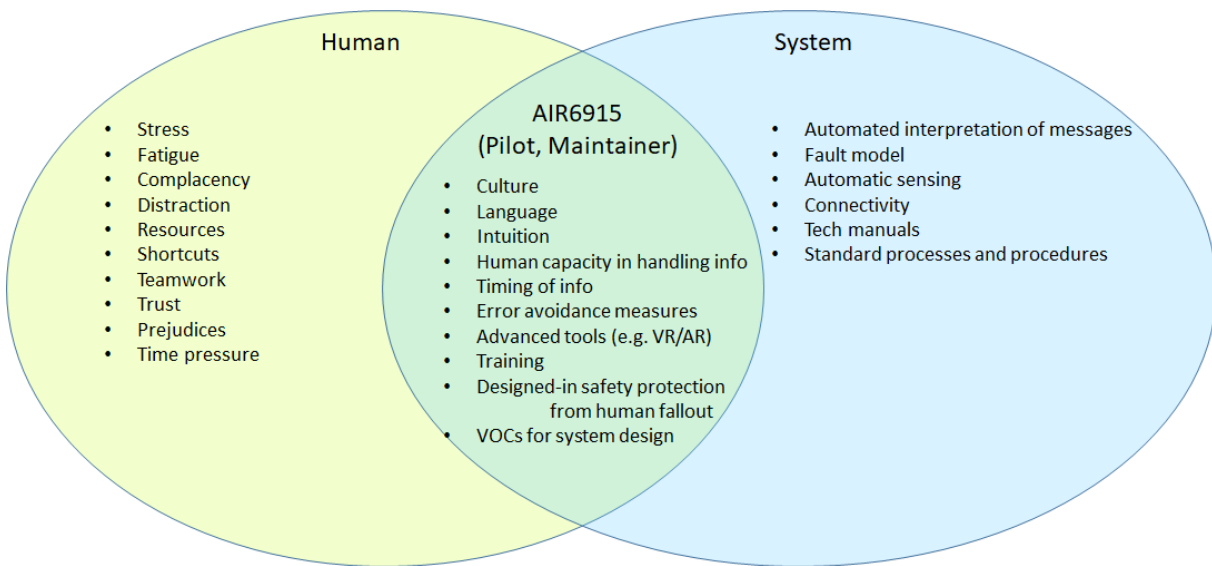


Figure 1 - Human-machine interface in the IVHM context

This document is focused on two types of users: flight crew (pilot) and maintenance crew (maintainer). The factors that may create errors when pilots and maintainers respond to the IVHM alerts and troubleshooting/maintenance actions include:

- **Culture:** Given a machine indication or command, people from different cultures may respond differently. The IVHM messages need to be tuned based on culture.
- **Language:** How users respond to the language used, including accuracy of translation and terminologies, may impact the resulted actions.
- **Intuition:** The IVHM messages and interfaces need to be designed so that it follows a normal human being intuition for reactions.
- **Human capacity in handling information:** The number of IVHM messages need to be limited to no more than the maximum number that can be handled at one time.
- **Timing of the information:** The IVHM messages should be tuned to a human response time, e.g., enough lead time before failure for human response, and displayed for a long enough time for a human to be able to capture it.
- **Error avoidance measures (designed-in safety measures):** The IVHM system should be designed so that foreseeable failures by a human are prevented.
- **Advanced tools:** The IVHM system should utilize advanced tools to simplify the responsive actions and increase convenience of executing actions.
- **Training:** For human failures that are hard to prevent by design, provide training to improve user knowledge and experience to mitigate the impact of those failures.
- **Voice of the Customer (VOC) for system design:** Fully understand the users' needs when designing human-IVHM system interfaces.

3.1 Role of IVHM - Historical Perspective

As IVHM grows in popularity, the situational awareness it may provide with respect to aircraft health and status make it tempting to include IVHM in the active operation of the aircraft, by making the information available to the flight crew for decision making. Before doing so, however, it is important to understand the implications of this approach by reviewing the historical perspective (for more information, see Reference 11).

Civil and military aircraft have traditionally used two separate and distinct systems for communicating aircraft health and status. For the flight crew, the crew alerting system (CAS, sometimes referred to as the caution and warning system) provides this function. For the aircraft maintainer, the onboard maintenance system is used. While both systems provide similar functionality, they serve different audiences and have been architected differently due to safety and criticality considerations.

Based upon health and status information provided by various aircraft systems, CAS determines the overall functional capability of the aircraft. The flight crew uses CAS to determine the fitness of the aircraft for flight, governed by the minimum equipment list that defines those systems that must be fully functional to initiate or continue a flight. Because CAS plays a significant role in the operation of the aircraft, it is classified as a safety-critical system and is subject to stringent development and certification processes.

CAS also serves a secondary audience. Upon completion of the flight, the aircraft maintainer uses CAS messages as one method of determining aircraft repair needs. These messages typically display only failure symptoms and effects. To address the fault isolation and repair needs of the aircraft maintainer, an onboard maintenance system is often used. This system collects health and status information from aircraft systems in real-time, applies fault isolation logic, and correlates the failures to CAS messages. This correlation enables the aircraft maintainer to determine which faults caused the CAS messages to appear and take the necessary corrective action to repair the aircraft and clear the CAS messages. This is important since the aircraft maintainer declares the aircraft has been returned to its nominal operating state following repair actions by using the “dark cockpit” approach, that is, the absence of CAS messages imply an airworthy healthy aircraft.

The ultimate role of the onboard maintenance system in aircraft repair is that of a tool the aircraft mechanic uses, and not the final judge of aircraft health—that role is fulfilled by CAS. As such, the onboard maintenance system is typically classified as a not safety-critical and is subject to much less stringent development and certification processes. Promoting the role of IVHM from that of a maintenance-only role to an aircraft operation role by providing flight crew visibility creates IVHM system design and certification challenges, as well as human factors challenges. This AIR addresses only the human factors challenges.

3.1.1 Cockpit Design and Presentation

The design of the cockpit has one specific task, namely, to provide a safe and efficient interface with the crew. However, the design can vary greatly between manufacturers and few standards exist for interface methods, although various guidelines are available. Unlike the technical system approval process that follows strict international standards and testing criteria, the human factors interface evaluation lacks such standards; however, guidelines—for example, AC 25-1302 and RTCA DO-372—exist. On the other hand, a desire to maintain cockpit similarity between families of aircraft can hinder the integration of new technologies such as IVHM.

New equipment presents a higher risk when different people must communicate with each other. Hierarchy is sometimes an issue here. This is a very important issue in the cockpit where very determined and strong-willed individuals must communicate.

In many cases, the accessories—flashy “nice to have” equipment—are a major item in the contract and sales but it is not so common to do a proper evaluation of the crew’s ability to use it. Only relevant information is wanted by the crew, but the definition of relevant information changes with stress and workload and has been found difficult to determine.

There is no standard position for all the different keys and warning lights and several function keys have a different use in each design. Take the navigation (NAV) key, for example: In one design it is used for navigation, while in other designs it is used for planning only. The flight plan (FPLN) keys in one design are used for planning while in others they are used for navigation. These features increase the risk of mistakes when transitioning between systems, thus requiring additional training for pilots.

There is also a lack of industry standards for color-coding which makes the task of integrating avionics difficult. The FAA does give some guidance but it is not obligatory.

Another dilemma is what type of text format to be used on the displays. The method of displaying text has traditionally used capital letters only. This might have been used due to software limitations in early days. Several research results show that a mixed case is easier to read, especially for longer text messages. The mixed case showed a much higher level of correct recall compared with the capitals only messages (see References 1 and 2).

3.1.2 Warning Design

Considering the risk of alerts during critical situations, annunciation must be obvious and trigger immediate attention. A warning should be given both visually and audibly. If the warning is only visual, the pilot needs to always have the notification panel within his field of view. Information about the failure must be presented in a way that the pilot does not have to go head down or release the controls.

All this data must be coordinated and prioritized such that the presentation, classification, annunciation, and failure criticality is generally consistent to avoid overload and confusion.

14 CFR 25.1309 (Reference 12) and AC 25-1309 (Reference 13) give significant guidance on alerting systems. Also refer to CS 25.1322 (Reference 14) and its associated AMC 25.1322 (Reference 15). Criticality is only one parameter or to be more specific, it could be broken down into:

- Always critical, immediate action needed whenever the failure occurs; e.g., APU fire, engine fire.
- Critical, needing immediate attention in certain situations; e.g., pitch control failure.
- Critical, but pilot actions do not have to be executed immediately.
- Loss of redundancy, no specific actions but higher risk exposure.

Different airplanes have different means of presenting text messages for information and warning. Each method usually has a philosophy behind it; some based on pilot action required, and some based on an index system.

Examples of three methods to display text of a hydraulic failure are given below. They are based on aircraft types commonly in use:

Side - system - function - status R HYD PRESS LO

System - side - function - status HYD R PRESS LO

System - function - status-side HYD PRESS LO R

There are different components of comprehension in regards to warning messages. Readability, coherence, explicitness, and brevity are important issues when looking at verbal messages. If pictorial symbols are used, the target user population, their experience with the product, competence, and hazard perception must be known and accounted for.

What humans perceive as the truth is often only attitudes and beliefs. This is very important to remember in order to understand risk perception when evaluating a warning message. Beliefs are any cognitive content, which is held as being true. If people do not believe that they need to take precautions, they will ignore the warnings.

3.1.3 Human Error Risks

Some factors that may appear to be purely technical in nature are, in fact, driven by human desires, needs, prejudices, etc. Human factor errors can be based on culture and hierarchy between pilot and crew. The cultural makeup of a certain individual can play a major role in how he or she reacts in a particular situation. Taking into account operator cultural and language variations, the interface must be clear, intuitive, and easy to understand. Cultural and language differences are seldom considered when determining text interface and a common assumption is that all users are fluent in the English language.

Unlike machines, humans have differing levels of motivation, awareness, or attitude, which will affect the conclusion that is drawn. Having reached a conclusion, humans react by making one or more decisions. In the absence of clear instruction, these decisions may be influenced by a variety of physical or psychological factors, which can lead to errors in the next stage, action, which is in turn followed by sensory feedback in that action and which may generate further errors.

The difficulty is to warn for unexpected failure but not to give false alarms. There is a tendency to think that computers are infallible.