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Description:

A view of the Wright Model A Flyer
in flight with a passenger onboard.

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FUNCTIONAL VISUALIZATIONS OF A HYDROGEN-ELECTRIC AIRCRAFT PROPULSION SYSTEM FOR SUPPORTING PILOT DECISION-MAKING

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Cognitive Work Analysis (CWA) and Ecological Interface Design (EID) were used to design a novel flight deck display for a regional turboprop aircraft that is being retrofitted with a Hydrogen Aircraft Powertrain Storage System (HAPSS). This research addresses the challenges of managing cognitive complexity in next-generation aviation systems, focusing on designing interfaces based on system constraints which are modeled through the Abstraction Hierarchy (AH). Visualizations were discussed in interviews with subject matter experts highlighting the need for further matching the mental model of the pilot by addressing simplicity, workload, and use case representations on the display. The iterative process included static and dynamic display testing and focused on three flying scenarios. Future research should involve controlled human-in-the-loop experiments with a larger participant pool to discuss, iterate, and test the proposed display designs.

With the growing emphasis on environmentally friendly aviation (Afonso et al., 2023), hydrogen as a fuel source has emerged as a potential replacement for traditional kerosene-based powertrains (Yusaf et al., 2024). This transition introduces additional complexity to traditional aircraft fuel systems by incorporating new energy transitional states and storage components (Adler&Martins, 2023). As a result, pilots' existing mental models of fuel systems will change, implying a re-evaluation of traditional aircraft display designs.

Traditional display design methods often focus on optimizing the presentation of information based on established guidelines, such as color contrast and layout efficiency. While these methods enhance the clarity and accessibility of data, they primarily support Rule-Based Behavior (Rasmussen, 1983) and may not adequately assist pilots in understanding complex system relationships, especially during unexpected or emergency situations. This limitation highlights the need for interface design frameworks that better support Knowledge-Based Behavior (Rasmussen, 1983) in complex systems. Cognitive Work Analysis (CWA) and Ecological Interface Design (EID) offer structured approaches to designing human-machine interfaces that make complex system relationships more salient and visually insightful. These frameworks have been successfully applied in various safety-critical domains where operators need insight into the complexity of their control problems, such as process control (Vicente&Rasmussen, 1992), traffic supervision (Feuerstack&Saager, 2022), and aviation (Dinadis&Vicente, 1999).

Notably, the work of Dinadis and Vicente (1999) demonstrated how EID could enhance pilot understanding and decision-making by providing deeper insights into the interactions of a fuel system. This research inspires us to apply the same approach to new-generation propulsion systems, such as HAPSS, with which pilots are not yet familiar.

Background

The introduction of hydrogen-electric propulsion systems necessitates a reevaluation of the cockpit's informational architecture due to the distinct operational parameters and monitoring requirements associated with these advanced technologies. Unlike traditional engines, hydrogen fuel cells involve complex subsystems such as hydrogen storage and distribution, fuel cell stacks, and electrical power management, each requiring precise monitoring and control. This shift allows for the design and implementation of new display interfaces that can more effectively present real-time data related to hydrogen levels, fuel cell efficiency, electrical output, and safety systems. The opportunity to incorporate advanced data visualization techniques, such as connected graphics and historical analytics, can enhance operator decision-making (Burns&Hajdukiewicz, 2004). Furthermore, this transition offers the potential to explore different frameworks to design the layout and hierarchy of information, prioritizing critical data.

Methods

Scope and scenario design

The scope of this research is centered on propulsion system management within the context of a retrofitted hydrogen fuel cell Dash 8 Q300 aircraft. Unlike broader analyses that encompass the entire flight mission management, this study specifically focuses on the complexities introduced by integrating hydrogen-electric propulsion technology into existing aircraft systems. By narrowing the scope to propulsion system management, we aim to provide a detailed examination of how pilots interact with this new type of propulsion system during various phases of flight.

Three scenarios were created in cooperation with a commercial pilot and the airworthiness engineer. Scenario 1 subjects the test pilot to a high oil temperature alert, scenario 2 describes an imbalance of fuel between the tanks, and scenario 3 shows a loss of power on one motor. The demographics are represented in Table I. These events can occur both on traditional powertrains as well as on the HAPSS platform but contain slight differences in the expected operational reaction of the pilot.

Table I

Demographics of the participants

Participants	Profession	Age	Experience	Education
Participant 1	Commercial Pilot	26	2 Years	B.Sc. Mathematics
Participant 2	Airworthiness Engineer	29	5 Years	M.Sc. Aerospace Engineering
Participant 3	Test Pilot	66	29 Years	B.Sc. Electrical Engineering

Iterative Design linked to CWA and EID

The iterative design of cockpit displays, anchored in CWA and EID, serves as a systematic approach to developing interfaces that aim to enhance pilot interaction with complex aviation systems. CWA provides a comprehensive framework for understanding the cognitive and contextual factors that influence pilot decision-making and task execution. By decomposing the work domain into various levels of abstraction, CWA helps identify the essential relationships between the system's components, their functions, and the overall goals. This is known as the Work Domain Analysis (WDA). EID complements this approach by focusing on the design of interfaces that support direct perception and action, minimizing the cognitive load on operators once they are trained properly (Arrabito et al., 2009). Incorporating test pilot interview feedback into this design process allows for the integration of empirical insights, ensuring the display system is grounded in practical experience. Their input enables the design team to refine the interface, improving its alignment with real-world operational demands and user expectations. Through successive iterations, the cockpit display evolves, integrating findings from CWA and EID with practical feedback from pilots.

Technical Aspects

The 2-hour long semi-structured interviews, either took place in person or on the online meeting platform Microsoft Teams. They were recorded for audio when done in person and recorded for audio and video when done online. After the interviews, the audio was transcribed, anonymized, and stored on a password-protected computer as well as backed up to a Onedrive account. The displays were created in Inkscape and animated in Svelte.

Results

The five levels of Abstraction are visualized in Figure I below and described layer by layer.

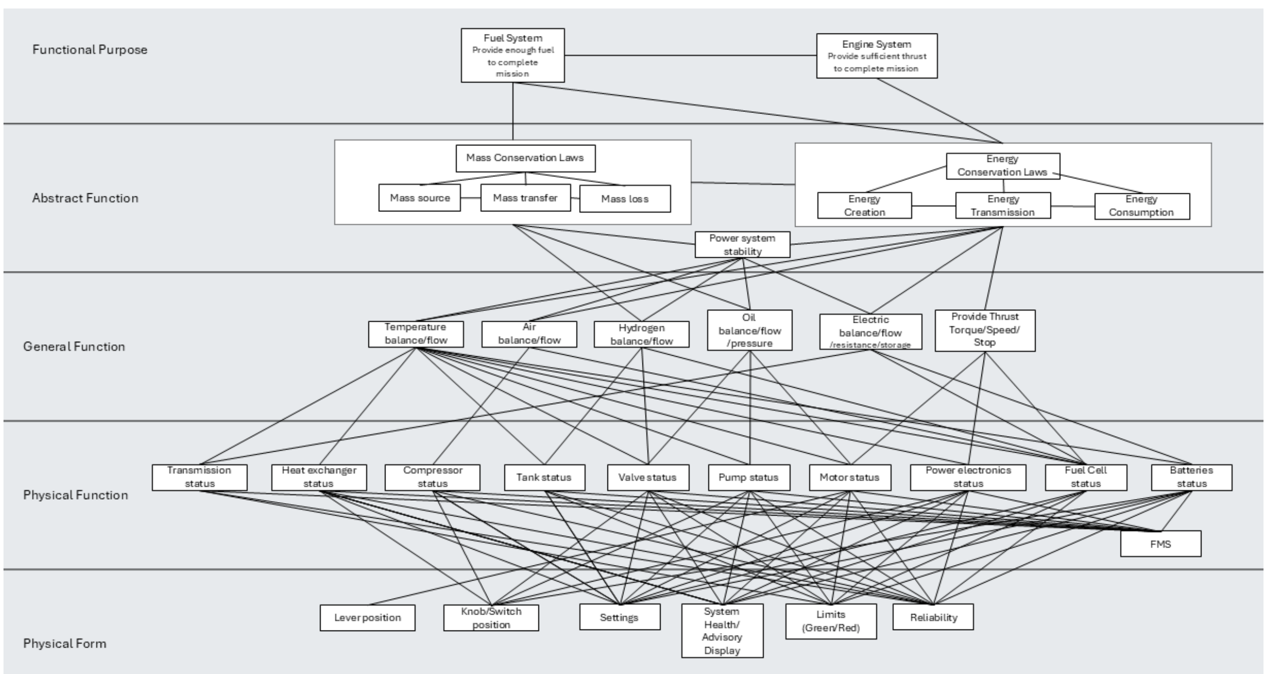

Figure I: AH of the powertrain of a HAPSS

Functional Purpose: The uppermost level of the AH consists of two different blocks that make up the functional purpose of the powertrain. The two blocks are the fuel system and the engine system respectively. The fuel system defines its functional purpose as providing enough fuel to complete the mission while the engine system is defined by the need to provide sufficient thrust to complete the mission. A similar example of a non-hydrogen powertrain can be found in the existing literature where Nick Dinadis and Kim Vicente explore the fuel system for a Hercules C130 (Dinadis&Vicente, 1999).

Abstract Function: The abstract function is composed of multiple blocks that relate to the laws of energy and mass conservation. These can be expanded to be more specific but are kept simplified in the diagram. Indeed the Energy Transmission block could be expanded to Ohmic losses and other transmission losses as an example.

General Function: The general function layer is composed of the different processes present in this powertrain. These are mainly related to the balance and flow of air, fuel, temperature, oil, and electricity. There is additionally a component concerning the process related to thrust production.

Physical Function: The physical function layer is decomposed into all the different subsystems of the HAPSS. It is possible to analyze how these interact with each other by following their respective connecting segment to the general function layer. By doing this, it is possible to understand which variables are connected to which system and subsystem and how these work in collaboration with each other. These can be visually relevant for the pilot to interpret the state of the powertrain in its entirety.

Physical Form: Due to the prototype nature of the system, there is little use for a description at a component level (such as specific power switches or valves) because the system is not yet finalized and is subject to change. The physical form layer refers more to the human-machine interactions such as the settings, limits, and reliability of the system.

Connection to the display design

Using the AH, it is possible to define interacting systems and components that could help represent the powertrain as a whole and not variables in isolation. Once these connections are made, it is possible to categorize variables that are relevant to the model representation of the system. These variables represent different characteristics of components of each subsystem. These are listed to sort them by the appropriate display. Using the Visual Thesaurus for Data Relationships (Burns&Hajdukiewicz, 2004) it is then possible to associate the different variables with the corresponding representation which is then used as a basis to create the displays.

Five interconnected displays resulted from the AH and are shown on a Multi-Function Display. Three of the five displays created are represented below (Figure II-IV).

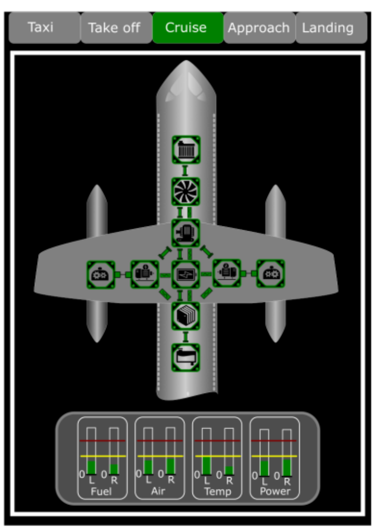

Figure II: Synoptic and stability display

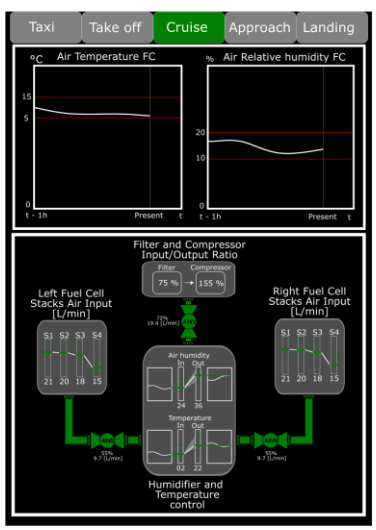

Figure III: Power monitoring display

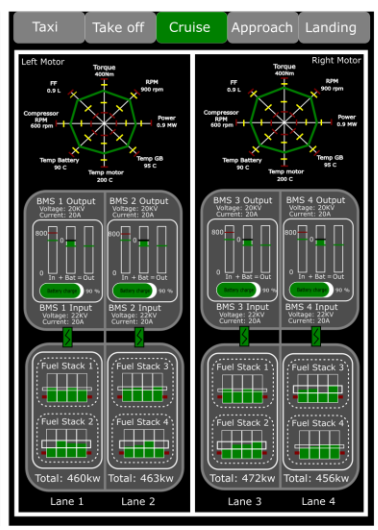

Figure IV: Air monitoring display

The synoptic and stability overview (Figure II) can lead to four different subsystem views namely the Air Monitoring (Figure III), the Power Monitoring (Figure IV), Fuel monitoring and Temperature monitoring.
There are consistent representations between the five displays such as the variable being associated with color changes when crossing an attention limit (yellow) and a need for action limit (red), the color green indicates a healthy state. Another example of consistency is the connectors between the systems represented as electrical, mechanical, or fluid links that illustrate the state of these transmission links.

Interview analysis

An inductive coding approach was used to analyze the interview transcript. The main themes that emerge across the different interviews relate to simplifying the visualizations (according to color, graphical representation, error prevention and clarity), addressing the workload component (according to cognition) that pilots want to mitigate during flights, and the use case of prototype aircraft versus commercial implementations.
The short flights of the Dash 8 makes the amount of time dedicated to Knowledge-Based Behaviour limited. There is an emphasis on immediately following the Quick Reference Handbook which can be associated with Rule-Based Behaviour.

Discussion

One of the main themes gathered during this project was the difference between designing displays for engineering purposes rather than for pilots: designing visualizations that are too complex to be used as a main display, but are more adapted as support displays, in case of large-scale malfunction during flight, pre-flight or post-flight checks. The main feedback gathered focuses on the pilot's lack of time on regional flights. This showcases the importance of only displaying relevant information that can be established during the WDA. The accessibility of the different displays in this case leads the pilot deeper into the system architecture but only if the pilot decides this is a necessary step in order to understand the issue that arises. Full system visualizations, as seen in previous literature (Dinadis&Vicente, 1999) are in this case not the best representation due to the expressed need for a limited workload. The pilot should have access to the information by using a navigational tool such as buttons located under the display if this information is needed. The main display should represent the overall health of the system, as seen in Figure II. The choices of selecting participants with both knowledge of the Dash 8 platform and the functioning of HAPSS severely limited the pool of available candidates. Additional testing with a more complex scenario could reveal the real strength of these displays as a more complex scenario would likely increase the system-wide interactions.

Conclusion

This study investigated the application of CWA and EID in the development of a novel display for a Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system. The findings are informed by interviews conducted with a regional commercial pilot, an airworthiness engineer, and a test pilot, which provided critical insights into the practical requirements and challenges associated with display design in aviation. The overarching themes are related to the specific application of the displays as well as the simplicity of the visualizations and the wanted reduction in cognitive workload.

Acknowledgment

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